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Towards Sustainable Farmland Fragmentation Management: A comprehensive Analysis and Modelling of Scenarios in Rwanda

Pierre Damien NTIHINYURWA

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1. Prof. Dr. Walter Timo de Vries
2. Prof. Dr. Anka Lisec

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Summary

Scientifically, both farmland fragmentation and farmland consolidation (defragmentation) are two sides of the same coin, theoretically and paradoxically considered as land management tools. Whereas farmland fragmentation is generally considered harmful and criticised for limiting farm efficiency and scale economies, there have been growing claims for its positive considerations (mainly related to climate change adaptation, crop diversification, exploitation of multiple diverse agro-ecological zones, production risks and land ownership and use related conflicts management, household food security and sovereignty, and farmland tenure security) which justify its persistence in the farming sector. However, since both standpoints (positive and negative) are academically and scientifically accepted, this poses a major dilemmatic problem to farmland policymakers and research scholars (whether they should devise policies and recommendations in favour of defragmentation or fragmentation conservation in farmland) as a knowledge gap. In order to address this gap, there was a need to generate comprehensive theoretical knowledge models about the typology of farmland fragmentation scenarios (***What***) and the conditions under which they become problematic and beneficial **(*When* *and* *Where)***, which could potentially show (***How*** *and* ***Why)*** one can opt for farmland fragmentation conservation or defragmentation policies for sustainable farmland fragmentation management, and their empirical test in a case study.

Therefore, following a pragmatic paradigm and soft systems methodology that relies on social dynamic research epistemology, this research intended to address this dilemma by deriving meaningful and appropriate answers to these three main research questions on farmland fragmentation paradox using the Rwandan context as a case study through a mixed methods research approach and multiphase exploratory sequential research design. To this end, an integrative concept-centric qualitative approach following the rationalist theory and deductive logical reasoning was conducted to generate three abstract theoretical models hypothetically stipulating the diversity and the coexistence of both tenure and physical beneficial and problematic farmland fragmentation forms in a set of 40 distinct scenarios and their sustainable management for food security and farmland tenure security motives. Drawing from the theoretical socio-spatial, economic, demographic, physical and agro-ecological diversity of 12 agro-ecological zones of Rwanda, semi-subsistence socio-spatial and economic conditions, farmland scarcity and the presence of land use consolidation program in the country, the study adopted a mixed methods research approach to empirically test these theoretical farmland fragmentation scenarios models in 24 distinct national-level statistically representative sites of the country. This empirical study was done through a comprehensive analysis of practically possible socio-physical farmland fragmentation scenarios and their causal-effects relationships statistical modelling from 487 farm households-level survey data and 14951 parcels from the landscape–level cadastral survey dataset.

The findings are fivefold: 1) A typology of seventeen farmland fragmentation scenarios grouped into five distinct classes and their significant spatial and topographical diversity across the 24 research sites from 12 AEZs of Rwanda was identified. These scenario classes include: *Physical & Tenure Fragmentation*; *Physical-Use-Tenure Fragmentation*; *Physical-Internal-Use & Tenure Fragmentation*; *Physical-Internal-Dispersion & Tenure Fragmentation*; and *Physical-Internal-Dispersion-Use & Tenure Fragmentation*. The pooled national-level values indicated the general trends of very high to excessive levels of landscape, high to extensive levels of tenure (in terms of ownership), high level of shape, moderate levels of internal, dispersion (scattering), use and usership, and low level of location (distance) fragmentation forms at statistically significant different degrees across research sites and AEZs. 2) A coexistence of both physical and tenure, problematic and beneficial farmland fragmentation forms at different degrees under different scenarios and socio-spatial analysis levels, mainly in farmland tenure-landscape-internal-dispersion-use and shape fragmentation predominant scenario in the country was found. This coexistence was justified as the farmers' choice for farmland tenure security, climate change adaptation and risk management through the exploitation of multiple agro-ecological zones and crop diversification,

and the multidimensional household food security and sovereignty on the one hand, and its adverse effects on farm efficiency and income, economies of scale, and farmland loss through boundaries on the other hand. 3) Farmland scarcity and population density, egalitarian-based partible inheritance (succession) principles and land distribution programs, agro-ecological diversity, climate change adaptation, farmland use consolidation (LUC) and land sharing programs, individual statutory private land tenure system and unrestricted land market, limited off-farm employment opportunities and farmland psychology were found as the main significant factors of farmland fragmentation in the country, mainly for farmland tenure and household food security motives. 4) The broad perception of farmland fragmentation inefficiency and problematic connotation *per se* was rejected in the study area since no statistically significant evidence was found to confirm the superiority of the negative impacts of farmland fragmentation over the positive ones. 5) The distance aspect was not a statistically significant factor in the classification of internal-location and dispersion fragmentation scenario as problematic since most parcels of the same farm were found to be located in the same topographical location within a radius of less than 1 km. Therefore, these findings support the popular argument for farmland fragmentation conservation stipulating the ability of small internally fragmented farms with scattered parcels to mitigate and buffer the adverse effects of tenure and farm landscape fragmentation under heterogeneous agro-ecological conditions, and the defragmentation approaches of internally fragmented and scattered farms under homogeneous agro-ecological conditions in the Rwandan context.

This diversity of farmland fragmentation scenarios implies the diversity and the localisation of their management strategies and intervention programs tailored to the needs and concerns of local farmers and conditions, which should be taken into account by farmland use policymakers and research scholars. Under the existing farmland scarcity conditions in Rwanda, this research recommends a paradigm shift in farmland management and use policies and interventions design from the focus on market-oriented agriculture expansion on large-scale consolidated farms for scale economies, towards an emphasis on policy perspective supporting small-scale farms intensification for efficient use of scarce farmland resources. Furthermore, these findings could support the government of Rwanda to devise scientifically informed decisions towards the achievement of its sustainable development goals and targets reflected in the UN-SDGs (1.4; 2.1, 2, 3, 4 and 5; 12.2; 13.1; and 15.3, 4, 5 and 9) of the agenda 2030 and the national Vision 2050, and be usefull in other sub-Saharan African Countries with similar conditions. Finally, considering the heterogeneous local social, demographic, economic, physical and agro-ecological conditions, the predominance of subsistence and rain-fed hillside agriculture, high incidence and vulnerability to climate change consequences and natural and weather shocks in the study area, and the identified diverse typology of farmland fragmentation scenarios despite the existence of farmland fragmentation combat strategies like land use consolidation and its supporting programs for food security purposes, this study questions the suitability of these strategies and interventions. It, therefore, inductively hypothesises and underscores their insufficiency and irrelevancy, a positive relationship between farmland fragmentation and household food security, and the unsuitability of modern government-led farmland consolidation programs for managing the identified farmland fragmentation scenarios in the country. Thus, it recommends a comprehensive critical performance and relevance analysis of these strategies and interventions with regard to farmland fragmentation and multidimensional food security nexus in the country; rigorous comparative study of the performance and competitiveness of small-scale and big farms in terms of socio-economic, spatial and agro-ecological aspects; the suitability analysis of farmland consolidation models; and the modelling of Fit-for Rwanda theoretical sustainable farmland fragmentation management strategies and interventions tailored to the specific and localised fragmentation scenarios, and their empirical test in the country as further research calls.

Keywords: farm; farmland parcel; farmland block, landscape; farmland fragmentation; farmland defragmentation; food security and sovereignty; farmland tenure security; farm efficiency; scenarios modelling; climate change adaptation; UN-SDGs (1,2,12,13,15); sustainable farmland fragmentation management

Zusammenfassung

Wissenschaftlich gesehen sind sowohl die Zerstückelung als auch die Flurbereinigung (Defragmentierung) landwirtschaftlicher Flächen zwei Seiten derselben Medaille, die theoretisch und paradoxerweise als Instrumente der Landbewirtschaftung betrachtet werden. Während die Zerstückelung der landwirtschaftlichen Nutzflächen im Allgemeinen als schädlich angesehen und kritisiert wird, weil sie die Effizienz der landwirtschaftlichen Betriebe und die Skalenerträge einschränkt, werden zunehmend positive Aspekte geltend gemacht (vor allem im Zusammenhang mit der Anpassung an den Klimawandel, der Diversifizierung der Kulturen, der Nutzung verschiedener agroökologischer Zonen, den Produktionsrisiken und dem Konfliktmanagement in Bezug auf Landbesitz und -nutzung), die ihr Fortbestehen in der Landwirtschaft rechtfertigen, weil sie die Sicherheit der Eigentumsrechte an den landwirtschaftlichen Flächen und die Ernährungssicherheit der Haushalte gewährleisten. Da jedoch beide Standpunkte (positiv und negativ) akademisch und wissenschaftlich anerkannt sind, stellt dies die politischen Entscheidungsträger und Forscher vor ein großes Dilemma (ob sie politische Maßnahmen und Empfehlungen zugunsten der Defragmentierung oder der Erhaltung der Zerstückelung von landwirtschaftlichen Nutzflächen ausarbeiten sollen), das eine Wissenslücke darstellt. Um diese Wissenslücke zu schließen, war es notwendig, umfassende theoretische Wissensmodelle über die Typologie der Zerstückelungsszenarien (***Was***) und die Bedingungen, unter denen sie problematisch und vorteilhaft werden (***Wann*** und ***Wo***), zu entwickeln, die potenziell zeigen könnten (***Wie*** und ***Warum***), dass man sich für die Erhaltung der Zerstückelung von Ackerland oder für Defragmentierungsstrategien für ein nachhaltiges Management der Zerstückelung von Ackerland entscheiden kann, und sie in einer Fallstudie empirisch zu testen.

Daher soll diese Studie, die einem pragmatischen Paradigma und einer Soft-Systems-Methodologie folgt, die sich auf eine sozialdynamische Forschungsepistemologie stützt, dieses Dilemma angehen, indem sie aussagekräftige und angemessene Antworten anhand des ruandischen Kontexts als Fallstudie mit Hilfe eines Forschungsansatzes mit gemischten Methoden ableitet. Zu diesem Zweck wurde ein integrativer konzeptzentrierter qualitativer Ansatz verwendet, der der rationalistischen Theorie und dem deduktiven logischen Denken folgt, um drei theoretische Modelle zu entwickeln, die sich direkt mit den drei Hauptforschungsfragen zum Paradoxon der Zerstückelung von Ackerland befassen. Das Ergebnis sind drei generische theoretische Modelle, die hypothetisch die Vielfalt und die Koexistenz von sowohl vorteilhaften als auch problematischen Formen der Zerstückelung von Ackerland in einer Reihe von 40 verschiedenen Szenarien und deren nachhaltiges Management für die Ernährungssicherheit und die Motive der Besitzsicherheit von Ackerland festlegen. Ausgehend von der theoretischen sozio-räumlichen, wirtschaftlichen, demographischen, physischen und agro-ökologischen Vielfalt der 12 agro-ökologischen Zonen Ruandas, den sozio-räumlichen und wirtschaftlichen Bedingungen der Semi-Subsistenzwirtschaft und dem Vorhandensein von Landnutzungsflurbereinigungsprogrammen im Lande wurde in der Studie ein Forschungsansatz mit gemischten Methoden gewählt, um diese theoretischen Szenarien für die Zerstückelung von Ackerland an 24 verschiedenen statistisch repräsentativen Standorten des Landes empirisch zu testen. Diese empirische Studie wurde durch eine umfassende Analyse praktisch möglicher sozio-physikalischer Szenarien der Zerstückelung landwirtschaftlicher Nutzflächen und ihrer kausalen Wirkungszusammenhänge auf der Grundlage statistischer Modelle für 487 Erhebungsdaten landwirtschaftlicher Haushalte und 14951 Parzellen aus dem Katasterdatensatz auf Landschaftsebene durchgeführt.

Die Ergebnisse sind fünffach: 1) Es wurde eine Typologie von siebzehn Szenarien für die Zerstückelung von Ackerland identifiziert, die in fünf verschiedene Klassen eingeteilt sind, und deren signifikante räumliche und topografische Vielfalt in den 24 Untersuchungsgebieten in 12 AEZ Ruandas. Zu diesen Szenario Klassen gehören: Physische und Besitzzerstückelung; Zerstückelung der physischen Nutzung und des Besitzes; Zerstückelung der physischen internen Nutzung und des Besitzes; Zerstückelung der

physischen internen Streuung und des Besitzes sowie Zerstückelung der physischen internen Streuung der Nutzung und des Besitzes. Die gepoolten Werte auf nationaler Ebene zeigten die allgemeinen Tendenzen einer sehr starken bis übermäßigen Landschaftszerstückelung, einer starken bis starken Besitzzerstückelung (im Sinne von Eigentum), einer starken Formzerstückelung, einer mäßigen internen Dispersion (Streuung), einer Nutzungs- und Verwendungszerstückelung und einer geringen Standortzerstückelung (Entfernung) in statistisch signifikantem Ausmaß über alle Untersuchungsgebiete und Umweltzonen hinweg. 2) Eine Koexistenz von sowohl physischer als auch eigentumsrechtlicher, problematischer und vorteilhafter Zerstückelung des Ackerlandes bildet sich in unterschiedlichem Ausmaß unter verschiedenen Szenarien und sozialräumlichen Analyseebenen, hauptsächlich in dem im Land vorherrschenden Szenario der Zerstückelung von Ackerland durch Eigentum, Landschaft, interne Streuung, Nutzung und Form. Diese Koexistenz wurde damit begründet, dass die Landwirte sich einerseits für die Sicherheit des Besitzes von Ackerland, die Anpassung an den Klimawandel und das Risikomanagement durch die Nutzung mehrerer agroökologischer Zonen und die Diversifizierung der Anbaupflanzen sowie die mehrdimensionale Ernährungssicherheit und -souveränität der Haushalte entschieden haben und andererseits für die negativen Auswirkungen auf die Effizienz und das Einkommen der Betriebe, die Größenvorteile und den Verlust von Ackerland durch Abgrenzung. 3) Landknappheit und Bevölkerungsdichte, agrarökologische Vielfalt, Klimawandel, Landnutzungsflurbereinigung (LUC) und Landaufteilungsprogramme, auf Gleichberechtigung basierende Prinzipien für die Teilung von Erbschaften (Nachfolge) und Landverteilungsprogramme, begrenzte außerlandwirtschaftliche Beschäftigungsmöglichkeiten und landwirtschaftliche Psychologie wurden als die wichtigsten Faktoren für die Zerstückelung der landwirtschaftlichen Nutzflächen in dem Land aus Gründen des Landbesitzes und der Ernährungssicherheit der Haushalte ermittelt. 4) Die weit verbreitete Auffassung, dass die Zerstückelung landwirtschaftlicher Flächen ineffizient und per se problematisch ist, wurde im Untersuchungsgebiet zurückgewiesen, da keine statistisch signifikanten Beweise gefunden wurden, die die Überlegenheit der negativen Auswirkungen der Zerstückelung landwirtschaftlicher Flächen gegenüber den positiven bestätigen. 5) Der Entfernungsaspekt war kein statistisch signifikanter Faktor bei der Einstufung des Szenarios der internen Lage und der Streuung der Zerstückelung, als problematisch, da die meisten Parzellen ein und desselben landwirtschaftlichen Betriebs in einem Radius von weniger als 1 km in der gleichen topografischen Lage lagen. Deshalb stützen diese Ergebnisse das gängige Argument für die Erhaltung der Zerstückelung von Agrarland, das besagt, dass kleine, intern fragmentierte Betriebe mit verstreuten Parzellen in der Lage sind, die negativen Auswirkungen der Besitzverhältnisse und der Zerstückelung der Agrarlandschaft unter heterogenen agrarökologischen Bedingungen abzumildern und abzupuffern, sowie die Defragmentierungsansätze für intern fragmentierte und verstreute Betriebe unter homogenen agrarökologischen Bedingungen im ruandischen Kontext.

Diese Vielfalt der Szenarien für die Zerstückelung von Ackerland impliziert die Vielfalt und Lokalisierung ihrer Bewirtschaftungsstrategien und Interventionsprogramme, die auf die Bedürfnisse und Anliegen der lokalen Landwirte und Bedingungen zugeschnitten sind. Angesichts der bestehenden Knappheit an Ackerland in Ruanda empfiehlt diese Studie einen Paradigmenwechsel bei der Bewirtschaftung und Nutzung von Ackerland und bei der Gestaltung von Interventionen, weg von der Konzentration auf marktorientierte landwirtschaftliche Expansion in konsolidierten Großbetrieben zur Erzielung von Größenvorteilen hin zu einer politischen Perspektive, die die Intensivierung von Kleinbetrieben zur effizienten Nutzung der knappen Ackerlandressourcen unterstützt. Darüber hinaus könnten diese Ergebnisse die Regierung Ruandas dabei unterstützen, wissenschaftlich fundierte Entscheidungen zu treffen, um die Ziele für eine nachhaltige Entwicklung zu erreichen, die in den UN-SDGs (1.4; 2.1, 2, 3, 4 und 5; 12.2; 13.1; und 15.3, 4, 5 und 9) im Rahmen der Agenda 2030 und der nationalen Vision 2050 sowie in anderen afrikanischen Ländern südlich der Sahara mit ähnlichen Bedingungen zum Ausdruck kommen. Abschließend werden die heterogenen sozialen, demografischen, wirtschaftlichen, physischen

und agrarökologischen Bedingungen vor Ort, das Vorherrschen von Subsistenz- und regengespeisten Hanglandwirtschaft, die hohe Häufigkeit und Anfälligkeit gegenüber Folgen des Klimawandels sowie Natur- und Wetterschocks im Untersuchungsgebiet berücksichtigt Trotz der Existenz von Strategien zur Bekämpfung der Zerstückelung landwirtschaftlicher Nutzflächen wie der Landnutzungsflurbereinigung und den dazugehörigen unterstützenden Programmen zur Ernährungssicherung wurden in dieser Studie unterschiedliche Typologien von Szenarios zur Zerstückelung landwirtschaftlicher Nutzflächen identifiziert. Die Eignung dieser Strategien und Interventionen wird in dieser Studie jedoch in Frage gestellt. Es stellt daher induktiv Hypothesen auf und unterstreicht deren Unzulänglichkeit und Irrelevanz, einen positiven Zusammenhang zwischen der Zerstückelung landwirtschaftlicher Nutzflächen und der Ernährungssicherheit der Haushalte sowie die Ungeeignetheit moderner staatlich geführter Programme zur Flurbereinigung landwirtschaftlicher Nutzflächen zur Bewältigung der identifizierten Zerstückelungsszenarien landwirtschaftlicher Nutzflächen im Land.

Schlüsselwörter: Landwirtschaftlicher Betrieb; Landwirtschaftliche Parzelle; Landwirtschaftlicher Block, Landschaft; Fragmentierung der landwirtschaftlichen Flächen; Defragmentierung der landwirtschaftlichen Flächen, Ernährungssicherheit und -souveränität; Sicherheit der landwirtschaftlichen Besitzverhältnisse; Effizienz der landwirtschaftlichen Betriebe; Modellierung von Szenarien; Anpassung an den Klimawandel; Nachhaltiges Management der Fragmentierung landwirtschaftlicher Flächen

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1. Introduction

1. 1. Research Preface and Justification

This dissertation is the outcome of a long research and empirical testing process which started in July 2018. This culminated in three integrative (exploratory) theoretical review journal articles and one exploratory empirical journal article, which served as the theoretical and conceptual fundaments for the empirical study within the ongoing policy framework of developing the sustainable Fit-for Rwanda farmland fragmentation management models as the long-term goal.

While the farmland fragmentation topic is not new in academics, it has gained renewed attention in developing countries characterised by fragmented subsistence farms, high population densities, land scarcity, diverse biophysical and ecological conditions, the ever-increasing climate change vulnerability, and food insecurity patterns. Scientifically, both farmland fragmentation and farmland consolidation (defragmentation) are two sides of the same coin, theoretically and paradoxically considered as land management tools. Whereas farmland fragmentation is generally considered harmful for reducing farm efficiency, there have been growing claims for its positive considerations and reasons why it persists in many countries despite the existence of its combat strategies. These positive claims are mainly related to climate change adaptation, crop diversification, exploitation of multiple diverse agro-ecological zones, production risks and land ownership and use-related conflicts management for land tenure security and food security purposes. This polarised nature stipulates the spatial coexistence of beneficial and problematic farmland fragmentation scenarios, explained by the diversity in socio-spatial, economic, demographic, physical and agro-ecological conditions of an area. However, since both standpoints (positive and negative) are academically and scientifically accepted, this poses a significant dilemma for farmland policymakers regarding whether they should devise policies in favour of defragmentation or fragmentation conservation in farmland. This dilemma is grounded in the lack of comprehensive knowledge about farmland fragmentation scenarios and their suitable management strategies and interventions. The empirical experience has revealed that the success and suitability of farmland fragmentation management strategies are dictated by the specificity of fragmentation scenarios and local conditions and governance factors of a country since the strategy which works well in one country or specific area might not function in another [1-4]. The documented evidence highlighted failures of European land consolidation programs and models in sub-Saharan African countries, including Rwanda, due to the overlook of local conditions during their design and implementation [1, 3-7]. This paradoxical nature of farmland fragmentation discourse and its management knowledge gap call for more comprehensive research about various forms and categories of farmland fragmentation and the conditions under which they become problematic and beneficial in a set of distinct informative scenarios to guide the decision-making process about its management for sustainable agriculture production, household food security and farmland tenure security. Scholars of this research stance call for the assessment of farmland fragmentation patterns (forms, causes and both problematic and beneficial impacts) in different case areas to derive the typology, similarities and disparities in fragmentation and defragmentation semantics, which can inform or guide the design and implementation of localised farmland fragmentation management approaches tailored to the needs and pragmatic realities of specific local fabric [1-5, 8-10].

Being a small, hilly, mountainous, landlocked, poor and one of Africa's most densely populated and best-developing countries, Rwanda was chosen as a case study for this dissertation to address these research calls. The choice for this case was merely purposive. This country is characterised by farmland scarcity, subsistence economy, semi-subsistence, small-scale hillside and rain-fed farming on small farm and parcel sizes, fragmented landscape, a mixed-cropping system with a progressive adoption of modern technologies and practices, high farming population density, high biophysical, spatial and topographical diversity, variations in social and agro-ecological conditions, and the ever-increasing climate change vulnerability [6, 11-39]. The pressure on existing farmland due to the increasing farming population is worsened by the lack of possibilities for agricultural land expansion and the lack of off-farm employment opportunities, which potentially increases farmland scarcity and fragmentation patterns [16, 40]. Furthermore, besides the existing customary egalitarian-based partible land allocation practices, this country has undertaken various historical farmland reforms, including land sharing programs and farmland subdivision restrictions, individual statutory public farmland tenure system and farmland use consolidation and isolated land banking programs to deal with land-related issues, including farmland fragmentation. In particular, the Land Use Consolidation Program (LUC) encouraging the cultivation of the same priority crops by neighbouring farmers and Article 30 of the 2013 Rwandan land law forbidding farmland subdivision were introduced as the primary interventions to tackle and contain farmland scarcity and fragmentation issues considered as the main barriers to agriculture production and food security goals and targets in the country.

However, the outcomes and impacts of these strategies and policy interventions are mixed and highly contested. Some studies and reports highlight their benefits in terms of boosting the national agriculture production of the eight priority crops at the expense of the non-priority crops, thereby increasing the national food availability [6, 21, 24, 27, 30, 35, 41-44]. On the other side, there are studies which found LUC and Article 30 forbidding farmland subdivision to be associated with adverse effects on household food security and sovereignty and farmland tenure security [4, 7, 12, 13, 25, 28, 31, 32, 35, 37, 43, 45-52]. Moreover, this fragmentation phenomenon persists in the farming sector despite the existence of its combat interventions. Besides that, in a country like Rwanda, where the majority of the rural population survives from subsistence and rain-fed hillside agriculture [21, 23, 41, 53] with high incidence and vulnerability to climate change consequences and natural and weather shocks, one would wonder whether these strategies are sufficient, relevant and the most suitable to overcome the problematic farmland fragmentation scenarios considering the heterogeneous local social, economic, physical and agro-ecological conditions of the country [4]. The main criticism of these strategies and policy interventions is their broadness and generality. They do not specify the targeted farmland fragmentation forms and scenarios, the socio-spatial levels of implementation, nor their success conditions, given that not all farmland fragmentation scenarios in Rwanda are problematic *per se* nor homogenous across the whole country [32].

These socio-spatial, economic, regulatory, demographic and agro-ecological traits and the diversity and specificity of local conditions and farming systems are viewed as potential factors and indicators of the above-discussed coexistence of both problematic (defective) and beneficial (rational) socio-spatial

(physical and tenure) fragmentation scenarios of farmland at different socio-spatial levels and their heterogeneous spatial distribution in the country [3, 4, 32]. Thus, these features make this country an interesting case study to answer the above research calls on the farmland use policy dilemma. Hence, this research intends to address this dilemma by deriving a meaningful and appropriate answer to the raised criticisms and research gaps in the Rwandan context. It aims to shed light on this issue and provide policy guidance for farmland fragmentation management, which could support the government of Rwanda to make scientifically informed decisions towards the achievement of its sustainable development goals and targets. The main objective was to comprehensively analyse and model all the practically possible socio-physical farmland fragmentation scenarios and their causal-effects relationships in Rwanda in the framework of developing the sustainable Fit-for Rwanda farmland fragmentation management models. The identification of scenarios in farmland management stands as a starting point in the process of devising scientifically informed decisions about sustainable farmland fragmentation management policies and interventions tailored to local conditions and the needs of local farmers of any country towards the achievement of its sustainable development goals and targets reflected in UN-SDGs (1.4; 2.1, 2, 3, 4 and 5; 12.2; 13.1; and 15.3, 4, 5 and 9). The choice of this case study and research topic was also motivated by the personal background and experience of the author in the farmland management domain and land consolidation matters in Rwanda and Germany. Being a land, soil and water manager and researcher in the perspective of agriculture and natural resources management, the author has previously conducted comparative research on the German and Rwandan land consolidation approaches, which helped to identify the main gaps in the design and implementation of LUC in Rwanda and culminated in research calls aligned with this research idea to address the identified lapses. This triggered and shaped this doctoral dissertation topic and the choice of the case study.

Nevertheless, as a new and emergent research topic in the field of farmland management which had not gained enough attention in the existing literature, there was a lack of comprehensive theoretical knowledge about generic farmland fragmentation scenarios typology (***What***) and the conditions under which they become problematic and beneficial **(*When* *and* *Where).*** These theoretical scenarios are critical in developing sustainable farmland fragmentation management models since they could potentially show or inform (***How*** *and* ***Why)*** one can opt for farmland fragmentation conservation or defragmentation policies and serve as a theoretical foundation for their empirical test in a real study case. Therefore, in light of this crucial information gap, there was a need to generate a theoretical and conceptual information base to build the theoretical and conceptual foundations for the empirical research and the main part of this dissertation. To this end, the overall aim of this dissertation was a comprehensive theoretical analysis and modelling of generic farmland fragmentation scenarios and their sustainable management strategies, as well as an empirical test of these theoretical models in the context of Rwanda. To address the above-mentioned knowledge gaps, this aim was explicitly translated into the following research questions susceptible to theoretical answers and their empirical correspondents (twins) in the context of Rwanda: ***What*** is the typology of farmland fragmentation scenarios (***RQ1***); ***When*** *and* ***Where*** various fragmentation scenarios may become problematic and beneficial and one could opt for farmland

fragmentation conservation or defragmentation policies (***RQ2***); ***How** and **Why)*** one can opt for farmland fragmentation conservation or defragmentation policies (***RQ3***).

1. 2. Research Approach and Thesis Structure

Following a pragmatic paradigm and soft systems methodology (SSM) which relies on the social dynamic research epistemology and systems theory [54-59], a *mixed methods research approach [60-63]* was adopted to understand the complexity of this phenomenon through the development of the theoretical farmland fragmentation scenario models and their empirical test in the context of Rwanda, as a new scientific knowledge generation in farmland management. This approach combines the deductive (rational), inductive (empirical) and abductive approaches and integrates both quantitative and qualitative theoretical and empirical research strategies and methods in the same research design. Being a problem-solving-oriented approach suitable for action research, it allows the researcher the flexibility to rely on different methods and analytical strategies to deeply understand complex phenomena like farmland fragmentation from different lenses and world views and provide balanced and sustainable solutions (accommodating different world views and beliefs) to complex and diverse problematical situations [60-63]. Therefore, this dissertation was divided in three distinct phases following the *multiphase exploratory sequential mixed methods research design*. This design facilitates the researcher to first explore and deeply understand the problem from different lenses using a more qualitative approach, then generate his own theoretical models or orientation based on his understanding of the problem, and finally, quantitatively test these models in a real-world or case context in different sequential phases [54, 57, 61-63].

The **first phase** consisted of the exhaustive and in-depth understating of the main research problem from multiple lenses and its rationale in the case study, which was performed through an exploratory empirical study on farmland fragmentation paradoxical impacts in a small case study of Bugesera district of Rwanda. This resulted in an exploratory article pinpointing the existence of the positive impacts of farmland fragmentation in the country besides the widely perceived negative ones on farm efficiency in the study area. This article was published in *Land Use Policy* Journal by Ntihinyurwa *et al*. [32] (see Appendix 1 (A1) for more details).

The **second phase** consisted of generating the required but missing comprehensive theoretical information about the topic, which served as a theoretical foundation of the empirical study. Therefore, using an integrative concept-centric qualitative approach following the rationalist theory and deductive logical reasoning, we conducted three integrative reviews and generated three theoretical journal articles exactly addressing three main research questions on the farmland fragmentation paradox, which were published in recognised international journals. The first one addressed the (***What**)* research question (***RQ1***) by generating a typology of 40 generic theoretical farmland fragmentation scenarios and published in *Land Use Policy Journal* by Ntihinyurwa and de Vries [64] (see Appendix 2 (A2) for more details); The second one addressed the (***When** and **Where***) research question (***RQ2***) by generating a comprehensive theoretical model indicating the comprehensive conditions under which various fragmentation scenarios may become problematic and beneficial and one could opt for farmland fragmentation conservation or defragmentation policies. This was published in *Ecological Indicators Journal* by Ntihinyurwa and de Vries

[3] (see Appendix 3 (A3) for more details); While the third one addressed the (***How*** *and* ***Why***) research question (***RQ3***) by generating a comprehensive theoretical food and tenure security responsive sustainable farmland fragmentation management model exhaustively indicating a set of strategies and interventions suitable for the sustainable management of both beneficial and problematic fragmentation scenarios for food security and farmland tenure security purposes. This was published in *Land Journal* by Ntihinyurwa and de Vries [4] (see Appendix 4 (A4) for more details).

The **third phase** consisted of testing the generated theoretical models in a national-level case study context of Rwanda, which resulted in 2 empirical journal articles combined in one empirical Chapter 2 as the core part and scope of this dissertation focussing on the typology of paradoxical farmland fragmentation scenarios and their causal-effects relationships models in the country. It helped to empirically answer the ***RQ1*** and ***RQ2*** using Rwanda as a case study. These two articles will be submitted to international journals for peer review at some point in time. This phase helped to deeply understand the phenomenon of farmland fragmentation and draw meaningful and useful conclusions about its different scenarios in the country. Due to time limitations and financial considerations, the third theoretical model calling for the development of Fit-for Rwanda sustainable farmland fragmentation management models (***RQ3***) was not exhaustively empirically tested in this dissertation, therefore leaving it as room for further research. It was only used to inform the empirical test of the first two theoretical models. The following **Figure 1** describes the overall research approach and scope.

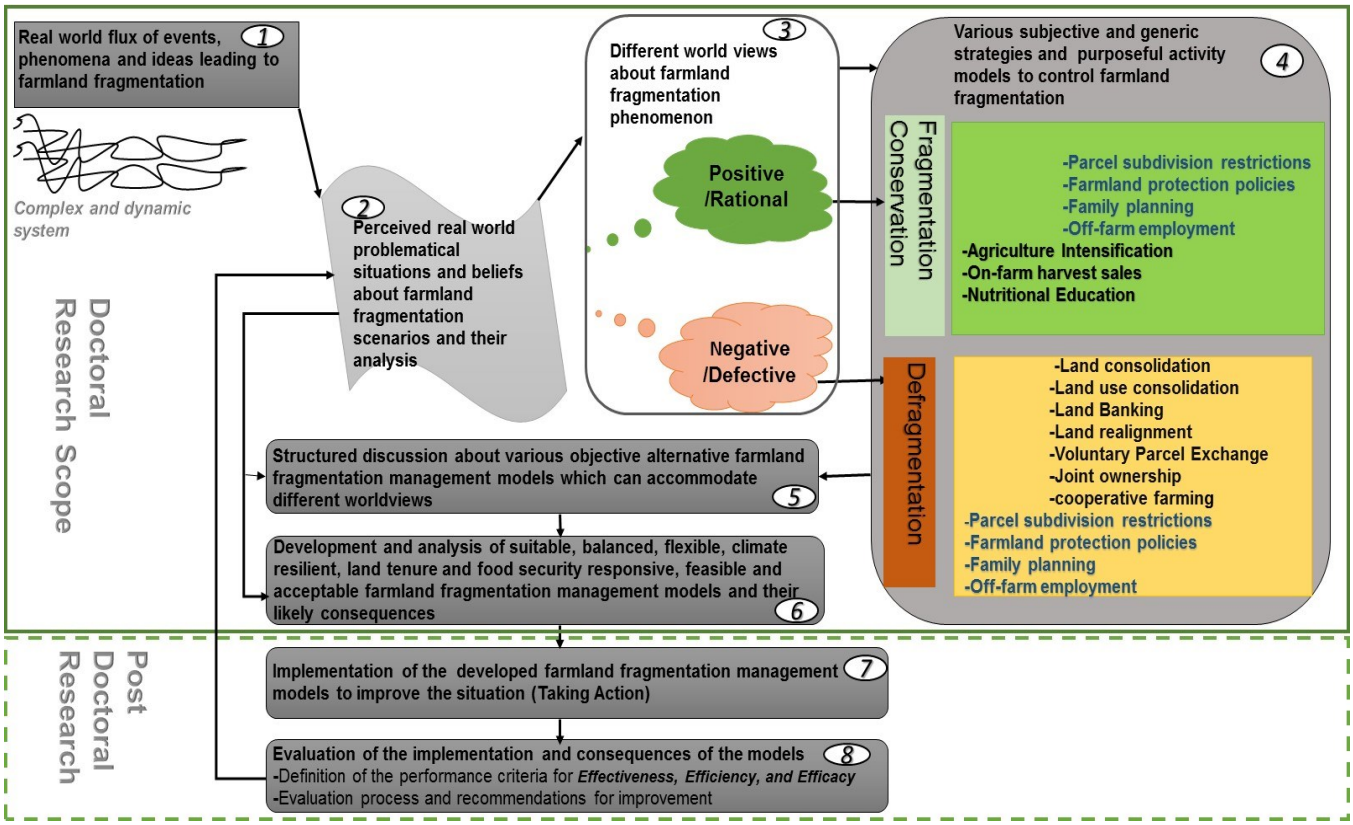

Figure 1. Overall research approach and scope

Source: Adapted from the Soft Systems Methodology (SSM) Cycle and the Pragmatic paradigm model [54-57]

Figure 1 illustrates the overall research approach and scope based on the Soft Systems Methodology (SSM) cycle Model and the pragmatic research paradigm. According to the SSM model, an action research-oriented requires a deep understanding of the problem to be addressed from different lenses in order to provide balanced and flexible solutions that accommodate different world views of the problem [54-57]. This model stipulates 7 to 8 different analytical steps in a cycle and sequential fashion with 4 distinct phases. Therefore, in this dissertation's context aiming to develop Fit-for-Rwanda sustainable farmland fragmentation models, 8 steps were planned. Since the subject matter is farmland fragmentation, the first step (**1**) consists of identifying the origins and causes of fragmentation concept from the complex dynamic system's flux of events, phenomena, ideas and beliefs in the real world. As farmland fragmentation may be perceived differently (positive and negative) by different stakeholders in various circumstances, the second step (**2**) consists of analysing different perceptions and beliefs on farmland fragmentation to identify its problematical situations and scenarios that need to be addressed. This step informs the third step (**3**), which is the analysis of worldviews about farmland fragmentation. This step involves the analysis of various fragmentation scenarios and the conditions under which they become problematic, beneficial or both (fragmentation causal-effects relationships). Generally, the perceptions and worldviews on a phenomenon dictate the behaviours of stakeholders about its management. Thus, the third step led and informed the fourth one (**4**), consisting of analysing existing subjective fragmentation control strategies and generating conceptual/theoretical models to manage different identified fragmentation scenarios. These models propose the problematic(negative) fragmentation combat strategies (defragmentation) on the one hand and the beneficial (positive) fragmentation conservation strategies on the other hand. These strategies and interventions include the problematic fragmentation preventive and mitigation measures and the beneficial fragmentation conservation support and protection measures. The fifth step (**5**) consists of testing(comparing) the developed conceptual/theoretical models in a real-world context (which is Rwanda in this research) through structured discussion with stakeholders and experts in the domain in order to identify changes and generate desirable and feasible models that accommodate various worldviews of farmland fragmentation phenomenon. This step is informed by the second and fourth steps. Based on the fifth step's findings and the proposed changes in the conceptual models, the sixth step (**6**) consists of generating the comprehensive desirable, feasible, sustainable and suitable fit-for scenarios fragmentation management models which accommodate various worldviews of farmland fragmentation and tailored to the needs of local stakeholders and conditions. This step also shows the likely consequences of the developed models on SDGs related to climate change resilience and adaptation, food security and sovereignty, and farmland tenure security. The seventh step (**7**) consists of implementing (taking action) the developed models in step (6) to improve the situation and address the identified problematical situations in step (2). The last step (**8**) is evaluating the implementation and consequences of the models based on the Effectiveness, Efficiency and efficacy criteria and the proposition of recommendations for improvement. The first six steps (**1-6**) form the scope of this doctoral dissertation, while the last two steps (**7-8**) make the scope of post-doctoral research as the long-term goal of this overall research. The following **Figure 2** displays the research design and conceptual framework of this dissertation.

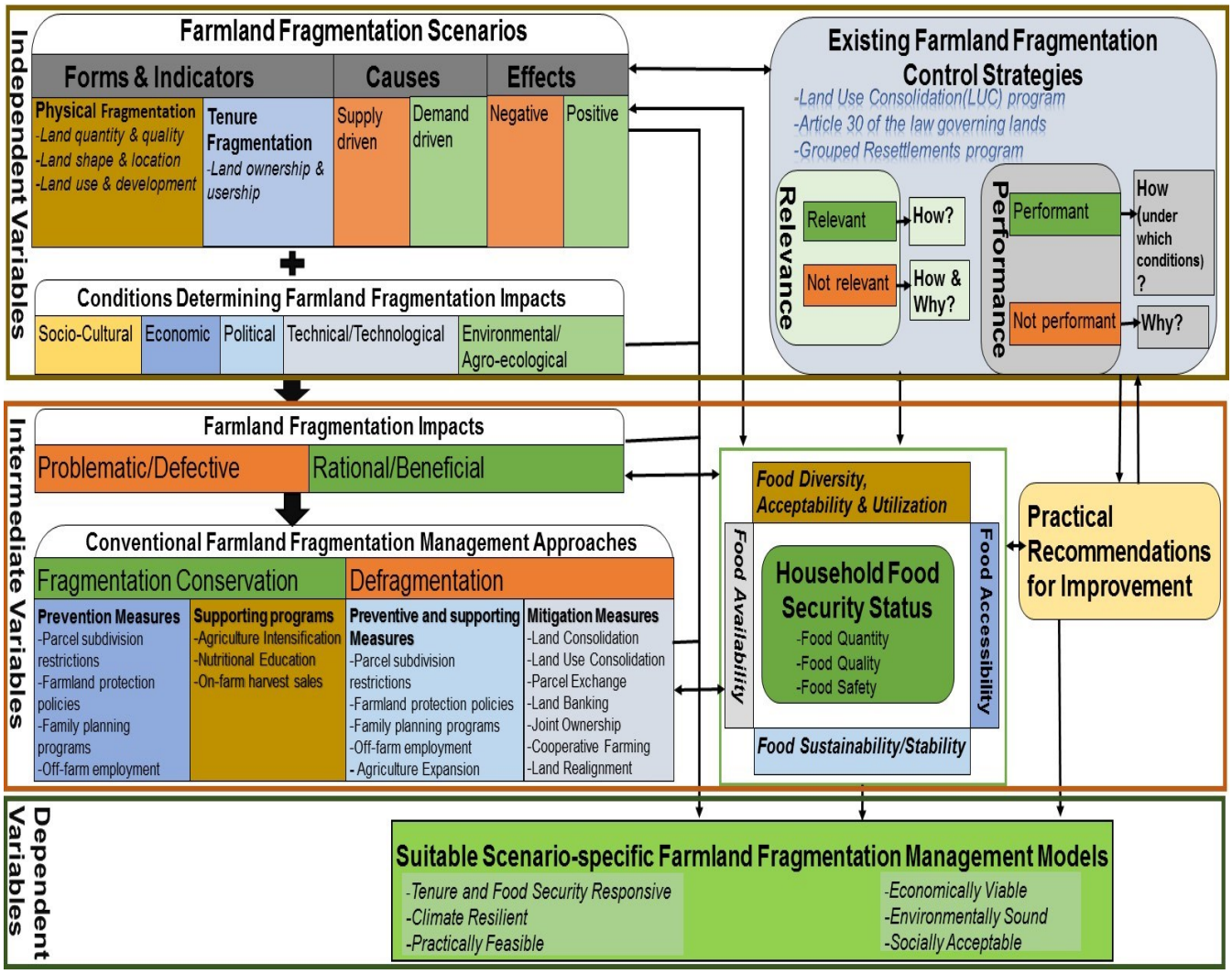

Figure 2. Research design and conceptual framework

Figure 2 depicts the design and conceptual framework of this doctoral dissertation. It shows the connections between different research variables and steps of this research, from the problem exploration, the development of theoretical models and their test in the real-world context, to the development of the empirical models. As this Figure reads, the development of Fit-for-Rwanda Sustainable Farmland Fragmentation Management Models (SFFMM) considered as the dependent variables, and the long-term dissertation goal is function of the types of farmland fragmentation scenarios (physical and tenure, positive and negative) and its extent in the country and the conditions determining the perceptions on its impacts (negative and positive) by local stakeholders and the performance and relevance of the existing strategies to control fragmentation as independent variables, and the types of fragmentation impacts (beneficial and problematic) and the household food security status, the suitability of conventional farmland fragmentation approaches in the country as intermediate or mediating variables. This design explains the conduct of this research in different phases involving several theoretical and empirical analyses, modelling and testing procedures using a mixture of qualitative and quantitative

methods in a purposive and mutually informative sequential fabric. These include the fragmentation problem exploration phase in Rwanda (qualitative), the theoretical fragmentation scenarios and their management models development phase (qualitative), the empirical test of the developed theoretical models in the country (mixture of quantitative and qualitative for scenarios-causal-effects analysis, existing strategies performance and relevance analysis, food security status analysis, and theoretical models suitability analysis), and the generation of fit-for the country sustainable fragmentation management models (qualitative). However, due to time and financial limitations, this dissertation was only limited to the analysis of farmland fragmentation scenarios in Rwanda as short-term scope to inform the generation of sustainable fragmentation management models as the long-term post-doctoral research scope. The following **Figure 3** displays the analytical framework and decision tree for farmland fragmentation scenarios and the development of its management models.

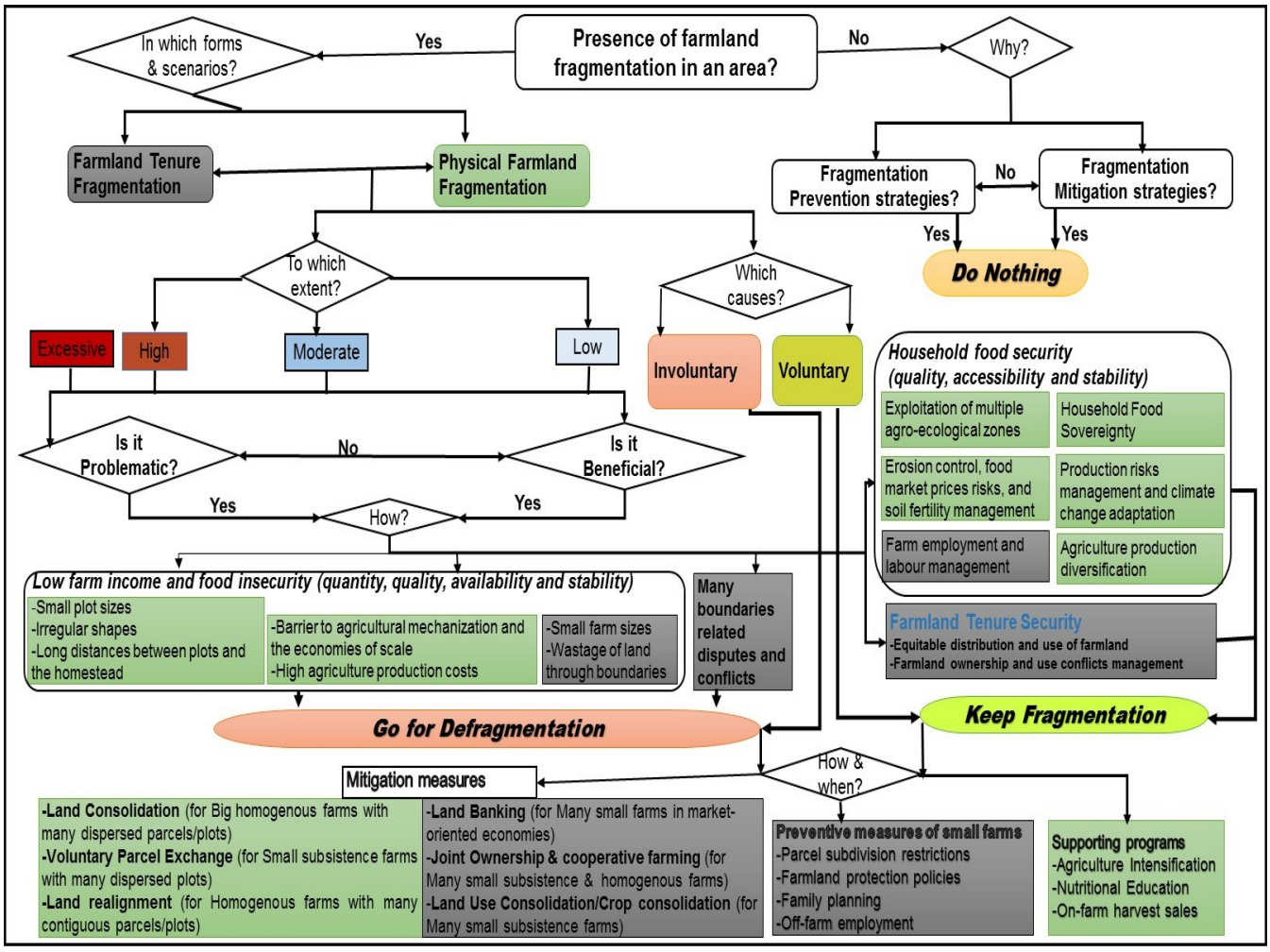

Figure 3. Analytical framework

Figure 3 shows the analytical steps and decisions one needs to take when developing farmland fragmentation management models in the real world. The first step is the assessment of the *presence of farmland fragmentation in an area*. If not present, the reasons for the absence must be identified to inform the next steps and decisions. These may include the absence of fragmentation factors and conditions or

the presence of preventive and mitigation measures in that area. In this case, the process stops from there. There is nothing else to do about fragmentation management (***Do Nothing***). On the other side, if fragmentation is present, the second step is the analysis of the typology of the present fragmentation forms (*Tenure and Physical fragmentation*) and scenarios. The third step is to analyse the extent and causes (voluntary and involuntary) of the present fragmentation forms and scenarios. The fourth step is the analysis of the perceptions of these present fragmentation scenarios from different worldviews and their categorisation into either *problematic* or *beneficial* based on their impacts. There is always a need to know if the identified scenarios are problematic or beneficial. The fifth step is to analyse how these scenarios are problematic or beneficial in terms of their impacts in relation to household food security and sovereignty, agriculture production and farm income, and farmland use and tenure security within the UN-SDGs framework (Scenarios-causal-effects relationships analyses). If the identified farmland fragmentation scenarios have positive impacts on the above-mentioned variables, then decide or advise policies supporting to ***keep those fragmentation scenarios*** for their benefits on farmers. On the other hand, decide or advise policies supporting the ***defragmentation interventions and strategies*** if the problematic fragmentation scenarios to farmers are found. The final step is to identify, analyse, and develop suitable interventions and strategies in the form of models to manage the identified fragmentation scenarios and improve the situation based on the policy decision. These may include the ***mitigation measures*** (land consolidation, voluntary parcel exchange and land realignment for physical fragmentation scenarios; land banking, joint land ownership and cooperative farming, and land use consolidation for tenure fragmentation scenarios) of the identified problematic scenarios, the ***supporting measures or programs*** (agriculture intensification programs and technologies, nutrition education programs, and on-farm harvest sales) to complement and facilitate farmers to optimise the benefits from the positive fragmentation scenarios conservation, and the ***preventive measures*** (farmland parcel subdivision restrictions, farmland protection policies, family planning programs, and off-farm employment) to avoid the worsening of problematic fragmentation scenarios. The following **Figure 4** displays the overall research framework and thesis structure.

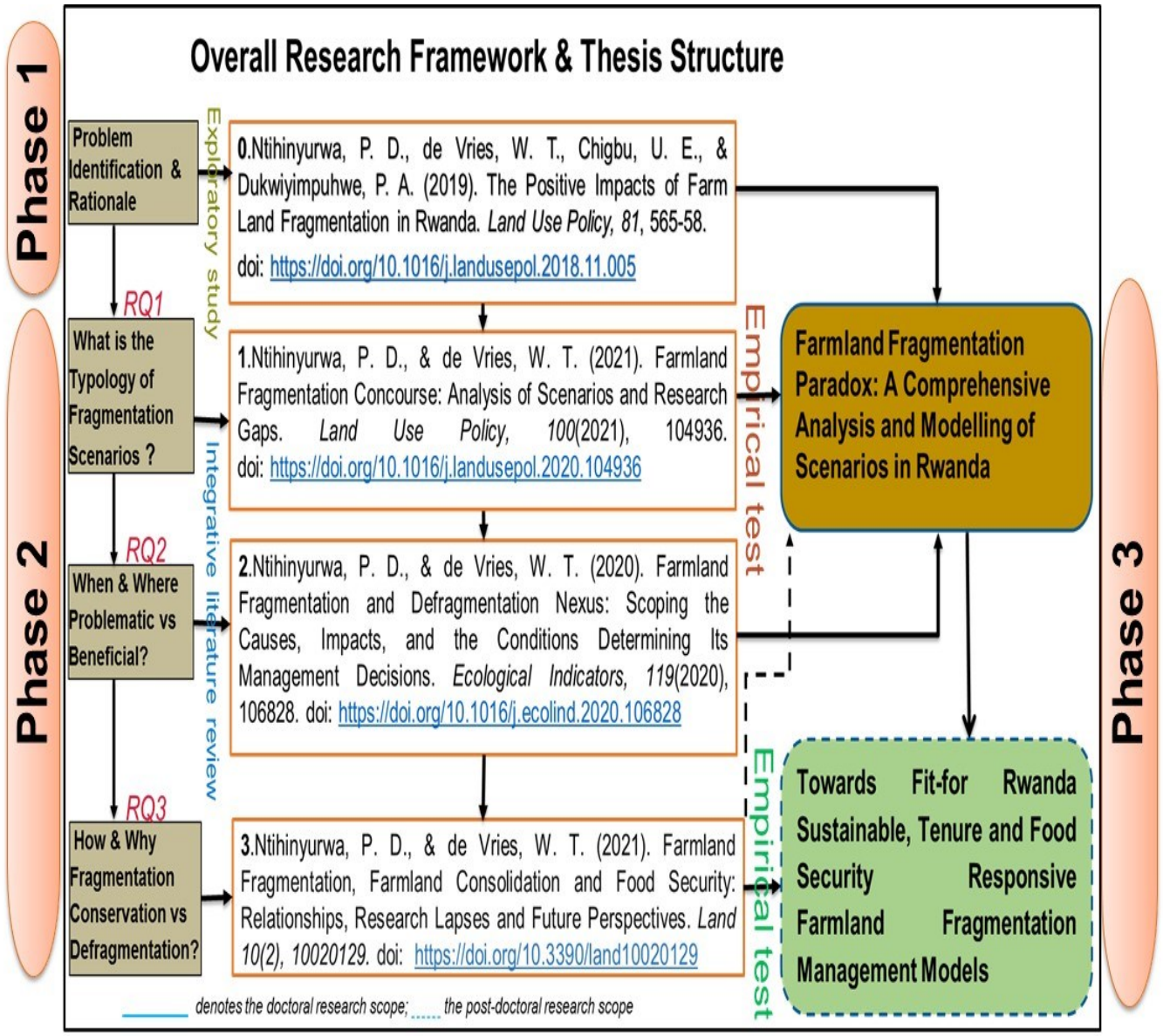

Figure 4. Overall research framework and Thesis structure

Figure 4 summarises the overall research process, its outcome, and the thesis structure as textually described in *paragraphs 2,3 and 4* of this *subsection 1.2*. It illustrates the research questions, the methodological approaches to answer them, the theoretical outcome in terms of theoretical models published in peer-reviewed journals, and the empirical outcome in the form of empirical models from the test of the theoretical ones in the Rwandan context and the connections between these research components. As discussed in previous figures and paragraphs, the research started with an exploratory study in a small case to deeply understand the problem of farmland fragmentation in Rwanda. This ***exploratory phase*** resulted in an empirical paper highlighting the coexistence of both positive and negative impacts of farmland fragmentation in Rwanda, published in a land use policy journal. This exploratory study helped formulate three dissertation research questions, thereby informing the ***second phase of an integrative review*** of farmland fragmentation scenarios and its conventional management

strategies and interventions, which resulted in the generation of 3 comprehensive theoretical models published in international peer-reviewed journals. This phase helped to theoretically answer the three research questions and informed the ***empirical phase*** to test these theoretical models and empirically answer these research questions in the real world of the Rwandan context. The third phase and scope of this doctoral research tested the two first research questions (*RQ1 and RQ2*) and resulted in two empirical articles on farmland fragmentation scenarios and their causal-effects relationships in Rwanda, which were used to generate the second chapter and main or core part of this dissertation. Therefore, the findings from this phase will inform the empirical test of the third theoretical model and empirically answer the third research question (*RQ3*), aiming to generate the fit-for-Rwanda sustainable farmland fragmentation management models as the long-term goal and scope of post-doctoral research.

Besides this introductory *chapter (1)*, the rest of the thesis is shaped in the following sequential order: *Chapter 2* describes the empirical analysis and modelling of farmland fragmentation scenarios in Rwanda and serves as the core part of this dissertation. It empirically tests two theoretical models on farmland fragmentation paradoxical scenarios and their causal-effects relationships and empirically answers this dissertation's first two research questions. *Chapter 3* presents the concluding remarks on the whole dissertation. It summarises the key findings and their policy and research implications, presents the encountered research limitations, and derives the recommendations for further research, including the post-doctoral research conceptual framework and design. Finally, the *appendices make* up the last part of this thesis, combining all previous publications within the scope of this doctoral research, which form the theoretical basis of this dissertation.

2. Farmland Fragmentation Paradox: A Comprehensive Analysis and Modelling of Scenarios in Rwanda

This chapter is the main and core part of this doctoral dissertation. It is the result of empirical test of two theoretical models on farmland fragmentation scenarios and their causal-effects relationships published in international peer reviewed journals, and empirically answer the first two research questions of this dissertation. Its findings will be used to inform the post-doctoral research aiming to empirically test the third theoretical model answering the third research question of this dissertation with the goal of generating Fit-for Rwanda sustainable farmland fragmentation management models. It also aims at generating two empirical articles which will be submitted to the international journals for peer review processes with the following tentative titles:

- *Farmland Fragmentation Typology: A comprehensive Empirical Analysis and Modelling of Scenarios in Rwanda.*
- *Farmland Fragmentation Causal-Effects Paradox: A comprehensive Analysis and Modelling of Scenarios in Rwanda.*

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2. 1. Introduction

2. 1. 1. Background and Rationale

From the lens of farm income and efficiency, market-oriented agriculture and food quantity, farmland fragmentation has historically been viewed as a negative phenomenon and a serious threat to agriculture production and food security due to its positive correlation with the increase in agriculture production costs, waste of productive arable land through boundaries, farmland boundaries related conflicts, farmland abandonment, and the barrier to the economies of scale [1-3, 64-83]. Most of the advocates of this position emphasise this farmland fragmentation as a defective pattern in agriculture that should be avoided and highlight various farmland consolidation and farmland banking models as a panacea to this quandary [2, 10, 67, 69, 71, 72, 80, 84, 85]. However, documented counterviews posit that farmland fragmentation is neither a problem *per se* nor all farmland fragmentation forms are defective [3, 4, 11, 12, 32, 86-99]. According to these scholars, there may be positive considerations or beneficial situations of farmland fragmentation mainly related to climate change adaptation, crop diversification, agriculture production risks and land ownership and use-related conflicts management, labour management, and the diseconomies of scale for farmland tenure security and food security purposes, which explain its persistence in the farming sector despite various strategies to tackle it [3, 4]. Farmland fragmentation is, in this case, considered as a demand-driven farmer's strategic choice for agriculture production risk and weather shocks mitigation and management, exploitation of multiple agro-ecological zones, labour bottlenecks management and self-sufficiency or independence in food production in subsistence communities through crop diversification, for household food security [3, 4, 32, 86, 87, 89, 91, 92, 96, 98, 99] and farmland use and *de facto* tenure security [3, 4].

Nevertheless, whether fragmented or consolidated, under the existing climate change threats and realities, farmland use requires a certain level of management to sustainably support its productive and supply potentials for food, feeder, shelter, fibre and energy demand of the ever-growing population, along with the biodiversity and ecosystem services provisions. Since both standpoints on farmland fragmentation (positive and negative) are academically and scientifically accepted as tools of land management, this poses a severe dilemmatic problem to farmland use policymakers, whether they

should devise policies in favour of defragmentation or fragmentation conservation in farmland, sometimes resulting in the development of broad and irrelevant farmland fragmentation management strategies ignoring specific farmland fragmentation forms, scenarios and local conditions. The empirical experience has revealed that the success and suitability of farmland fragmentation management strategies are dictated by specific local conditions and governance factors of a country since the strategy which works well in one country or specific area might not function in another [1-4]. There exists documented evidence highlighting failures of European land consolidation programs and models in Sub-Saharan African and Asian countries due to the overlook of local conditions during their design and implementation [1, 3-7].

Hence, the proponents of this research stance recommend the consideration of the diversity in local conditions before the design and implementation or transfer of farmland fragmentation management strategies (instruments) and the assessment of their suitability, operational and success requirements in subject areas [1, 3-5, 8, 48, 100-106]. Some scholars in this group further call for the assessment of farmland fragmentation patterns (forms, causes and both problematic and beneficial impacts) in different case areas to derive the typology, similarities and disparities in fragmentation and defragmentation semantics, which can inform or guide the design and implementation of localised farmland fragmentation management approaches tailored to the needs and pragmatic realities of specific local fabric [1-5, 8-10]. Similarly, these contradictory standpoints and the polarised nature of farmland fragmentation discourse call for more comprehensive research about various forms and categories of farmland fragmentation and the conditions under which they become problematic and beneficial in a set of distinct informative scenarios to guide the decision-making process about its management for sustainable agriculture production, household food security and farmland tenure security. In response to these key research calls in the farmland fragmentation management scientific domain, drawing from the existing fragmented literature on farmland fragmentation, Ntihinyurwa and de Vries [64] developed a set of 40 realistic theoretical farmland fragmentation scenarios from 64 mathematical possibilities by combining the six main physical and social characteristics of land and indicators of various farmland fragmentation forms (size, shape, location/dispersion, use, value, and tenure in terms of ownership or usership).

However, these scenarios do not indicate when and where farmland fragmentation can be problematic or beneficial, nor how and why they can sustainably be managed for food security motives. For this, through an integrative review of the existing information about farmland fragmentation, the same authors [3] further developed the conditions under which these farmland fragmentation scenarios may become problematic or beneficial. They categorized them into two theoretical paradoxical groups: problematic scenarios that need to be avoided and the beneficial scenarios that should be conserved. Furthermore, these authors [4] developed a comprehensive theoretical model for managing these paradoxical fragmentation scenarios under various conditions through an integrative review of farmland fragmentation, consolidation, and food security nexus. The same study further recommends an empirical comprehensive analysis of both problematic and beneficial farmland fragmentation scenarios and the consideration of both the benefits and costs of policy interventions and strategies (instruments) to adapt the extent of farmland fragmentation under specific local contexts (see Ntihinyurwa and de Vries [3, 4, 64] for more details about these theoretical farmland fragmentation scenarios and their management).

Nonetheless, these abstract theoretical scenario models have not yet been empirically tested since their development.

Therefore, this study tests these theoretical farmland fragmentation scenarios in the contextual case of Rwanda, characterised by farmland scarcity, subsistence economy, semi-subsistence, small-scale hillsides and rain-fed farming on small farm and parcel sizes, fragmented landscape, the mixed-cropping system with a progressive adoption of modern technologies and practices, high farming population density, high biophysical, spatial and topographical diversity, variations in social and agro-ecological conditions, and the ever-increasing climate change vulnerability [6, 11-39]. Furthermore, this country has undertaken various historical farmland reforms, including land sharing programs and farmland subdivision restrictions, individual statutory public farmland tenure system and farmland use consolidation and isolated land banking programs to deal with land-related issues, but still experiences high levels of farmland-related conflicts, limited off-farm employment opportunities, imperfect farmland, labour, and agriculture inputs and outputs market, farmland fragmentation and tenure security issues, and household food insecurity patterns [6, 12, 13, 17-25, 28-32, 35, 37-39, 41-44, 46, 47, 107-109]. These traits are viewed as potential factors and indicators of the above-discussed coexistence of both problematic (defective) and beneficial (rational) physical and tenure fragmentation scenarios of farmland at different socio-spatial levels [3, 4, 32], which makes this country a suitable case for this empirical test.

Despite the fast and steady economic growth, with agriculture being the second leading contributor to the national GDP in the last decades, with 24 per cent [110] after services, both the demographic, physical (topography and agro-ecology), economic, and socio-cultural features of Rwanda make farmland very densely populated and scarce. These features reduced the farm size to the national average of 0.6ha, often composed of 3 to 4 scattered parcels with 3.2 crops per parcel, thereby increasing farmland fragmentation [14, 21, 39, 41], limiting the achievements of food demands and preferences of the growing population and worsening the household food and nutrition security [6, 23, 32, 41, 53], and keeping the poverty level among the highest in the world with 38.2 per cent and 16 per cent of extreme poverty [29]. In the absence of farmland expansion options due to its scarcity, Rwanda embarked on various agriculture development strategies and policy interventions to support its transformation from subsistence agriculture towards the commercial one, prioritising agriculture intensification programs and farmland-saving technologies. These interventions are in line with its path to the long-term economic transformation plans from a subsistence economy towards a middle-income economy by 2035 and a high-income economy by 2050 in the framework of Vision 2050 as a replacement of the Vision 2020, the Sustainable Development Goals (SDGs 1, 2, 12, 13 and 15) within the UN-agenda 2030 translated through the short term strategies and plans like the First National Strategy for Transformation (NST1, 2018–2024) as a replacement of the Economic Development and Poverty Reduction Strategy (EDPRS 2013–2018) with agriculture being the backbone [6, 21, 23, 28, 39, 41, 109].

Considering farmland scarcity and farmland fragmentation as the main challenge to the achievement of these goals and targets, the government of Rwanda developed a Crop Intensification Program (CIP) in 2008 and the Land Use Consolidation (LUC) Program as its integral part and central pillar in 2010, and various farmland subdivision restrictions (Article 30 of the 2013 law governing lands in

Rwanda) and protection regulations, family planning programs, isolated farmland banking projects, and cooperative farming systems [3, 4, 6, 19-21, 23, 28, 30, 32, 41, 42]. The main objectives of these interventions were to overcome the general effects of fragmentation, thereby boosting national agriculture production, increasing farm income and household food and nutrition security, alleviating poverty, and improving the livelihoods of the rural population. In the Rwandan context, LUC denotes the consolidation of the use of farmlands where all farmers with close parcels grow the same crop in a synchronised way up to the minimum size of 5ha from the list of 8 priority food crops (maize, beans, wheat, rice, Irish potatoes, banana, cassava and soybeans) broadly chosen by the government at the national level based on their suitability in the Agro-ecological Zones (AEZ) of the country, with no change in the individual land rights [4, 19, 21, 28, 32, 35, 37, 45, 47]. This aspect of keeping individual land rights intact makes LUC different from other modern land consolidation programs, with the exception of land banking models involving the expropriation of small farmers by big farmers (investors) to create big consolidated and irrigated parcels in some particular LUC cases. Some studies call it "*Crop Consolidation*" by referring to its monoculture aspect and adverse effects on agriculture production and household food and farmland tenure security [7, 46, 108]. Article 30 of the law governing land forbade the subdivision of agricultural and livestock land, which would result in small pieces of less than 1ha, thereby encouraging the joint ownership of such parcels and their cooperative farming to contain or prevent farmland fragmentation [3, 4, 6, 20, 32].

However, the outcomes and impacts of these strategies and policy interventions are mixed and highly contested. Some studies and reports highlight their benefits in terms of boosting the national agriculture production of the eight priority crops at the expense of the non-priority crops, thereby increasing the national food availability [6, 21, 24, 27, 30, 35, 41-44]. On the other side of the coin, there are studies which found LUC and Article 30 forbidding farmland subdivision to be associated with adverse effects [4, 7, 12, 13, 25, 28, 31, 32, 35, 37, 43, 45-52]. These mainly include the barriers to crops and agriculture production diversification, climate change adaptation, production and market fluctuations risks management capacity, perceived individual farmland tenure security, enjoyment of individual farmland use rights, household food sovereignty and security (diversity, quality, accessibility, sustainability); increase in internal, location, dispersion and hidden ownership fragmentation of farmland for exploitation of various agro-ecological zones and crops diversification in different LUC sites, familial farmland use and tenure related conflicts; and the boost in farm profits of big farmers at the expense of small farmers. Recent findings of Isaacs *et al*. [37], Niyonzima [31] and Nilson [28] highlighted the outperformance of the benefits of the improved intercropping system over the ones from LUC-based government-led mono-cropping system in terms of household food security and risks management insurance, mainly due to the market imperfections. These studies recommend supporting mixed farming systems or conserving beneficial farmland fragmentation scenarios as a promising solution for agricultural production and household food security concerns. Moreover, they pinpoint the higher performance of LUC in marchlands and lowlands, often subject to cooperative farming under government ownership, than in hilly and highlands in terms of agriculture production, farmland tenure security, resistance of farmers, and farm profitability, thereby recommending it for the former one [48, 52]. Besides that, in a country like Rwanda, where the majority of the rural population survives from subsistence and rain-fed hillside agriculture (more

than 70 %) [21, 23, 41, 53] with high incidence and vulnerability to climate change consequences and natural and weather shocks, one would wonder whether these strategies are sufficient, relevant and the most suitable to overcome the problematic farmland fragmentation scenarios considering the heterogeneous local social, economic, physical and agro-ecological conditions of the country [4], since this fragmentation phenomenon persists in the farming sector despite the existence of its combat interventions.

Recognising these critics, to address the challenges of farmland fragmentation and the reduction of the number of small-scale farmers in favour of large-scale commercial agriculture to meet the food demands of the ever-growing population with limited farmland resources, the Ministry of Agriculture (MINAGRI) and the Ministry of Environment in charge of land resources management put a particular focus on tackling farmland fragmentation issues as the main barrier to the achievement of the governmental long term development strategies targets and goals of boosting the national agriculture production. This focus implied the introduction of agriculture insurance schemes and encouragement of the growth of high value and yielding, diversified and climate change resistant crop varieties; promotion of cooperative farming and voluntary parcel exchange, and kitchen gardens to complement LUC or overcome its weaknesses; and farmland market legal enforcement (formalisation) to prevent informal farmland transaction and facilitate farmland leasing and voluntary farmland consolidation. All these strategies are documented in the National Agriculture Policy (NAP 2017-2030) [21] via the Strategic Plan for Agricultural Transformation, currently in its fourth phase (PSTA4 2018–2024), along with the protection of potential agricultural land provided by the National Land Use and Development Master Plan (NLUDMP 2020-2050) [23] and the National Land Policy [22]. However, these strategies and policy interventions are still broad since they do not specify the targeted farmland fragmentation forms and scenarios, the socio-spatial levels of implementation, nor their success conditions, given that not all farmland fragmentation scenarios in Rwanda are problematic nor homogenous across the whole country [32]. Unfortunately, farmland fragmentation in Rwanda is often synonymously documented as small-sized farms and plots with little focus on the number of parcels and plots per farm and their spatial dispersion and as a barrier to farm profitability and the economies of scale which should be eliminated through farmland consolidation strategies in most of the governmental reports and policies [21-23, 41]. Nevertheless, various empirical studies over time found an inverse relationship between farm (or parcel) size and the output (yield) [11, 16, 17, 26, 51, 52].

Hence, this study aims to shed light on this issue and provide policy guidance for farmland fragmentation management, which could support the government of Rwanda to make scientifically informed decisions towards the achievement of its sustainable development goals and targets.

2. 1. 2. Research Objectives and Hypotheses

Drawing from the theoretical socio-spatial and agro-ecological diversity of 12 agro-ecological zones of Rwanda and its derived hypothetical coexistence of various localised fragmentation scenarios in the country, the study addresses the following two main objectives in the study area:

1. To comprehensively and empirically analyse and classify all possible socio-physical farmland fragmentation forms, extent and scenarios.
2. To model farmland fragmentation socio-spatial scenarios-causal-effects relationships and the predictors of their categorisation into problematic and beneficial paradoxical classes.

Despite these primary objectives, this study also extends the studies of Blarel *et al*. [16] and Ntihinyurwa *et.al*. [32] that found farmland fragmentation as farmers demand driven risk management strategy, the lack of evidence of its inefficiency in three provinces of Rwanda, and both positive and negative effects of farmland fragmentation in Bugesera district, Eastern province of Rwanda respectively. Since these studies called for the extension of their research at the macro and national levels, this study stands, therefore, as a response to these research calls. Besides the generic literature hypotheses about farmland fragmentation and the theoretical fragmentation scenarios of Ntihinyurwa and de Vries [64] and Ntihinyurwa and de Vries [3] in the Rwandan context, this study tests the following set of null (H_0) and alternative research (H_A) hypotheses:

- ***H_{A1}*:** Rwanda has a significant spatial and topographical diversity of farmland fragmentation forms, extent and scenarios.
- ***H_{A2}*:** There is a coexistence of both physical and tenure, as well as problematic and beneficial farmland fragmentation forms at different socio-spatial levels across and within Rwanda's agro-ecological zones (AEZs).
- ***H_{01}*:** Landscape and tenure fragmentation forms are significantly negatively associated with topography (smaller farm and parcel sizes are found in flat (lowlands) than hilly (highlands) of Rwanda).
- ***H_{A3}*:** Internal farmland fragmentation is significantly negatively correlated with farmland tenure fragmentation across different AEZs of Rwanda (the number of parcels and plots per farm increases with the increase in farm size), while farmland tenure fragmentation is significantly negatively correlated with farm-level farmland use and dispersion fragmentation forms (the smaller the farm size, the smaller the number of crops per parcel and farm, the smaller the number of farms with scattered parcels in different topographical locations), and positively correlated with parcel-level use fragmentation (the bigger the farm size, the smaller the number of crops per parcel).
- ***H_{A4}*:** There is a significant negative correlation between internal and farmland use fragmentation at the parcel level and a significant positive correlation between these fragmentation forms and the dispersion fragmentation at the farm and farmland block levels (the multicultural system at the parcel level decreases with the increase in the number of parcels per farm, and increases at the farm and farmland block levels, while the scattering of parcels increases with the number of parcels).
- ***H_{02}*:** The perceived negative impacts (problematic scenarios) of farmland fragmentation in Rwanda do not significantly outweigh its positive ones (rational scenarios), and their categorization and predictors are similar across research sites and AEZs.
- ***H_{A5}*:** Internal, dispersion, farm-level use, and farmland usership fragmentation forms in Rwanda are significantly positively linked with the spatial, topographical and agro-ecological diversity of

farmland for exploitation of diverse agro-ecological zones, LUC sites and agriculture seasons, crop diversification for climate change adaptation and agriculture production diversification as risks management strategy and household food security, egalitarian based land distribution principles in inheritance and succession as customary practices, farmland transactions or market for farm expansion, farmland related intra-familial conflicts management, subsistence farming for self-independency in food security (sovereignty), farmland subdivision restrictions and cooperative farming through LUC, and erosion control measures under beneficial fragmentation scenarios; While farmland tenure, landscape, and parcel-level use fragmentation forms are significantly positively linked with the farm population density, farmland scarcity, egalitarian based land distribution principles in inheritance and succession as customary practices, food production independence, sovereignty and security, on-farm employment and farm landlessness, farmland psychology and tenure security, farmland market, farmland reforms, laws and policies, farmland sharing and redistribution programs, and farmland use efficiency under both the problematic and rational scenarios.

Subsequent to this introductory section, the rest of this chapter is structured in the following sequential order: Section 2 describes the theoretical approach (frame and foundation) for this research. Section 3 describes the research approach and design, and the methodological framework for empirical data collection, processing, analysis and conclusions drawing. Section 4 displays the empirical findings and their discussion, while the last section (5) draws the study's key conclusions and derives policy implications and recommendations for further research.

2. 2. Theoretical Approach

2. 2. 1. Farmland Fragmentation Typology: Concepts, Forms and Scenarios

In general, the literature conceptualises farmland fragmentation differently. This variation may be attributed to the differences in the farmland parameters and spatial levels (parcel, farm, land block or landscape) considered when defining farmland fragmentation. However, despite the ontological diversity of this concept, the derived fragmentation forms are generally grouped into two categories of *Physical* and *Tenure* or *Social fragmentation* which could separately exist or coexist in the same spatial area at the parcel, farm, and farmland block levels under ideal farmland block level conditions as the scientifically recognised farmland fragmentation management unit in land management science [4, 5, 32, 64, 70]. A large number of research scholars commonly define *farmland fragmentation* at the farm or household level as the situation where a single farm consists of numerous spatially separated (non-contiguous) small parcels often scattered over a wide area [4, 16, 32, 64, 65, 87, 111-115]. This definition has, however, been linked with internal *fragmentation* form or *farm fragmentation* (*within farm fragmentation)*, reflecting the situation when a single farm or household operates or owns many parcels scattered in different locations (scattering), often subdivided into small plots (parcelling) [32, 64, 70, 92, 116-119]. The studies of Ntihinyurwa *et al.* [32] and Ntihinyurwa and de Vries *[64]* separated these two aspects of internal fragmentation. They suggested a new form of *location fragmentation* to reflect the scattering of parcels belonging to the same farm or household in different locations since there are situations under which a farm or a household may operate or own many small contiguous parcels located

in the same area. Another wave of studies viewed farmland fragmentation from the land block or landscape level and described it as a situation when a small land block is subdivided into many small farms owned by many owners or operated by many farmers (owners or tenants). From this lens, farmland fragmentation is ontologically conceptualised in the ownership and use (tenancy) of farms under a new form of farmland tenure (ownership and use) fragmentation characterised by spatial and social features of entire land block or region such as the number of farms, their respective sizes, the total number of owners and users (tenants), or the number of farmers who are using their own farms in a given defined relatively small area [10, 32, 64, 70, 73, 119-127]. Drawing from these scholars and the land management concept, Ntihinyurwa *et al*. [32] and Ntihinyurwa and de Vries [4, 64] derived a *Usership fragmentation* as a new form of fragmentation referring to the large number of farmers using leased land (tenants) in a given relatively small area, contrary to its twin "*Ownership fragmentation*" reflecting a situation when these farmers are using their own lands. In this case, Usership fragmentation replaces the term land use fragmentation which refers to the actual utilisation of farmland in terms of the number and types of crops cultivated in a given land block or parcel from the farmland management perspective [64].

From the ownership fragmentation form, the concepts of external (outer) and internal (inner) land ownership fragmentation, referring to the *Visible or documented* (many recorded land owners) and *Hidden or undocumented* (many unrecorded land owners or co-owners) land ownership fragmentation also known as *Co-ownership fragmentation* in a relatively small land unit respectively got introduced [32, 64, 70, 122, 123, 127, 128]. This phenomenon of hidden ownership fragmentation has been frequently identified in customary communities with shared ownership of land by all the family members where the individuals are only assigned with the use rights over land [1, 2, 5, 32, 64, 120], and in countries like Rwanda, Albania, Slovakia and Bulgaria promoting farmland subdivision restrictions and the cooperative farming systems [32, 64, 122, 123, 126]. However, most of these conceptualisations ignore the aspect of shape as one of the descriptors of land, which has also more often been linked with the disadvantages of fragmentation as a barrier to agriculture mechanisation and farm efficiency when it comes to irregularly shaped parcels at the farm and landscape levels. Drawing from various studies that developed different indices to assess this spatial-morphological aspect of land [113, 115, 129, 130], the studies of Ntihinyurwa *et al.* [32] and Ntihinyurwa and de Vries [64] derived a new form of fragmentation named *shape fragmentation* of farmland indicated by an above average number or percentage of irregularly shaped parcels and plots at the parcel, farm and farmland block levels, or specific shape fragmentation measurement indexes. In the realm of assessing the extent of internal and physical fragmentation, some research scholars introduced two new forms of *Excessive fragmentation* [32, 64, 70, 131, 132] and *Extensive fragmentation* [32, 64, 70, 111, 112] which reflect the situations when the number of parcels per farm exceeds its size in ha, and the presence of high average number of very small parcels which are not economically viable (less than 0.9 ha) at the farm and land block levels respectively. Regardless of the spatial levels and fragmentation forms, Igbozurike [133] developed a more objective and holistic conceptualisation of agricultural land fragmentation by defining it as the process by which a contiguous block of land is split into two or more parts. Following this logic, farmland fragmentation is then conceptualised as *landscape fragmentation or physical fragmentation,* referring to the disconnectivity of a *landscape* [64].

Prior to the design of the 40 comprehensive theoretical fragmentation scenarios, Ntihinyurwa *et al.* [32] and Ntihinyurwa and de Vries [64] argued that farmland fragmentation conceptualisation, forms typology and management should draw from the existing characteristics of farmland (object), including its relationship with people (subject) in land management paradigms, and different socio-spatial levels. These studies, therefore, describe farmland fragmentation as a natural (spatial structure) and socio-economic phenomenon that occurs at different socio-spatial levels (parcel, farm, land block and landscape) and management strategy [4]. Following the concept of farmland block or landscape as a wide area of land used for agricultural purposes [133, 134] and farmland fragmentation management unit, a farm as the total area of land (sum of all parcels) operated or tilled as a single agricultural enterprise (unit) [132, 135-137], household landholding as total area of land under a single ownership, parcel as an area of land unit with determined boundaries and unique legally recognised homogenous interests and the smallest recorded land unit in land administration [138], and plot as a continuous land parcel or portion of parcel used for specific agricultural purpose [134], Ntihinyurwa and de Vries [64] hypothesised the existence of various social (tenure) and physical fragmentation scenarios at these different socio-spatial levels under a set of the above mentioned specific scenarios. The argument is that any fragmentation in the physical characteristics of a land block or land parcel as an object (size, use, shape) and a farm (number of parcels, their qualities or values and locations) implies the existence of landscape, parcel, use, and shape fragmentation, and internal and location fragmentation as physical fragmentation forms respectively [4, 64]. Simultaneously, the fragmentation resulting from socio-economic relationships (rights, restrictions and responsibilities) between the spatial units (land block, farm, or land parcel) as an object and people (subject) or household derives the existence of various social or tenure (both visible and hidden ownership and usership) fragmentation forms [4, 64]. In this regard, *farmland fragmentation* refers to the split of the farming structure in a relatively small land block or region into many small farms (visible and hidden tenure fragmentation in terms of ownership and usership) or many small plots or parcels (physical fragmentation) [4]. It is denoted as *parcel* or *field fragmentation* when this split into many plots happens at the parcel level [64, 139]. *Farm fragmentation* (often referred to as internal or within farm fragmentation) in this context reflects the situation when a single farm is physically split into many relatively small parcels or small plots either spatially dispersed or contiguous (physical fragmentation), or shared by many undocumented co-owners or co-users (hidden tenure fragmentation in terms of ownership or usership) [4, 64].

The 40 theoretical fragmentation scenarios of Ntihinyurwa and de Vries [64] are henceforth grounded in the belief of the separate existence and coexistence of various physical and tenure (social) fragmentation forms at different socio-spatial levels [4, 32, 64, 135]. They encapsulate the six primary farmland fragmentation descriptors of the farmland block size, the number of parcels and plots in a land block and their respective sizes, the number of parcels and plots per farm and their respective sizes, shapes, uses and locations as indicators of physical fragmentation forms (internal, landscape, use, shape, dispersion and location), and the number of farms, farmers, farmland owners, co-owners and tenants in a land block as indicators of farmland tenure fragmentation forms (visible and hidden ownership, and usership). Being the farmland fragmentation management spatial unit, this study of Ntihinyurwa [64] suggested the farmland block as the main analysis level for farmland fragmentation

scenarios as the best option to inform its management policies and strategies. As mentioned above, the 40 scenarios were grouped into ten main scenarios derived from the combination of four main socio-physical fragmentation aspects of internal, location, ownership and usership replicated four times in combination with the aspects of use (monoculture vs multiculture) and shape (regular vs irregular). The ten groups of scenarios are listed as follows: ***Physical fragmentation scenarios***: *Internal*; *Internal and location*; ***Tenure fragmentation scenarios***: *Ownership (visible & hidden)*; *Usership (tenancy)*; *Visible ownership and usership*; *Hidden co-ownership and usership*; *Hidden ownership (co-ownership)*; *Visible ownership and hidden co-ownership;* ***Physical and Tenure (social) fragmentation scenarios:*** *Ownership (Usership) and internal*; *Ownership (Usership), internal & location.* However, the parcel-level scenarios were ignored as they mostly overlap with the ones at the higher levels (farm and farmland block), and the aspects of extensiveness and excessiveness indicating the extent of physical fragmentation (landscape and internal) were not considered. Thus, this study of Ntihinyurwa and de Vries [64] left room for additional scenarios if new aspects were considered and introduced in the equation. The spatial distribution and the extent of these scenarios in a given area are dictated by local socio-cultural, economic, agro-ecological, demographic, environmental and political conditions, and spatial heterogeneities as the main determinants of their causes and impacts [3, 8, 32, 64, 140, 141].

Although these theoretical scenarios stipulate the coexistence of tenure (ownership and usership) and internal fragmentation forms, various studies have empirically proven a contradictory and disputed correlation between farm size and the number of parcels per farm. Some studies posit that the number of parcels decrease with the increase in farm size and vice versa, which indicates a positive correlation between internal fragmentation and tenure fragmentation forms [16, 64, 111]. Bentley [111] and Blarel *et al.* [16] backed this hypothesis by arguing that small subsistence farms tend to be more internally fragmented than big mechanized farms, thereby positing the possible practical coexistence of physical (internal) and tenure (ownership/usership) fragmentation forms at the same degrees under certain conditions. However, some counter studies postulate that the internal fragmentation decreases (decrease in the number of parcels per farm) with the decrease in farm size (tenure fragmentation) and vice versa [5, 64, 142, 143]. Theoretically, the number of parcels and plots per farm is determined by the surface area of the farm, structure of agricultural land, soil quality classes, and natural terrain conditions [144]. In this regard, the increase in the number of owners in a relatively small land block would imply the reduction in farm size and the number of parcels per owner/farm, and obviously the decrease in internal fragmentation, thereby stipulating a negative correlation (relationship) between farmland tenure and internal (physical) fragmentation forms in a given area. From the later hypothetical position, the two forms cannot theoretically coexist in the same location at the same degrees [64]. The coexistence of these two distinct fragmentation forms would practically be possible only at different degrees (high degree of ownership and/or usership fragmentation and moderate to low degree of internal fragmentation, and vice versa) [64].

2. 2. 2. Farmland Fragmentation and Defragmentation Nexus: Theoretical Scenarios and Paradox

The comprehensive theoretical farmland fragmentation scenarios of Ntihinyurwa and de Vries [64] do not indicate when and where farmland fragmentation can be problematic or beneficial, nor how and

why it can sustainably be managed for food security and farmland teneure security motives. For this, through an integrative review of the existing information about farmland fragmentation, the same authors [3] further developed the conditions under which these farmland fragmentation scenarios may become problematic or beneficial and categorised them into two theoretical groups of problematic scenarios that need to be avoided and the beneficial scenarios which should be conserved. Drawing from the logic that not all farmland fragmentation forms are problematic nor beneficial, the categorisation of these scenarios was grounded in the critical analysis of the causes and impacts of various fragmentation forms and the conditions under which they occur. This theoretical study found a close connection between the causes and effects of farmland fragmentation. Referring to the studies of McPherson [132] and Blarel et al. [16], Ntihinyurwa and de Vries [3] categorised the causes (factors) and effects (impacts) of farmland fragmentation as twofold, in both demand (voluntary causes versus positive or beneficial effects) and supply factors (imposed or involuntary causes versus adverse or problematic effects). The supply-side arguments stipulate that fragmentation has adverse effects on agricultural production and farm efficiency, while the demand-side explanations reason from the presumption that farmland fragmentation is a farmer's choice for its perceived benefits of food sovereignty, food security, production risks management, and farmland tenure security [3].

From the supply position, the disadvantages of farmland fragmentation have been associated with both physical and tenure fragmentation at all socio-spatial levels. In this vein, both physical and tenure fragmentation have hypothetically been linked with the farming and urban population growth on scarce and stable land resources, partible egalitarian inheritance principles and culture in land distribution, individual private land tenure system, land market, infrastructure development, land laws, regulations and policies, along with land reforms such as land redistribution, land restitution and land sharing programs in different countries undermined by conflicts [3, 32]. Some studies claimed that farming and urban population growth combined with egalitarian principles in partible inheritance and land distribution systems lead to both physical (internal and location) and tenure (ownership and usership) fragmentation under scarce farmland conditions [3, 32, 111]. This happens through the increase in the number of farmers (owners and tenants) and farms in a relatively small farmland block (small farms), reduction in farm size, increase in household size and food consumption, and increase in the number of parcels and plots per farm from the acquisition of contiguous (adjacent) or non-contiguous parcel to meet the food demands of the growing population [3]. Farmland tenure and landscape fragmentation forms in this scenario are considered problematic by acting as a barrier to the economies of scale and commercial agriculture through small, non-viable farms and parcels (ibid). The farming population growth alone in the presence of farmland subdivision and partible inheritance restrictions or in the absence of egalitarian-based principles in land distribution systems may not lead to any physical and visible tenure fragmentation forms. Instead, it gives rise to hidden tenure (ownership and usership) fragmentation forms in the case of co-ownership of family land by all the family members or its hidden undocumented subdivision for individual use rights in the form of tenancy or private ownership rights [3]. Under growing and strong economies, market-oriented agriculture and restricted and perfect land market conditions, farmland market, individual private land tenure system, land reforms and sharing programs have often been associated with physical farmland fragmentation in terms of internal, use and location forms. This

occurs when farmers expand their farms by acquiring additional non-contiguous parcels to existing farms to boost agriculture production and farm income, crop diversification, and food security due to increased economic land value and profitability [3, 119]. Under abundant farmland conditions (big farms), the number of contiguous or scattered parcels and plots per farm often increases, indicating internal and location fragmentation [3]. This increases the number of boundaries and distance between parcels and the farm, thereby acting as an obstacle to agriculture mechanisation, farm efficiency (through the increase of farm production and supervision costs), and a source of farmland boundaries and use-related conflicts among farmers [3].

Moreover, in circumstances of failed economic incentives, especially in subsistence economies with free but uncertain or imperfect land markets, the social value of land outweighs its economic value [3, 119]. This feature is characterised by the high attachment of farmers to land as their means of subsistence (land considered by farmers as a social resource rather than an economic asset or commodity) [119]. Under these conditions, the above-mentioned factors lead to many small subsistence farms and parcels in relatively small areas as indicators of land tenure (in terms of ownership) and physical landscape fragmentation [3]. The farmland subdivision restrictions promoting cooperative farming, monoculture and joint land ownership systems have been found to lead to farmland tenure fragmentation in terms of hidden ownership and visible usership, and physical fragmentation in terms of internal, use, dispersion and location [1, 3, 120]. This is the case of various policies like land use consolidation encouraging the cultivation of the same priority crop by neighbouring farmers in a synchronised way and Article 30 of the outdated law governing land in Rwanda forbidding the subdivision of agricultural land into parcels of less than 1 ha [3, 4], and the customary land tenure systems in many African customary communities [1, 5]. This happens when individual farmers desire to acquire their own undocumented parcels from hidden subdivision of the family land for individual agriculture use and perceived farmland tenure security on one hand, and additional parcels located in other agro-ecological microzones and consolidation sites with different crops growing conditions which could give them the possibility to grow diverse crops for risks and labour management, and food diversity and security purposes on the other hand [1, 3, 5, 6, 28, 32, 46]. In these theoretical fragmentation scenarios of Ntihinyurwa and de Vries [3], the grouped settlements programs and land-based dowry marriage principles were also identified among the factors of farmland location and internal fragmentation. This occurs through the increase in the distance between the farm parcels or plots and the farmstead or when two partners start a new household, thereby putting together their individual often scattered (non-contiguous) farm parcels in one new joint internally fragmented farm. In contrast, the scattered settlements inside more compact farms and the settlement of the new farming couple (joint farm) in the farming area generally reduce the distance-based fragmentation issues and land tenure fragmentation by reducing the number of farms, respectively [3, 4]. The same study found farmland shape fragmentation to be linked with all the above-discussed natural and artificial drivers that lead to any farm landscape subdivision into different irregularly shaped fragments in the absence of land shape control strategies. These may include, among others, the natural waterways and bodies, tectonic movements, the construction of infrastructure (roads, railways, etc.), and pathways.

The advantages (benefits) of farmland fragmentation are generally associated with internal and dispersion as physical fragmentation forms at the parcel and farm or household level. Most of the demand position causes of farmland fragmentation have been theoretically linked with both physical (internal, use, dispersion and location) at the parcel and farm or household levels and tenure (both hidden and visible ownership and usership) fragmentation forms at the farm and land block levels [3]. It has been claimed that under heterogeneous farmland conditions (diversity in soil qualities and types, slope, microclimates, topography, exposure, crop suitability and growing conditions, and farmland production potentials) and the absence of risk management strategies (agriculture insurance systems, high yielding and resistant crops varieties, crop diseases and pests control measures, and other land saving technologies), farmers prefer to have parcels of all grades or classes often scattered in different agro-ecological micro-zones [3, 32, 89, 98]. The egalitarian principles in land allocation processes (partible inheritance, land sharing, land distribution and restitution, and other land reforms) and farmland market (buying and selling farmland parcels) are reported as the main channels to this scenario [3]. This choice is often spurred by the purposes of crop diversification and rotation, crop production and price risks management, farm expansion and income increase, agrobiodiversity conservation and climate change adaptation, soil fertility management, erosion control (via radical and progressive terraces), and multidimensional food security and sovereignty (food quality, quantity, availability, accessibility and sustainability) [3, 16, 32, 64, 86-92, 95, 96, 98, 111, 145]. This leads to physical fragmentation in terms of internal fragmentation of individual farms and location, dispersion, farm-level use and shape fragmentation when farmers grow different crops (multicultural) on many small or big irregularly shaped and spatially scattered parcels or plots in different locations, and farmland tenure fragmentation forms in terms of ownership (many owners) and usership (many tenants) in case of farmland scarcity conditions leading to many small farms in a relatively small land block [3, 32, 92, 96, 124, 125].

Besides the above-mentioned rational reasons for fragmentation, in subsistence economies characterised by farmland and capital scarcity, subsistence agriculture, failed economic incentives, imperfect market (for labour, agricultural inputs and food), higher social land value than its economic one, the absence of risks management strategies and off-farm employment opportunities, abundant farm labour (high farming population density), and heterogeneous socio-spatial and agro-ecological conditions, farmers choose to have their own small farms made of small heterogeneous contiguous farmland parcels and plots or scattered in different locations [3, 4]. This indicates the coexistence of farmland tenure fragmentation (ownership) and physical fragmentation (internal, use, dispersion and location) for the motives of individual farmland tenure security (ownership and use), land ownership and use-related conflicts management, labour use and weather shocks management, and self-sufficiency or independency in production of diversified food basket to meet the nutritional requirements and food preferences as the cheapest strategy to meet the household food security [3, 4, 32]. In this situation, farmers seek to maximise the returns through scarce factors (land and capital) rather than abundant factors (labour) by improving farming technologies through land-saving strategies such as insurance, high-yielding varieties and different agriculture intensification programs to increase farm efficiency and meet the food needs of this growing population [3, 111, 146, 147]. Fragmentation is therefore considered

as a source of employment for household members and a positive factor of agricultural production in scarce land conditions lacking off-farm employment opportunities [3, 16].

Furthermore, under imperfect labour market conditions, small farms may mitigate the adverse effects of farmland fragmentation by reducing labour costs, including supervision and employment costs, through high labour use intensity and high labour per land ratio. The argument is that the smaller the farm, the lower the internal fragmentation, the higher the labour use intensity, the higher the productivity of the farm [3, 111, 148, 149]. This argument supports the theory of diseconomies of scale that stipulates a negative relationship between farm size and farm output, and the competitiveness of small farms over big ones [3, 11, 12, 16, 51, 52, 148, 149]. However, as previously discussed in the supply side causes of fragmentation, this scenario can simultaneously be considered as an external imposition to farmers by the socio-cultural practices such as egalitarian partible inheritance and natural conditions (topography, soil type, climate change) and become a problematic and unwanted fragmentation to farmers [64]. Moreover, in order to answer the questions of how and why these scenarios can be sustainably managed, through another integrative literature review on the nexus between farmland fragmentation and consolidation and food security, Ntihinyurwa and de Vries [4] developed a comprehensive theoretical model for the management of these paradoxical fragmentation scenarios under various conditions. This model describes various preventive and mitigation strategies for problematic farmland fragmentation avoidance and different supporting strategies for rational farmland fragmentation conservation. It stipulates that the best management of farmland fragmentation for food security and farmland tenure security purposes can be achieved by minimising the problems associated with physical and tenure aspects of farmland fragmentation and optimising its potential benefits [4].

In summary, while the market-oriented agricultural system is well known for its big consolidated farms (in case of unrestricted land market) and big internally fragmented farms (in case of restricted land market) (physical fragmentation in terms of internal, location, dispersion and use), the subsistence one is characterised by small and sometimes internally fragmented and scattered farms (tenure and physical fragmentation) as a result of subsistence motives, traditional farming methods (shifting cultivation), physical, social and demographic factors. In the same respect, these theoretical farmland fragmentation management models of Ntihinyurwa and de Vries [3] stipulate that both physical in terms of internal, use, dispersion and location, and tenure fragmentation of farmland in a given heterogeneous and mountainous areas (when the costs of defragmentation outweigh its benefits) under the subsistence and middle-income economies may be beneficial and conserved either in combination with or without agriculture intensification programs (farmland saving technologies). This may be done for the discussed purposes of subsistence motives, crop production diversification, crop rotation, exploitation of multiple agro-ecological zones, agrobiodiversity conservation, soil fertility management, labour, risks and conflicts management, climate change adaptation, food sovereignty, household food security and farmland tenure security [3].

On the other hand, both physical in terms of internal, dispersion, use, shape and location, and tenure fragmentation of farmland under homogenous agro-ecological conditions, and physical fragmentation under heterogeneous agro-ecological conditions and strong complex economies

characterised by market-oriented agriculture and modern risk management strategies may be problematic and revoked through various defragmentation (prevention and mitigation) measures [3]. The sole purposes of improving farm efficiency and income, agriculture mechanisation, farmland boundaries and use-related conflicts management, reduction of farmland wastage through boundaries, food quantity and supply, and food security motives may motivate this decision. In this line, under diverse local socio-spatial, economic and agro-ecological conditions, farmland consolidation, voluntary parcel exchange and on-field harvest sales, farmland realignment, and farmland use (crop) consolidation were stipulated as suitable strategies for controlling physical fragmentation problems. In contrast, farmland banking and off-farm employment, restrictions about the minimum parcel sizes subdivision and absentee owners, joint ownership, cooperative farming, farmland use (crop) consolidation, agricultural land protection policies, and family planning measures could be suitable to prevent and minimise farmland tenure fragmentation problems [4]. In contrast, various agriculture intensification programs, agro-ecological approaches, and land-saving technologies were preconised as the most suitable strategies to maximise the income from agriculture on fragmented farms and parcels under the circumstances of rational fragmentation [4]. In the case of the coexistence of both rational and defective fragmentation scenarios in the same area, different specific strategies, like localised and multi-cropping-based land consolidation approaches, in combination with or without agriculture intensification programs could provide better and more balanced optimal solutions [4]. The following section describes the methodological framework for empirically testing these theoretical scenarios and hypothetical positions in the context of Rwanda as a case study.

2. 3. Methodological Framework

2. 3.1. Research Approach, Philosophy and Design

Considering the complex nature of the farmland fragmentation phenomenon and the aim of the study, the type of research questions and hypotheses, and the required multidimensional and multilevel data to test and answer them, this research follows a pragmatic paradigm. It adopts a mixed methods research approach combining the deductive (rational), inductive (empirical) and abductive approaches, and integrates quantitative and qualitative research strategies and methods in the same research design to draw meaningful and useful conclusions about farmland fragmentation scenarios in Rwanda as new scientific knowledge generation. According to the studies of Cohen *et al*. [61], Dudovskiy [60] and Creswell [62, 63], this pragmatic philosophical stance may use a combination of objective and subjective ontologies, positivist and interpretivist epistemologies, and various methods (qualitative and quantitative) for qualitative and quantitative data collection and analysis to address the main research question (objective) as a comprehensive approach to analyse complex scenarios. The same studies posit that this approach allows the researcher to rely on different methods and analytical strategies to understand and provide solutions to complex problems.

Being a socio-spatial phenomenon involving both physical, social, demographic, economic and agro-ecological aspects of farmland, the analysis of farmland fragmentation scenarios requires the collection of both primary and secondary numerical and categorical (nominal) spatial and non-spatial data at different socio-spatial levels (parcel, farm, household, land block or landscape and community). Furthermore, the analysis and modelling of fragmentation scenarios in a heterogeneous country like

Rwanda as the case study involve testing the existing generic theoretical scenarios in a specific Rwandan context and generating or modelling the particular objective or subjective farmland fragmentation scenarios in different agro-ecological zones of the country which will inform the design of farmland fragmentation management strategies, policies and interventions suitable for the identified specific Rwandan fragmentation scenarios. Consequently, the study adopted the deductive approach to test the generic theoretical fragmentation scenarios in the Rwandan context through a set of quantitative research strategies and methods. Moreover, it used the inductive and abductive approaches through qualitative and quantitative methods and strategies to modify and specify these scenarios to the particular case study context and generate new specific ones in different research sites and agro-ecological zones, and formulate new general theories grounded in the empirical findings. According to Ntihinyurwa and de Vries [64] and Ntihinyurwa and de Vries [3], the analysis of both problematic and beneficial farmland fragmentation scenarios implies the survey of its conventional forms through mathematical calculations and measurements of farmland metrics (descriptors) and their interactions at the parcel, farm and landscape (land block) levels, and the investigation of its conventional and specific causes and effects at the farm (household) and community (land block) levels as perceived by local farmers, government and non-governmental officers, and national academic and scientific experts in the field of farmland management. This justifies the choice of a mixed research approach and pragmatic epistemology.

This approach has previously been used by Ntihinyurwa *et al.* [32] and Chigbu *et al*. [6] in a similar context, and Rushemuka and Bock [33] by applying the Multiscale and Nested Hierarchy Land System Reasoning to tailor soil fertility management inputs to specific soil types in Rwanda. Given the scope, the purpose and nature of the study, as dictated by this research approach, the convergent parallel research design stipulating simultaneous collection and analysis of both qualitative and quantitative data through both quantitative and qualitative methods at different socio-spatial levels was adopted as a framework for both socio-spatial data collection, analysis, exploration and conclusions drawing about various farmland fragmentation scenarios in 12 Agro-ecological zones of Rwanda. This design helps to collect primary and secondary qualitative and quantitative data in the same period to build a complete complementary dataset with less resources and time [60, 62, 63]. In this regard, we simultaneously conducted both the farm households and cadastral surveys, field observations, focus group discussions, documents review and key informants' interviews to collect both quantitative and qualitative data about farmland fragmentation forms and both descriptive and inferential statistics along with thematic analysis to analyse and model the possible existing farmland fragmentation scenarios and their relationships in Rwanda in a comprehensive fashion. Drawing from the previously discussed content in the introduction section, the theoretical farmland fragmentation scenarios (*FFSc*) are a function of four main factors of farmland fragmentation forms and extent (*FFF*), their causes (*FFCa*), local conditions (*FFCo*) and effects (*FFE*) at different socio-spatial levels. Thus, the empirical analysis of farmland fragmentation scenarios in a given area can be expressed in the following mathematical **Equation 1:**

$$FFSc = fx\ (FFF + FFCa + FFCo + FFE) \qquad \textbf{(1)}$$

Figure 5 displays the farmland fragmentation scenarios analytical approach and design in Rwanda. As illustrated in Equation 1, the analysis and prediction of the classification of farmland fragmentation

scenarios into three categories (problematic, beneficial, and problematic-beneficial) is dependent on the identified farmland fragmentation forms (Physical and Tenure), their extent and analysis levels (parcel, farm, landscape), the local conditions (demographic, socio-cultural, agro-ecological, biophysical, environmental, political, legal, technical and technological), the causes of fragmentation (internal and external) and its impacts (negative and positive) in the study area. This design implies the analysis and modelling of farmland fragmentation scenarios through several fragmentation forms-causal-effects relationships empirical models. The scenarios can develop from separate forms of fragmentation (physical or tenure) or a combination of different socio-spatial forms at different or the same analysis levels.

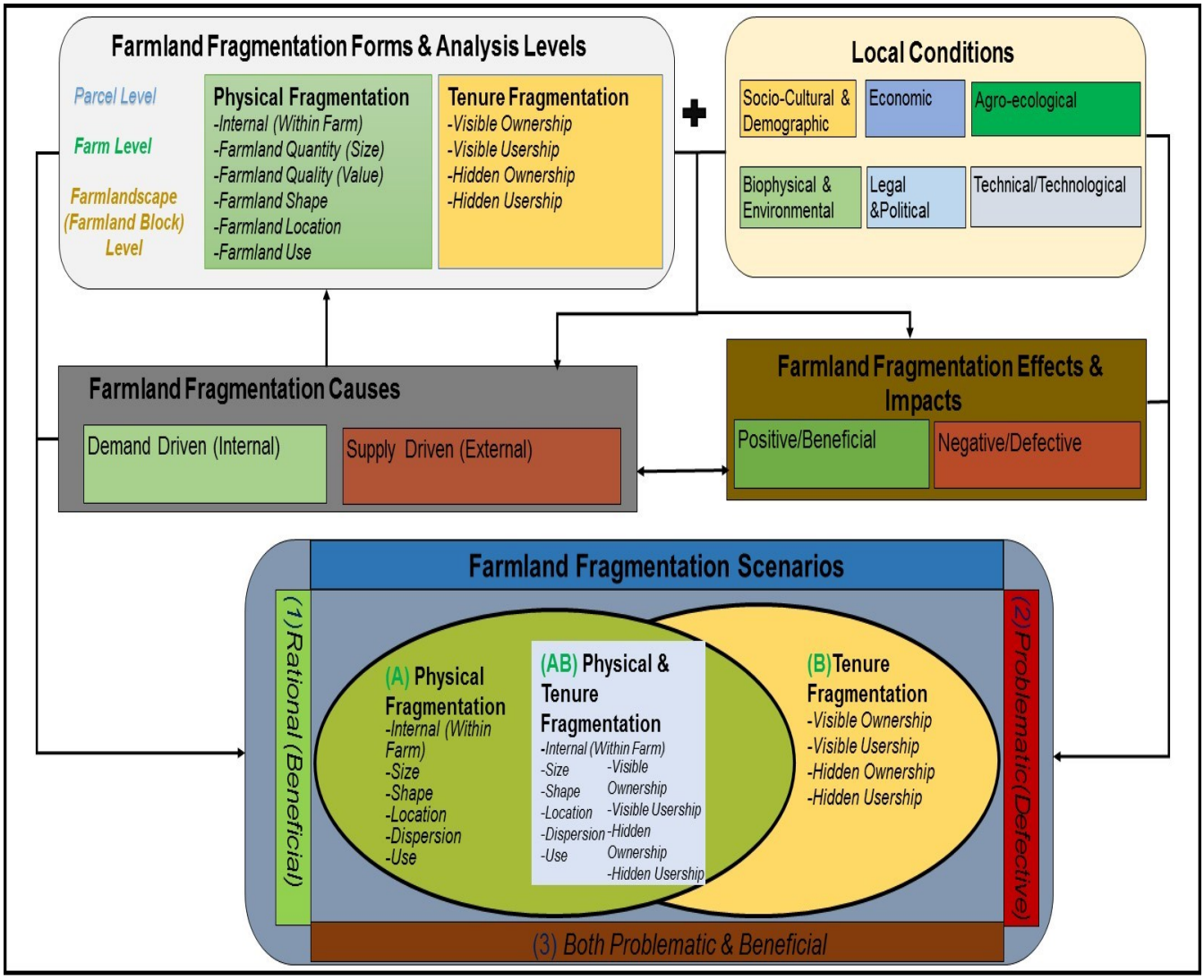

Figure 5. Farmland fragmentation scenarios analytical approach and design

2. 3. 2. Study Area Description and Research Sites Distribution

In light of the hypothetical socio-spatial diversity and distribution of farmland fragmentation scenarios across various local conditions, this study was conducted in twelve agro-ecological zones of Rwanda as the suitable strategy to test this theory. The choice of this approach and the study area is

grounded in the highly diverse and very specific localised socio-cultural, demographic, economic, spatial, soil, agro-climatic and ecological conditions and farming systems of Rwanda [150], which explains the possibility of the diverse and heterogeneous spatial distribution of farmland fragmentation scenarios in the country. Being a small, hilly and mountainous, landlocked, poor and one of Africa's most densely populated countries, Rwanda is located in the Eastern Central region bordering Burundi, Uganda, Tanzania and the Democratic Republic of Congo (DRC) [40]. It is characterised by a relatively high degree of spatial agro-ecological diversity with 12 different generic agro-ecological zones (AEZs) and tremendous micro-ecological variation of land and soil types over very short distances within the same Agro-ecological zone due to its drastic variation in topography or relief (altitudes and slopes), parent materials (soil type and quality), and temperature and rainfall patterns [33, 40, 150, 151]. Besides the altitude, rainfall and soil type, Clay and Dejaegher [150] further considered the farm characteristics like farm size, number of parcels per farm, crop production and livestock ownership, and the demographic features like the population density and the household size to reduce and group these 12 agro-ecological zones (Eastern Savanna, Buberuka Highlands, Volcanic Summits and high plains, Eastern Ridges and Plateaus, Congo-Nile Divide, Central Plateau, Granitic Ridges, Kivu lakeside, Cyangugu backside, Bugarama Plain (Imbo), Bugesera, and Mayaga) into five heterogeneous regions of the country (South-West, North-West, South-Central, North-Central, and East). However, this classification failed to capture the socio-economic and soil factors behind the diversity in farming systems among various regions of Rwanda, which stipulates the hypothetical existence of many more diverse agro-ecological and socio-economic zones, and the diversity of farmland fragmentation scenarios between and within AEZs over short distances.

The country is administratively subdivided into five provinces, 30 districts, 416 sectors, 2148 cells, and 14837 villages as the smallest administrative units spread over the 12 AEZs. These administrative units are assumed to be spatially, socio-economically, culturally, and agro-ecologically diverse, except on the aspect of local language. The total national area covers a surface of 26,338 square km, with a total national available land area of 2.377 Million ha, out of which 1.4 Million ha was delineated for agricultural purposes in the calendar 2020-2021, and 1.1 Million covered by seasonal food crops [30]. Its population was estimated at 12955455 people and 3 Million households, 4.4 people per household on average, with a population density of about 512 people per sqkm, and an annual population increase of 2.4% in 2021 [39, 110, 152, 153]. The majority of the Rwandan population lives of subsistence rain-fed agriculture with about 70% nationally and 94% in rural areas, where farmers operate small-scale agriculture on less than 0.6 ha of farm size with three parcels per farm on average [30, 39, 41, 53]. Being a backbone of the national economy, agriculture is highly sensitive to climate variability and extreme weather conditions such as droughts, floods and severe storms, and high seasonality dependent [40]. Though the rainfall figures generally tend to increase with altitude from the East, South, North to the West and vice versa with the temperature, farm and parcel size and the number of parcels per farm [150], recent studies reported critical changes in rainfall and temperature patterns due to climate variability which negatively affect the agriculture production and household food and nutrition security. These socio-spatial, economic, demographic and agro-ecological features of Rwanda make farmland in the country a very scarce resource and justify the above-mentioned hypothetical existence of various socio-spatial

fragmentation scenarios in the country and, therefore, the suitability of our study area choice. The pressure on existing farmland is worsened by the lack of possibilities for agricultural land expansion and the lack of off-farm employment opportunities, which will potentially increase farmland fragmentation patterns [16, 40].

Therefore, considering the study objectives, hypotheses and the above-discussed features of topographic, socio-economic, and agro-ecological diversity in the country, 24 research villages were purposively selected across the 12 agro-ecological zones as research sites (farmland blocks) and farmland fragmentation scenarios analytical socio-spatial units. The consideration of this aspect of socio-spatial and agro-ecological diversity in the analysis of farmland fragmentation scenarios has been recommended by various recent studies, as these scenarios and their management strategies may vary from area to area [8, 9, 33, 41, 140]. **Figure 6** portrays the spatial distribution of research sites across 12 AEZs.

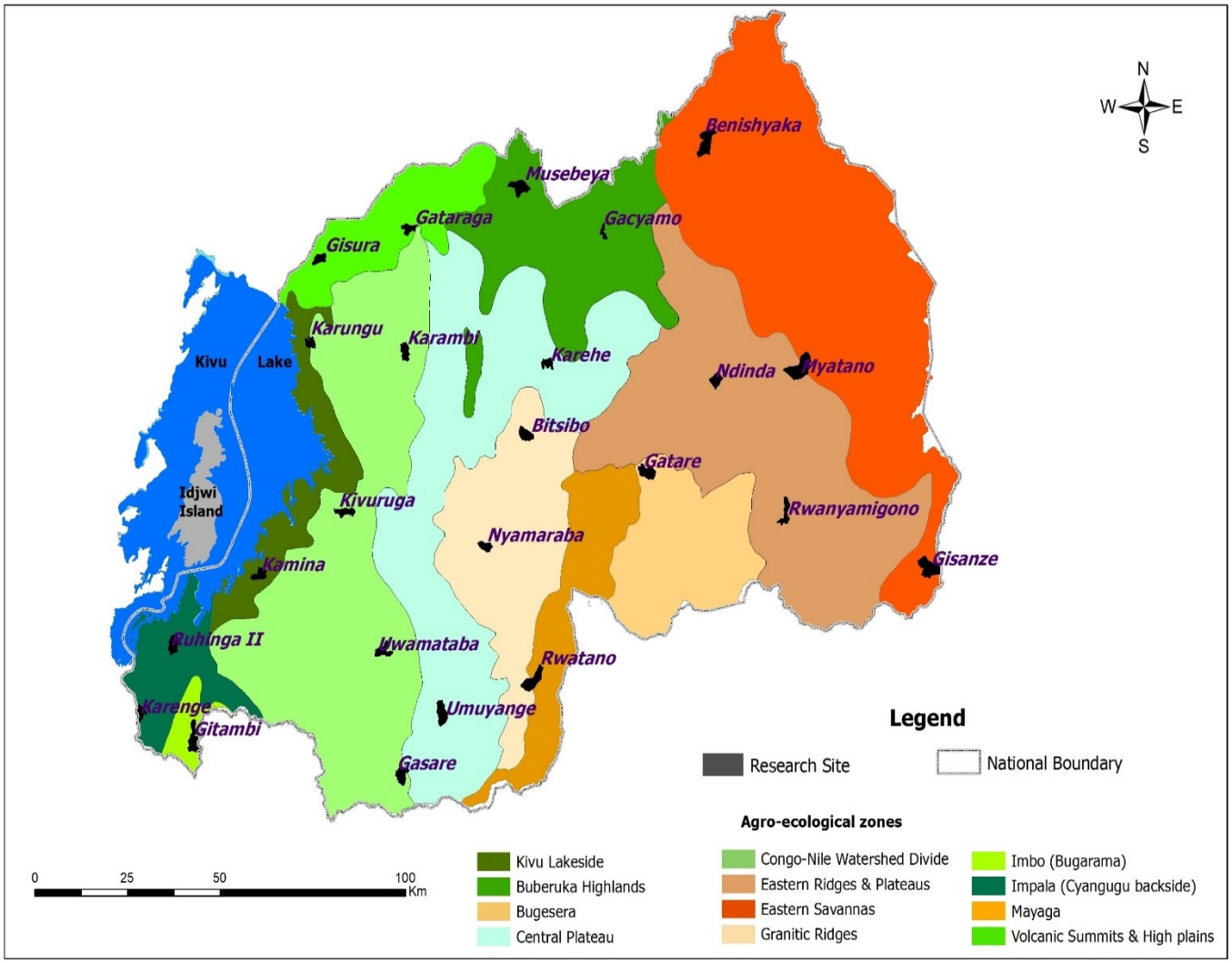

Figure 6. Spatial distribution of research sites across 12 AEZs

Source: Visualisation from cadastral-level dataset analysis

2. 3. 3. Data Sources and Collection Methods

Based on the nature of this research and the adopted approach and design, the multidimensional and multilevel data combining primary and secondary qualitative and quantitative ones were collected in 24 villages (research sites) from 12 agro-ecological zones of Rwanda from January to August 2021. This approach helped to answer the main research questions and test the research hypotheses through a wide range of triangulated data collection methods for comparison, reliability and validity purposes. In order to gather the information about available farmland fragmentation forms, causes and impacts in respective research sites, the sample-based farm households survey was used to collect the farm, parcel and plot-levels primary numerical and nominal data about the farm characteristics (farm size, number of parcels and plots per farm and their respective sizes, shapes, locations, agriculture uses in terms of the number and types of crops, relative fertility status, tenure status, and means of acquisition) and their underlying conditions. This survey was conducted by a team of eight experienced enumerators and two field supervisors from May to July 2021 (Agriculture Season B 2021). For data comparison and complementation purposes aiming at a comprehensive farmland fragmentation forms analysis, the socio-spatial farm landscape (farmland block)-level primary information (farmland block size, number of household holdings, parcels and their respective sizes, shapes and tenure statuses) in the 24 research sites was collected from the national digital cadastre and land registry from the Rwanda Land Management and Use Authority (RLMUA) through the provision of the shape files of farmland parcels for the selected research sites.

The key informant's interviews with the national farmland management policymakers and researchers, local leaders, and agriculture and land management officers, the focus group discussions with five groups of farmers from the five heterogeneous farming regions of Rwanda, and extensive field observations were used to collect the primary qualitative information. This information consisted of the perceptions of various stakeholders on farmland fragmentation concept, its potential forms, causes and impacts, and their determining conditions at the community, agro-ecological and national levels, and the general picture of farm landscape fragmentation in terms of shape, topography and use. The secondary quantitative data about farmland characteristics and transactions descriptive statistics were collected by the primary investigator (author) through the review of various survey reports and datasets from governmental institutions like the National Institutes of Statistics of Rwanda (NISR), the Ministry of Agriculture and Animal Resources (MINAGRI), and Rwanda Land Management and Use Authority (RLMUA) of the Ministry of Environment (MoE). The review of various documented national policies, laws and regulations and research publications in the fields of farmland use and management, agriculture and climate change management and their nexus with SDGs 1, 2, 12, 13 and 15 was similarly used as a source of additional qualitative and crucial information for the analysis of the possible farmland fragmentation scenarios in Rwanda.

A mixed sampling approach was used to select the research sites and respondents. For the household survey and cadastral survey, a multistage purposive sampling was adopted to select the 24 research villages considered as farmland blocks in this research from the 12 national AEZs. In principle, considering the variations in agro-ecological, topographic, soil and socio-economic conditions among the

12 AEZs, one research site or village per AEZ was supposed to be used as a proxy. However, due to the size differences in the AEZs and their internal micro variations or heterogeneities in the above-mentioned conditions over short distances, two or three spatially dispersed and theoretically heterogeneous villages were selected in large AEZs to capture these internal heterogeneities which could consequently imply the internal diversity of farmland fragmentation scenarios within the same AEZ. In contrast, only one site was selected from small theoretically homogeneous AEZs. To avoid socio-spatial overlap of administrative units and AEZs and ensure that the 24 selected villages are socio-spatially diverse and representative of 4 provinces, 22 different districts, 24 sectors and 24 cells of Rwanda, the administrative criterion was included in the selection process. A systematic random sampling technique was adopted to select the village-level statistically representative sample of farm households (family farms) to be interviewed from the total number of farm households in the 24 villages using the simplified formula of Yamane [154] appropriate for small homogenous case studies, with 5% precision level and 95% confidence interval considering the heterogeneity of our research sites. A total sample size of 487 farm households derived from the formula computations and 30% of compensation for missing responses or biased information [155] (representing 11.7% of the total households) was considered for the survey from a total number of 4173 farm households. This sample size was spatially and statistically distributed among the research sites based on the total number of farm households per village. **Table 1** displays the characteristics of the 12 agro-ecological zones of Rwanda and the statistical distribution of the sample among research sites.

Table 1. Research sites characteristics and statistical sample distribution

FID	*AEZ*	*Province*	*District*	*Sector*	*Cell*	*Research site (village)*	*Sample size*	*Area in sqm*	*Altitude in m*	*Rainfall in mm*	*Soil type*
1	***Bugarama (Imbo)***	Western	Rusizi	Gikundamvura	Kizura	Gitambi	20	158317856	1100	1200	Fluvents/Vertisols/ Alluvial soils
2	***Cyangugu Backside (Impala)***	Western	Rusizi	Gashonga	Muti	Karenge	21	649535168	1700	1400	Oxisols/ Ultisols/ Heavy, clayey soils derived from basalt
			Nyamasheke	Bushenge	Kagatamu	Ruhinga II	22				
3	***Kivu lakeside***	Western	Nyamasheke	Macuba	Mutongo	Kamina	15	735929536	1600	1200	Oxisols/Vertisols/ Clay loam soils
			Rutsiro	Kivumu	Bunyunju	Karungu	25				
4	***Volcanic summits & high plains***	Northern	Musanze	Gataraga	Rubindi	Gataraga	33	908868160	2200	1500	Endosols/ Ultisols derived from volcanic materials
		Western	Rubavu	Busasamana	Gasiza	Gisura	15				
5	***Congo Nil Divide***	Western	Ngororero	KABAYA	Mwendo	Karambi	18	3919296512	2100	1600	Oxisols/ Humic acid soils
			Karongi	Gitesi	Nyamiringa	Kivuruga	19				
		Southern	Nyaruguru	Munini	Giheta	Gasare	20				
			Nyamagabe	Kibirizi	Uwindekezi	Uwamataba	22				
6	***Buberuka Highlands***	Northern	Gicumbi	Byumba	Nyakabungo	Gacyamo	25	13598568	2000	1200	Oxisols at high altitude
			Burera	Rusarabuye	Kabona	Musebeya	12				
7	***Central plateaus***	Northern	Gakenke	Muhondo	Gihinga	Karehe	20	5297718272	1700	1200	Oxisols/ Humic soils at medium altitude
		Southern	Huye	Karama	Gahororo	Umuyanjye	28				
			Kamonyi	Musambira	Rukambura	Bitsibo	22				
8	***Granitic ridges***	Southern	Ruhango	Bweramana	Gitisi	Nyamaraba	15	73812040	1600	1100	Gravelly sandy loam soils
9	***Mayaga***	Southern	Gisagara	Musha	Bukinanyana	Rwatano	24	2235731456	1450	1050	Oxisols/ Ultisols/Clay soils derived from shale
10	***Bugesera***	Eastern	Bugesera	Mwogo	Kagasa	Gatare	12	2235731456	1400	900	Oxisols, Ultisols, Alfisols
11	***Eastern Ridges & Plateaus***	Eastern	Kayonza	Gahini	Urugarama	Myatano	25	3813668608	1500	950	Oxisols with high iron oxide
			Rwamagana	Fumbwe	Mununu	Ndinda	13				
			Ngoma	Gashanda	Giseri	Rwanyamigono	15				
12	***Eastern Savana***	Eastern	Nyagatare	RUKOMO	Rurenge	Benishyaka	20	4797606912	1400	850	Oxisols, Old infertile soils with texture variable
			Kirehe	Mahama	Mwoga	Gisanze	17				
Total	**12**	**4**	**22**	**24**	**24**	**24**	**487**				

Source: Developed from farm household survey and literature

A purposive sampling method was used to select 16 key informants at the AEZs and National levels including 14 government officials (12 local-level agronomists and land managers and two ministry-level policymakers from the Ministry of Environment and the Ministry of Agriculture and Animal Resources responsible for farmland management in the country), and two national university researchers. These were chosen based on the quality of information they held and their expertise in farmland management issues in Rwanda. Three types of questionnaires were prepared in English language, translated in Kinyarwanda and administered to different categories of respondents. A household survey questionnaire of structured and semi-structured questions was administered to the household representative. A community-level questionnaire of semi-structured and unstructured questions was administered to the local level key informants and groups of farmers through key interviews and focus group discussions around the above mentioned required information and themes. Lastly, a national-level key informant's questionnaire of semi-structured and unstructured questions was used for key interviews with policymakers and researchers around all the possible required information about farmland fragmentation scenarios and their management strategies in the country.

A computer-assisted personal interview (CAPI) system through the *SurveyCTOCollect* data collection application was used for all the interviews. All the questionnaires were entered and programmed in the data collection devices equipped with Android systems, such as tablets and smartphones, by a qualified IT technician responsible for the technical part of the survey and the servers. For data quality assurance, prior to the start of the survey, the eight experienced enumerators and two field supervisors with university degrees in agriculture sciences and land management were trained on the questionnaires and the methodology for that particular farm household survey for two weeks, which ended with a pilot survey in Bugesera district for identification of inconsistencies and challenges in the questionnaires. The authorization for national-level field research was provided by the National Council for Science and Technology (NCST) under permit **No: *NCST/482/230/2021*** after a thorough assessment and approval of the proposed research methodology. During the interviews, all the answers were recorded for further data processing steps. This mixed methods research approach combining the households survey (quantitative non-experimental) and qualitative data collection methods in a concurrent parallel fashion is widely used in socio-spatial phenomena and causal-effects analytical studies involving the farming structure and farm characteristics in a similar context in Rwanda, which makes it a credible and reliable approach [6, 16, 32, 35, 41, 42, 49, 150]. Besides the data and the methodological triangulation, the back-checking technique was used to test the validity and reliability of the collected farm household level data, and both strategies were chosen for their wide use in mixed studies. The focus groups discussion data collection session was limited by the COVID-19 pandemic control measures forbidding physical meetings of more than ten people, which resulted in the selection of small groups of five to ten farmers. Furthermore, the country's travel restrictions during that critical pandemic period also delayed the field data collection phase.

2. 3. 4. Data Processing and Analysis Methods

The data from the farm household survey were directly sent by enumerators from their tablets and other android-equipped devices to the server, checked for consistency by the IT technician and

the principal investigator, transmitted in Microsoft Excel database and exported to IBM SPSS Statistics 23.0 software, and cleaned prior to statistical analysis. Spatial data in shape file format were imported in ArcGIS 10.8 software and processed in a GIS environment, from which useful descriptive and quantitative information was directly imported to Excel tables for further sophisticated analyses and visualisations. The descriptive and inferential statistics were used to analyse categorical (descriptive) and numerical (quantitative) data from the household survey and cadastral datasets. Due to the complex nature of the farmland fragmentation phenomenon, a comprehensive analysis of its scenarios requires the combination of various datasets at different analysis units (socio-spatial levels) for comparison and complementarity purposes. In this regard, the analysis of farmland fragmentation forms involved the combination of farm characteristics from the farm household survey and farm landscape characteristics from the national cadastre and land registry. The analysis of visible and hidden farmland ownership, usership and internal fragmentation at the farm and parcel levels, dispersion (scattering), location, landscape (size) and shape, and excessive and extensive fragmentation forms was performed through mathematical and statistical computations of various simple and complex fragmentation indices and descriptors. The computations captured the farm-level information about the variables of farm size, number of parcels and plots per farm, their respective locations and distances from the homestead, shapes, and their tenure statuses comparatively and complementarily combined with the farm landscape-level data about the farmland block size, the number of farms and parcels in the block and their respective sizes and owners. The analysis of farmland use fragmentation was exclusively performed from the farm-level data about the number and type of crops per parcel and farm and field observations. This technique of combining the farm-level data from a farm household survey, socio-legal data from the land register and spatial data from the national cadastre or land/parcel information system (LIS/LPIS) has been previously used by Sklenicka *et al.* [124] in quite similar way when analysing farmland fragmentation paradoxical scenarios in the Czech Republic.

The descriptive statistics (mean and median for central tendency, frequencies and percentages) were performed to summarize and describe these fragmentation indicators at the sample level. The comparison tests like T-tests, Analysis of Variance (ANOVA) tests, the Pearson and Spearman rank correlation tests, and Pearson Chi-Square Contingency Table Analyses (Crosstabs) tests as parametric and non-parametric statistical tests were performed to analyse and test various hypothetical inferences from quantitative and categorical fragmentation indicators at the selected research sites level. Considering the abnormal distribution of farmland metrics at the landscape level caused by the skewness of governmental farmland holdings in terms of large disparities in landholding sizes and number of parcels and their respective sizes, the median was chosen over the arithmetic mean (average) as an objective representative and indicator of the central tendency. To standardise the computations at all spatial levels, both the mean and median were used as indicators of central tendency at the landscape, farm and parcel level data. Using farm-level data from the household survey, the causal-effects inferential statistical analyses through Multilinear regression models for numerical dependant variables and Binary logistic (Multiple logistic or logit) and Multinomial logistic regression models for categorical dependant variables were performed to estimate and test the research hypotheses about farmland fragmentation scenarios-causal-effects relationships in the selected research sites. This inferential statistical method is widely

used in different empirical studies and was recently adopted in a similar study by Ndip *et al.* [99] to assess the relationships between farmland fragmentation, crop diversification and incomes in Cameroon. The key qualitative data from key informant interviews, focus group discussions, field observations and literature analysis were transcribed, summarized and thematically analysed for key trends and patterns to complement the analysis and categorization of farmland fragmentation scenarios from the farmers' perceptions and quantifiable fragmentation indicators in a form of theoretical and spatial models. The spatial distribution of the discovered farmland fragmentation scenarios among the selected research sites and AEZs was visualised using GIS in ArcGIS 10.8. The national-level secondary statistical and descriptive data about farmland metrics and farm characteristics as well as the qualitative primary and secondary data were only used for the contextualisation and discussion of empirical findings in a side-by-side comparison fashion.

2. 3. 4. 1. Farmland fragmentation metrics (indicators) and quantification strategy

The indicators and measurement of farmland fragmentation forms have been explicitly discussed by Ntihinyurwa and de Vries [64] in their theoretical article on farmland fragmentation scenarios typology. As a multidimensional and multilevel phenomenon, farmland fragmentation does not have a universal standard measure that captures all its socio-spatial descriptors in a single index. This complicates a holistic measurement of various farmland fragmentation forms in a given area. Considering this diversity of farmland fragmentation metrics, various studies recommended the comprehensive use of multiple fragmentation measurement metrics and indices to analyse the complete picture of farmland fragmentation by covering all fragmentation forms in a given area [32, 64, 114, 122-124, 140, 156]. Therefore, this study follows this recommendation and uses a variety of commonly used farmland fragmentation metrics to analyse all the possible fragmentation scenarios at different spatial levels in Rwanda from multiple theoretical combinations of its descriptors. Generally, the quantification of farmland fragmentation metrics has largely been dominated by the use of simple isolated indices considering only one or two parameters at the farm and farmland block levels. The most commonly used ones are the average farm and parcel sizes to measure farmland tenure (ownership and usership) and landscape fragmentation forms, the average number of parcels and plots per farm or their percentages, and Simmons, Simpson and Januszewski indexes [16, 127, 128, 156-158] to measure the internal and landscape fragmentation at the farm, parcel and landscape levels, which were used in this study. Since the Simpson index is the opposite and derivate of the Simmons index [159], we decided to use one of them, which is the former in this case. However, these indices ignore the aspects of distance, shape and agricultural use of parcels at different spatial levels. The Shape Index (SI) or Landscape Shape Index (LSI), also known as the parcel compactness index [130, 160-162] and the Mean Parcel Shape Index (MPSI) [163] are the most commonly used metrics of parcel shape fragmentation used in this study.

The topographical dispersion index similar to Simpson fragmentation index used by Blarel *et al*.[16] and the average distance of the parcels to the homestead, the percentage of farms with scattered parcels in different locations were used to measure farmland parcel dispersion and location fragmentation, while the number of crops per parcel for farmland use fragmentation at the parcel, farm and farmland block levels were also respectively used in this study [16, 32, 64]. The average number or percentage of tenants

in a given farmland block has been recently used as an emerging indicator of farmland usership fragmentation form, while the average number or percentage of undocumented parcels and their owners in a land block is used as an indicator of hidden ownership or co-ownership fragmentation forms [32, 64] and considered in this research. With the aim of a comprehensive analysis of a complete picture of all the possible farmland fragmentation forms for land consolidation projects purpose, Demetriou *et al*. [128, 129] developed the Global Land Fragmentation Index (GLFI) and the Parcel Shape Index as complex indices which integrate six farmland fragmentation indicators (the ownership size, the number of parcels belonging to the owner, the size of each parcel, the shape of each parcel, the spatial dispersion of the parcels and the accessibility of the parcels) in the same equation. However, these indices are more flexible and project-specific-oriented. They can vary from project to project based on the considered indicators (variables) and ignore the aspect of use and tenancy of farmland, which compromises their suitability in studies like this one aiming to comprehensively analyse the generic multidimensional farmland fragmentation scenarios regardless of the specificity of projects.

The comparison of farmland holding and farm metrics (farm vs holding size, number of parcels per farm vs number of parcels per holding and their respective sizes, and the number of plots vs the number of parcels) at the farmland block level was used as novel and complementary indicator of farmland tenure, internal and landscape fragmentation forms in this study. In order to assess the extent and the degree of internal, farmland tenure and landscape fragmentation, the aspects of *excessive* (when the number of parcels per farm exceeds its size in ha) and *extensive* (high average number or percentage of very small non-economically viable parcels and farms) fragmentation forms at the farm and land block levels as discussed in the introduction section were also respectively integrated in the analysis of the scenarios. This approach has been used in a quite similar context by Blarel *et al*. [16] and Ntihinyurwa *et al*. [32] in the analysis of some farmland fragmentation forms within a limited spatial scope in Rwanda. The use of multiple indicators to assess a single farmland fragmentation form is a methodological triangulation strategy for validity and reliability control motives. Some used fragmentation indices are described in the **Equations 2-7** below:

$$\textit{Simmons Index } (FI) = \frac{\sum_{i=1}^{n} \alpha^2}{A^2} \qquad \textbf{(2)}$$

$$\textit{Simpson Index (SI)} = 1 - \frac{\sum_{i=1}^{n} \alpha^2}{A^2} \qquad \textbf{(3)}$$

$$\textit{Januszewski Index } (K) = \frac{\sqrt{\sum_{i=1}^{n} \alpha}}{\sum_{i=1}^{n} \sqrt{\alpha}} \qquad \textbf{(4)}$$

Where *n* is the number of parcels belonging to a holding (farm), α; the size of parcel, A; the total holding (farm) size. These three indices take values between zero and one, where the values closer to zero indicate a higher degree of fragmentation, and one indicates that holding consists of one farmland parcel or no fragmentation for *FI* and *K,* contrary to the values of *SI* which indicate the opposite (1 for highest fragmentation and 0 for total consolidation). From their values, fragmentation increases with the decrease in farmland block or farm size and the increase in the number of parcels per farm or farmland block, which logically explains their suitability for farmland fragmentation analysis at the farmland block level.

Topographical location dispersion Index (DI): $1 - \frac{\sum_{i=1}^{n} t^2}{A^2}$ ***(5)***

Where *t* is the area of land located in topographical location *i*, and A is the total farm area. This index also called Dispersion Index (DI) takes the values between zero and one. It is equal or closer to zero when all parcels are located in a single topographical location *i*, while it approaches one when the parcels are scattered in different locations indicating a high degree of dispersion.

Mean Shape Index(MSI) = $\frac{\sum_{i=1}^{n}\left[\frac{pi}{2\sqrt{\pi ai}}\right]}{n}$ ***(6)***

Where *n* is the number of parcels, *pi* denotes the perimeter of *i* parcel, and *ai,* the area of *i* parcel. The MSI values vary from 1 when the parcel is circular or square and increase without limit as the parcel shapes become more irregular.

Landscape Shape Index (LSI) = $\frac{4\pi ai}{pi^2}$ ***(7)***

Where *pi* denotes the perimeter of *i* parcel, and *ai,* the area of *i* parcel. The LSI takes the values between 0 and 1, where 1 indicates the best shape represented by circular or square and decreases towards 0 as the parcel shapes become more irregular.

The quotient of parcel perimeter (length) and estimated approximate farmland boundary width was used to estimate the size (in ha) of farmland loss through boundaries at the farm, farmland block and the overall sample research sites levels.

2. 3. 4. 2. Variables description and inferential modelling strategy

The analysis of the causal-effects relationship between various farmland fragmentation scenarios indicated by a set of categorical and numerical dependent variables and their causes and effects as both categorical and numerical explanatory variables requires a cognitive choice of suitable regression models after a thorough test of data compliance with their various statistical assumptions or requirements of normality, collinearity, homogeneity of variance, linearity, independence of observations, and sample statistical representativeness [154, 164]. The sample size in this study is large and representative enough (*N*=487> 200) and satisfies the requirements of most inferential statistical tests, including the regression analysis models [155]. In this regard, after checking for data compliance with all the statistical assumptions, the relationships between farmland tenure fragmentation indicated by the farm size and the internal farmland fragmentation indicated by the number of parcels per farm, Simpson and Januszewski indexes, farmland parcel dispersion fragmentation indicated by the topographical dispersion index, and farmland use fragmentation indicated by the number of crops per farm and parcel, and their various causes (farmers' perceptions and other objective farm characteristics), were estimated through *multiple linear regression models* under the following **Equation 8**:

$$y = \beta_0 + \beta_1 C_1 + \beta_2 C_2 + \cdots + \beta_n C_n + \epsilon \quad \textbf{(8)}$$

Where y denotes the predicted value of farmland fragmentation metrical indicators, β_0 is the y-intercept (value of y when all other parameters are set to 0 or constant), $\beta_1 C_1, \beta_2 C_2$, the regression coefficients (β_1, β_2) of fragmentation causes 1 and 2 (C_1, C_2) or the effects of increasing the value of the causes *1* and *2* on the farmland fragmentation metric value, $\beta_n C_n$ indicating the regression coefficient of the fragmentation cause *n* as the last independent variable, and finally ϵ being the model error showing how

much variation in the estimation of y variable [164, 165]. This relationship was independently assessed on all discovered farmland fragmentation forms. The least-squares is generally used as the estimation method in this model. The regression coefficients, *t* statistics, and *p*-values for each regression coefficient in the models are the most important aspects in this research to scrutinize the significant factors of farmland fragmentation scenarios in the study area.

This same relationship was also modelled from the farmers' perceptions by linking various farmland fragmentation scenarios as dichotomous outcome variables with their respective perceived explanatory causes through *multiple binary (binomial) logistic (logit) regression models*. These scenarios vary from small farms (tenure and landscape fragmentation), small scattered and irregularly shaped parcels (internal, dispersion, landscape and shape fragmentation), small contiguous and irregularly shaped parcels (internal, landscape and shape fragmentation), big scattered and irregularly shaped parcels (scattering or dispersion and shape fragmentation), leased-in farms and parcels (usership fragmentation), to farm and parcel multi-cropping (use fragmentation) and parcels subdivision (parcel level internal and landscape fragmentation). Contrary to the multilinear regression models, this multiple logistic regression model uses the maximum likelihood method to estimate the probability (odds) of an outcome variable (fragmentation scenario in our case) of occurring (or not) from a set of multiple predictor variables or factors (perceived fragmentation causes in our case) [164, 165]. Using the natural log of the odds of the outcome as the dependent variable (fragmentation scenario), this relationship is specified and assessed through the following **Equation 9**:

$$Log\left[\frac{Y}{1-Y}\right] = \beta_0 + \beta_1 C_1 + \beta_2 C_2 + \cdots + \beta_n C_n \qquad \textbf{(9)}$$

Where Y denotes the binary category of dependent variable (farmland fragmentation scenario), $Log\left[\frac{Y}{1-Y}\right]$ is the natural log of the odds (probability) of the dependent variable Y, β_0 is the intercept (constant), and $\beta_1 C_1, \beta_2 C_2, \beta_n C_n$ being the regression coefficients or slopes $(\beta_1, \beta_2, \beta_n)$ of perceived fragmentation causes *1, 2* and *n* (C_1, C_2, C_n). The odds ratio can be any non-negative number[164, 165]. An odds ratio of 1 is used as the baseline for comparison and indicates the lack of association between the response and predictor. An odds ratio greater than 1 indicates higher odds of success for higher levels of a continuous predictor (factor), while an odds ratio less than 1 shows low odds of success for higher levels of a continuous predictor (factor). Farther values from 1 indicate stronger degrees of association. In both multilinear and logit equations, the standard interpretation of the models is that for a unit change in the predictor variable, the probability or logit of outcome is expected to change by its respective parameter estimate or coefficient, when holding all other explanatory variables constant [164, 165].

The *multinomial (nominal) logistic (logit) regression model* was chosen to predict farmers perceived factors determining the classification of farmland fragmentation scenarios into three classes (problematic, beneficial and problematic-beneficial) based on various effects of the described farmland fragmentation scenarios on diverse socio-economic, agro-ecological, environmental, food and farmland tenure security, and farm performance aspects of rural livelihoods. These scenarios are indicated by small farms with irregularly shaped parcels and multi-cropping (tenure-use-landscape-shape fragmentation), small farms with small scattered irregularly shaped parcels and multi-cropping (internal-dispersion-landscape-use-shape fragmentation), big farms with big scattered irregularly shaped parcels and multiple crops (internal-dispersion-use-shape fragmentation) and small farms with contiguous irregularly shaped parcels and multi-cropping (internal-landscape-use and shape fragmentation). Since these effect-based farmland

fragmentation scenarios categories are unordered polynomial dependant (response) variables, the model specifies one category as a baseline category with which the probabilities of falling into the other two categories are compared, which is in many cases by default, the last category (problematic-beneficial in this test) and function of the above-perceived farmland fragmentation effects as explanatory variable [164, 165]. Similar to the binary logistic regression, this model uses the natural log of the odds of the response variable and the maximum likelihood method to estimate the probability (odds) of the outcome, as specified in the following **Equation 10**:

$$Log\left[\frac{Y}{Y}\right] = \beta_0 + \beta_1 E_1 + \beta_2 E_2 + \cdots + \beta_n E_n \qquad \textbf{(10)}$$

Where Y denotes the fragmentation scenario category as response variable, $Log\left[\frac{Y}{Y}\right]$ as the natural log of the odds (probability) of the dependent variable Y, β_0 is the intercept (constant), and $\beta_1 E_1, \beta_2 E_2, \beta_n E_n$ being the regression coefficients or slopes $(\beta_1, \beta_2, \beta_n)$ of perceived farmland fragmentation effects and other farm factors as explanatory variables *1, 2* and *n* (E_1, E_2, E_n). Given that all other variables in the model are held constant, as the parameter estimates are relative to the referent group, the standard interpretation of the multinomial logit is that for a unit change in the predictor variable, the logit of outcome relative to the referent group is expected to change by its respective parameter estimate (in log-odds units) [164, 165].

Table 2 describes a comprehensive set of various variables and indicators used in different models. In this table, some variables stand simultaneously as both dependent and independent variables on one hand and causal and effects variables on the other hand in different models.

Table 2. Statistical models variables description and indicators

Variables	Description and codes
Dependant (outcome) variables	
Farmland fragmentation forms indicators	
Percentage of small-scale farms (<1ha)	Ownership fragmentation (landscape level)
Number of Tenants (leasing farmers) ≥ Number of Owner-users	Usership fragmentation
Parcel and plot sizes (ha)	Landscape fragmentation (landscape, farm & parcel)
Number of parcels per farm/ Percentage of internally fragmented farms	Internal fragmentation (landscape & farm level)
Number of plots > number of parcels per farm	Internal fragmentation (landscape, farm & parcel)
Simpson Index (SI) & Januszewski Index (K)	Internal and landscape fragmentation (landscape, farm & parcel)
Dispersion Index (DI)	Parcels topographical/ location dispersion (scattering)
Number of crops per farm and parcel	Farmland use fragmentation/ Multiculture (parcel, farm & landscape level)
Estimated parcel distance from the farmstead/Percentage of Parcels close to the farmstead (≤ 1 km)	Location fragmentation (parcel, farm & landscape level)
Percentage of farms with scattered parcels/scattered parcels in different locations	Parcels topographical/ spatial dispersion (scattering)
Mean Shape Index (MSI) & Landscape Shape Index (LSI)	Shape fragmentation
Farmland fragmentation scenarios indicators	
Small-scale farms (<1ha)	Tenure and landscape fragmentation
Small scattered and irregularly shaped parcels (<0.9ha)	Internal, dispersion, landscape, shape, excessive and extensive fragmentation
Small contiguous and irregularly shaped parcels(<0.9ha)	Internal, landscape, excessive, extensive, and shape fragmentation
Big scattered and irregularly shaped parcels	Scattering or dispersion and shape fragmentation
Leased-in small farms and irregularly shaped small parcels	Usership and shape fragmentation
Farm and parcel multi-cropping	Use fragmentation
Parcels split into small plots	Parcel level internal and landscape fragmentation
Farm size > Holding size	Visible ownership fragmentation
Farm size < Holding size	Usership or hidden ownership fragmentation
Number of parcels per farm > Number of parcels per holding	Internal fragmentation
Number of parcels per farm < Number of parcels per holding	Usership fragmentation
Farm parcel size < Holding parcel size	Usership, hidden ownership, landscape and internal fragmentation
Farm parcel size > Holding parcel size	Ownership fragmentation
Fragmentation Scenarios Classes	Three categorical classes: 1 for problematic, 2 for beneficial and 3 for both problematic and beneficial
Problematic fragmentation	1
Beneficial fragmentation	2
Both Problematic & Beneficial fragmentation	3
Independent (explanatory/predictor) variables	
Agro-Ecological Zones	12 nominal AEZs
Research Sites	24 nominal research villages
Farm characteristics	Farm size, number of parcels and plots per farm, their locations, shapes, uses, relative fertility, and tenure status, and means of acquisition
Fragmentation Causes	Dummy variables with 1 for the presence of the cause and 0 for its absence
Egalitarian-based partible inheritance/succession principles and land distribution programs among the heirs as part of customary practices under Inheritance/Succession culture	C_1
Intra-familial land related conflicts	C_2
Land market (land purchase and sale)/ Purchase and lease of additional parcels with different irregular shapes for farm expansion	C_3

Market-oriented agriculture	C_4
Subsistence farming for self-independence in food security (sovereignty)	C_5
Land scarcity (small farms) and farmland population density due to uncontrolled population growth and poverty	C_6
Poverty of farmers	C_7
Lack of Off-farm Employment and Poverty	C_8
Land reforms, Individual land tenure system and land market (purchase and sale)	C_9
Production risks and labour management on small farm, and land and soil protection/ security of distant parcels through differences in crops harvesting time (Mixture of early maturing crops like beans and late maturing ones like cassava)	C_{10}
Diseconomies of scale and farm efficiency (high output/input ratio, small farms require low production costs)	C_{11}
Food production independence (sovereignty) and security, farmland psychology and tenure security	C_{12}
Efficient use of farmland through the mixture of early maturing crops like sweet potatoes and late maturing ones like cassava for the purposes of increasing crops production and diversification from the profitable complementary combination of crops on small farm, climate change adaptation, production risks management and household food security (diversity, sovereignty and sustainability) under multi-cropping customs	C_{13}
Spatial and topographical diversity (slope differences)	C_{14}
Variations in soil quality and types	C_{15}
Closeness/distance of the parcels to the homestead (location of the parcels)	C_{16}
Egalitarian-based partible inheritance/succession principles and land distribution programs among the heirs	C_{17}
Exploitation of multiple agro-ecological zones with different soil types and qualities (Wetlands/lowlands vs highlands) and all agriculture seasons	C_{18}
Crops diversification in different (LUC) sites with different priority crops or different agro-ecological zones as the production risk management strategy	C_{19}
Food diversification, climate change adaptation and production risk management strategy through crops diversification in various micro-climatic and agro-ecological conditions or LUC sites	C_{20}
Micro-climatic and agro-ecological variations (Exploitation of multiple and diverse agro-ecological zones and all agriculture seasons)	C_{21}
Climate change adaptation and production risk management strategy	C_{22}
Proximity of the farm to infrastructures and waterways	C_{23}
Land sharing, distribution, redistribution and restitution programs	C_{24}
Individual/private land tenure system	C_{25}
Customary land tenure system	C_{26}
Natural features and waterways (swamps structure)	C_{27}
Marriage and land-based dowry culture	C_{28}
Topographical location of parcels and their exposure to the sun and wind	C_{29}
Pathways, natural features, waterways and soil erosion	C_{30}
Erosion control measures including bench and progressive terraces (Soil and water erosion control and crops protection against wind and other natural disasters)	C_{31}
Livestock forage	C_{32}
Parcel exchange of small plots	C_{33}
Location and status (structure) of available leasing parcels	C_{34}
Bench and progressive terraces	C_{35}
Subdivision of the parcel for residential house construction	C_{36}
Relocation for grouped resettlements program	C_{37}
Donation of distant parcels	C_{38}
Infrastructures development	C_{39}
Expansion of the farm for food security (diversity and quantity) and market satisfaction (cheapest and affordable option for small farm expansion for agriculture production and income increase, and household food security purpose)	C_{40}
On-farm employment and Farm landlessness	C_{41}
Absentee owners	C_{42}
Farmland subdivision restrictions, cooperative farming in land use consolidation (LUC) program for agriculture production and farm income increase , food sovereignty and security, and market facilitation and satisfaction	C_{43}

Fragmentation scenarios classes determinants (factors)	Dummy variables with 1 for the presence of the cause and 0 for its absence
Problematic	
High farm (agriculture) production costs (travel costs and labour supervision costs) and low farm income	PE_1
Barrier to agricultural mechanization through irregular shapes, small plot sizes, boundaries and absentee owners	PE_2
Many farmland boundaries-related conflicts	PE_3
Break down of collective land tenure system and social cohesion	PE_4
Barrier to the economies of scale, farm efficiency and income, climate change and natural shocks risks management, professional or market-oriented farming and household development	PE_5
Wastage/loss of land through boundaries and related conflicts	PE_6
Household food and nutrition insecurity through food security uncertainty and hunger (low food quantity, diversity, quality, accessibility and sustainability), and risks of losing the whole crops production in case of extreme weather and natural shocks	PE_7
Parcel crop production insecurity against robbery and uncontrolled grazing	PE_8
Obstacles to timely farming and labour management through very tiring and time consuming farming activities leading to the lease-out and the abandonment of distant parcels	PE_9
Obstacles to land consolidation for market-oriented monoculture	PE_{10}
Low farm income leading to permanent poverty and risks of multiculture for food security (diversity and sustainability), and leaving the farming sector due to the struggles for finding additional On-farm or Off-farm employment for survival	PE_{11}
Barrier to parcel fallow and crops rotation leading to costly intensive use/overuse of farmland which reduces soil fertility status and increases its degradation	PE_{12}
Barrier to market-oriented production, professional farming, and household development	PE_{13}
Risks of leasing non-contiguous unsuitable (distant and infertile) parcels for farm expansion, and spending high costs for leasing and improving the quality, which sometimes results in a loss and food insecurity once the owners decide to take back their improved parcels	PE_{14}
Barrier to egalitarian based land distribution among heirs through inheritance (insufficient farmland to the heirs), which results in land ownership related conflicts and the risks of landlessness	PE_{15}
Barrier to crop diversification and crops rotation and food diversity, leading to food insecurity (low food quality, cultural acceptability and sustainability)	PE_{16}
Beneficial	
Agriculture production diversification and exploitation of soil agro-ecological diversity through suitability based crops diversification as production risks management strategy and food security	BE_1
Crops intensification and diversification, agriculture production and market diversification for household food security and income increase, climate change adaptation, and food production and market imperfections risk management	BE_2
Household food independence/sovereignty and security (food diversity and sustainability)	BE_3
Increase in farm income, household food and nutrition security (diversity, quantity, sustainability, availability, acceptability and sovereignty) and market satisfaction from the surplus	BE_4
High costs of defragmentation in highlands	BE_5
Equitable distribution and use of farmland for farmland use and tenure security	BE_6
Land ownership and use-related conflicts management strategy	BE_7
Labour and production risks management strategies in agriculture through farm employment	BE_8
Climate change adaptation strategy	BE_9
Agrobiodiversity conservation	BE_{10}
Erosion control, fallow and crop rotation for soil fertility management	BE_{11}
Exploitation of multiple/diverse agro-ecological zones and all agriculture seasons	BE_{12}
Crops intensification and diversification for climate change adaptation, food diversity and household food security	BE_{13}
Diseconomies of scale and farm efficiency (high output/input ratio, small farms require low production costs)	BE_{14}
Soil fertility improvement through agricultural intensification (high inputs/farm size ratio)	BE_{15}

***Note**: The causes and effects as explanatory variables are linked with particular farmland fragmentation scenarios as outcome variables. Some causes and effects may overlap and stand for both sides in the model. Similar causes and effect may predict various fragmentation scenarios.* ***Source**:* Compilation from the farm household survey and literature

2. 4. Results and Discussion

2. 4. 1. Farmland Fragmentation Typology: Forms, Extent and Scenarios

In order to analyse the existing farmland fragmentation forms, their extent and the underlying scenarios in the 24 selected research sites from 12 AEZs of Rwanda and test the first two research hypotheses, the descriptive statistics along with the means, medians, and percentages comparison tests through One-Way ANOVA, Two-sample (independent) T-tests, and Pearson Chi-Square crosstabs analysis tests at the farmland block (landscape), holding, farm and parcel levels were performed. The traditional 2-tailed significance level ($p \leq .05$) was used. A Likert scale was used to indicate the presence or absence of a specific fragmentation form and its extent. The outputs from these tests are summarized in **Table 3** and visualised in **Figures 7, 8, 9 and 10**. They are interpreted and discussed against the displayed information in **Table 2**, the introduction and theoretical sections, the methodological section, particularly with **Equations 3, 4, 5, 6 and 7**, and the qualitative findings from key interviews, focus group discussions and field observations.

Table 3. Summary statistics of various farmland fragmentation metrics, forms and extent

Fragmentation Variables		AEZ	Buberuka Highlands		Bugarama (lmbo)	Bugesera	Central plateau			Congo Nil Divide				Cyangugu Backside (lmpala)		Eastern Ridges &Plateau			Eastern Savana		Granitic Ridge	Kivu lakeside		Mayaga	Volcanic summits & high plains		Difference Significance level ($p \leq .05$)	
		Research Sites (Villages)	Gacyamo	Musebeya	Gitambi	Gatare	Bitsibo	Karehe	Umuyange	Gasare	Karambi	Kivuruga	Uwamataba	Karenge	Ruhinga II	Myatano	Ndinda	Rwanyamigano	Benishyaka	Gisanze	Nyamaraba	Kamina	Karungu	Rwatano	Gataraga	Gisura	$F / X^2 / t$	
Fragmentation Metrics & Indicators		Average Farm Size (AVFS)	0.231	0.261	0.314	0.27	0.657	0.945	0.374	0.472	0.651	0.437	0.453	0.415	0.379	1.04	0.92	0.152	1.725	0.207	0.272	0.509	0.187	0.644	0.227	0.363	**10.8**	**<.001**
		Median Farm Size (MFS)	0.178	0.229	0.3	0.165	0.614	0.636	0.241	0.409	0.631	0.3	0.205	0.280	0.345	0.932	0.891	0.120	1.762	0.150	0.171	0.158	0.115	0.399	0.2	0.24	**10.1**	**<.001**
		Average Number of Parcels Per farm (AVNP)	3.16	3.75	2.85	1.833	4.409	3.6	5.536	3	6.556	3	3.227	3.952	3.5	3.28	4.462	1.533	1.9	1.118	3.375	3.2	3.04	3.75	1.333	3.467	**8.34**	**<.001**
		Median Number of Parcels per farm (MNP)	2	3.5	3	2	4	3	5	3	5.5	3	3	4	3	3	4	2	2	1	3	3	3	3.5	1	2	**6.39**	**<.001**
		Average Farm Parcel Size (APS)	0.073	0.07	0.11	0.148	0.149	0.262	0.068	0.157	0.099	0.146	0.14	0.105	0.108	0.317	0.206	0.099	0.908	0.185	0.081	0.159	0.061	0.164	0.17	0.105	**23.73**	**<.001**
		Median Farm Parcel Size (MPS)	0.057	0.06	0.1	0.06	0.067	0.084	0.025	0.062	0.056	0.054	0.063	0.06	0.05	0.202	0.126	0.075	0.875	0.153	0.055	0.045	0.035	0.09	0.175	0.07	**7.398**	**<.001**
		Average Number of Plots per farm (AVNPl)	3.280	4	4.5	1.833	7.727	4.2	6.036	3.5	7.778	4.421	4.318	4.619	5.227	4.2	5.154	1.667	3.25	1.647	4.75	4.467	4.08	5.792	1.727	3.733	**8.062**	**<.001**
		Median Number of Plots per farm (MNPl)	2	3.5	4	2	8	3.5	5	3	6.5	4	4	4	5	4	5	2	3	1	4	4	4	6	2	2	**7.276**	**<.001**
		Average Plot Size	0.071	0.065	0.070	0.148	0.085	0.225	0.062	0.135	0.084	0.099	0.105	0.090	0.072	0.248	0.179	0.091	0.531	0.126	0.057	0.114	0.046	0.111	0.131	0.097	**12.93**	**<.001**
		Median Plot Size	0.055	0.054	0.050	0.060	0.050	0.080	0.020	0.055	0.056	0.054	0.040	0.060	0.050	0.113	0.121	0.060	0.300	0.096	0.047	0.060	0.035	0.069	0.100	0.070	**8.66**	**<.001**
		Simpson Index (SI)	0.979	0.968	0.974	0.906	0.973	0.952	0.956	0.944	0.981	0.948	0.912	0.96	0.965	0.975	0.963	0.943	0.958	0.929	0.977	0.883	0.957	0.959	0.965	0.971	**2.559**	**<.001**
		Januszewski Index (K)	0.121	0.157	0.142	0.237	0.118	0.143	0.098	0.157	0.105	0.158	0.156	0.129	0.133	0.126	0.148	0.216	0.178	0.243	0.12	0.196	0.138	0.119	0.164	0.148	**5.928**	**<.001**
		Dispersion Index (DI)	0.918	0.878	0.929	0.707	0.801	0.898	0.88	0.742	1	0.699	0.798	0.892	1	0.938	0.887	0.71	0.847	0.00	0.869	0.496	0.892	0.00	0.294	0.706	**3.74**	**<.001**
		Average Number of Crops per parcel	1.63	1.96	1.63	1.1	2.2	3.14	1.15	1.28	1.03	1.46	1.19	1.72	1.52	1.6	1.64	1.3	1.61	2.37	1.57	1.42	1.28	1.99	1	1.46	**21.3**	**<.001**
		Average Number of Crops per farm	4	4	3	3	6	7	5	3	6	4	4	5	5	4	6	2	3	3	5	5	4	6	1	5	**5.562**	**<.001**
	Farm level	Percentage of leased farms	0.00	0.00	0.00	25.00	0.00	0.00	10.71	15.00	0.00	0.00	4.55	4.76	4.55	4.00	0.00	13.33	15.00	0.00	0.00	0.00	8.00	0.00	0.00	0.00	***16.59***	**<.001**
		Percentage of leasing farmers	48	83.33	50	50	81.81	30	75	50	0	47.36	68.18	76.19	54.54	48	38.46	26.66	45	0	54.16	40	48	66.66	3.03	40	***30.8***	**<.001**
		Percentage of leased-in parcels (Parcel tenure status)	18.99	22.22	19.30	36.36	49.48	12.50	57.42	30.00	0.00	31.58	39.44	33.73	25.97	21.95	15.52	26.09	42.11	0.00	28.40	14.58	25.00	31.91	4.55	19.23	***189.6***	**<.001**
		Percentage of small-scale farms	100	100	100	91.66	90.9	60	96.42	85	83.33	89.47	86.36	90.47	95.45	52	69.23	100	25	94.11	96	93.33	96	79.16	100	93.33	***38.78***	**<.001**
		Percentage of internally fragmented farms	84	100	95	58.33	100	85	89.29	80	100	73.68	77.27	100	100	100	100	53.33	60	5.88	91.67	100	88	79.17	15.15	73.33	***99.73***	**<.001**

		Percentage of farms with scattered parcels	84	100	95	42	100	85	79	50	100	58	50	100	100	100	100	33	40	0	83	93	88	79	9	60	***22.62***	**<.001**
		Percentage of farms with scattered parcels in different locations	60	83	85	42	27	70	43	40	100	32	23	67	100	92	92	20	40	0	42	13	84	0	6	33	***269.8***	**<.001**
		Percentage of Parcels close to the farmstead (≤ 1 km)	96.1	84.5	91.2	90.9	75.2	95.9	76.7	68.3	82.3	75.5	78.5	81.9	98.7	89	86.2	100	94.8	100	79	95.8	98.7	86.1	93.2	73.1	***456.6***	**<.001**
	Holding level	***Average Holding Size***	0.216	0.315	0.322	0.38	0.711	0.618	0.521	0.685	0.163	0.612	0.448	0.375	0.307	0.445	0.247	0.348	2.023	0.636	0.261	0.273	0.093	0.531	0.122	0.159	**14.98**	**<.001**
		Median holding size	0.125	0.101	0.151	0.194	0.311	0.356	0.187	0.232	0.091	0.236	0.246	0.183	0.171	0.252	0.141	0.224	1.727	0.447	0.125	0.134	0.047	0.212	0.068	0.086	**21.5**	**<.001**
		Average Number of Parcels per Holding	2.141	2.835	1.984	1.657	2.99	2.721	4.537	6.263	1.868	1.645	3.654	2.332	2.134	1.721	1.628	1.715	1.23	1.327	2.101	3.073	1.623	2.632	1.78	2.118	**2.336**	**<.001**
		Median Number of Parcels Per Holding	1	2	1	1	1	2	2	2	1	1	2	1	1	1	1	1	1	1	1	2	1	2	1	1	**4.688**	**<.001**
		Average holding Parcel Size	0.101	0.222	0.163	0.229	0.238	0.454	0.229	0.109	0.174	0.74	0.243	0.321	0.288	0.259	0.152	0.405	1.645	0.479	0.248	0.177	0.114	0.403	0.069	0.075	**94.14**	**<.001**
		Median holding Parcel Size	0.07	0.045	0.099	0.152	0.079	0.088	0.033	0.029	0.046	0.172	0.043	0.096	0.069	0.136	0.093	0.124	1.524	0.338	0.057	0.04	0.04	0.081	0.045	0.057	**65.9**	**<.001**
		Simpson Index (SI)	0.997	0.814	0.992	0.99	0.993	0.995	0.987	0.990	0.993	0.895	0.978	0.997	0.995	0.994	0.993	0.994	0.99	0.992	0.988	0.993	0.995	0.99	0.997	0.997	**2.303**	**<.001**
		Januszewski Index (K)	0.036	0.059	0.037	0.067	0.043	0.046	0.057	0.043	0.047	0.086	0.049	0.039	0.049	0.054	0.058	0.053	0.082	0.069	0.05	0.051	0.056	0.05	0.033	0.041	**8.633**	**<.001**
		Mean Parcel Shape Index (MSI)	2.556	2.811	2.664	2.761	3.043	2.719	3.715	3.414	2.908	2.691	3.671	2.625	2.706	2.695	2.622	2.618	2.627	4.703	3.159	3.744	2.764	3.292	2.703	2.621	**32.29**	**<.001**
		Landscape Shape Index (LSI)	0.5	0.56	0.603	0.562	0.545	0.581	0.51	0.483	0.536	0.588	0.477	0.61	0.596	0.602	0.612	0.619	0.628	0.202	0.516	0.505	0.569	0.546	0.589	0.616	**90.84**	**<.001**
	Farm vs Holding	***ΔAVFS***	0.02	-0.05	-0.01	-0.11	-0.05	0.33	-0.15	-0.21	0.49	-0.18	0.01	0.04	0.07	0.59	0.67	-0.20	-0.30	-0.43	0.01	0.24	0.09	0.11	0.10	0.20	***1.735***	**.087**
		ΔMFS	0.05	0.13	0.15	-0.03	0.30	0.28	0.05	0.18	0.54	0.06	-0.04	0.10	0.17	0.68	0.75	-0.10	0.03	-0.30	0.05	0.02	0.07	0.19	0.13	0.15	***5.591***	**<.001**
		ΔAPS	-0.03	-0.15	-0.05	-0.08	-0.09	-0.19	-0.16	0.05	-0.08	-0.59	-0.10	-0.22	-0.18	0.06	0.05	-0.31	-0.74	-0.29	-0.17	-0.02	-0.05	-0.24	0.10	0.03	***-6.29***	**<.001**
		ΔMPS	-0.01	0.01	0.00	-0.09	-0.01	0.00	-0.01	0.03	0.01	-0.12	0.02	-0.04	-0.02	0.07	0.03	-0.05	-0.65	-0.18	0.00	0.00	0.00	0.01	0.13	0.01	***-2.14***	**.036**
		ΔAVNP	1.02	0.92	0.87	0.18	1.42	0.88	1.00	-3.26	4.69	1.36	-0.43	1.62	1.37	1.56	2.83	-0.18	0.67	-0.21	1.27	0.13	1.42	1.28	-0.45	1.35	***5.36***	**<.001**
		ΔMNP	1.00	1.50	2.00	1.00	3.00	1.00	3.00	1.00	4.50	2.00	1.00	3.00	2.00	2.00	3.00	1.00	1.00	0.00	2.00	1.00	2.00	1.50	0.00	1.00	***13.53***	**<.001**
		ΔAVNPI-P	0.12	0.25	1.65	0.00	3.32	0.60	0.50	0.50	1.22	1.42	1.09	0.67	1.73	0.92	0.69	0.13	1.35	0.53	1.38	1.27	1.04	1.88	0.39	0.27	***-8.96***	**<.001**
		ΔMNPI-P	0.00	0.00	1.00	0.00	4.00	0.50	0.00	0.00	1.00	1.00	1.00	0.00	2.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	2.50	1.00	0.00	***-7.82***	**<.001**
Fragmentation Forms & Extent	***Tenure***	***Ownership***	***Hidden***	L	X	X	L	L	L	L	H	L	M	L	L	L	X	X	L	H	H	L	X	L	X	L	X		
			Visible	VH	VH	VH	VH	VH	M	VH	VH	H	VH	VH	VH	VH	VH	M	M	VH	VL	VH	VH	VH	VH	H	VH	VH		
		Usership	***Visible***	L	H	L	M	H	L	H	M	X	M	M	M	M	L	L	L	M	X	M	L	L	M	VL	L		
		Internal	***Farm***	M	H	M	M	H	H	VH	VH	VH	M	M	H	H	M	H	M	M	X	M	M	M	H	X	M		
			Parcel	X	X	M	X	H	L	L	L	M	M	M	L	H	M	M	X	M	L	M	M	M	H	L	X		
	Physical Extent	***Location (Distance)***		VL	L	VL	VL	L	VL	L	M	L	L	L	L	VL	VL	VL	X	VL	X	L	VL	VL	VL	VL	L		
		Dispersion/Scattering		H	VH	VH	M	M	H	M	M	VH	M	M	H	VH	VH	VH	L	M	X	M	M	VH	X	VL	M		
		Use		M	M	M	L	M	H	L	L	L	L	L	M	M	M	M	L	M	M	L	L	M	X	L			
		Landscape		VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	M	VH	VH	VH	VH	VH	VH	VH		
		Shape		H	H	H	H	VH	H	VH	VH	H	H	VH	H	H	H	H	H	H	VH	VH	VH	H	VH	H	H		
		Excessive		V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	X	V	V	V	V	V	V	V		
		Extensive		V	V	V	V	V	X	V	V	V	V	V	V	V	V	X	X	V	X	V	V	V	V	V	V	V		

Notes*: Δ** denotes the difference between various farm and farmland holding metrics at the farmland block level. ***F *refers to* ***F-statistic*** *values from* **ANOVA** *tests,* ***X²*** denotes the **Pearson Chi-Square** test values, while ***t*** denotes the ***t-statistic*** values from **T**-tests. **VL**, **L**, **M**, **H**, **VH** and **E** refer to the ***Likert scale*** levels indicating Very Low, Low, Moderate, High, Very High, and Excessive degrees of fragmentation respectively, while **V** and **X** indicates the absence of fragmentation. ***Source*:** Field survey primary data analysis

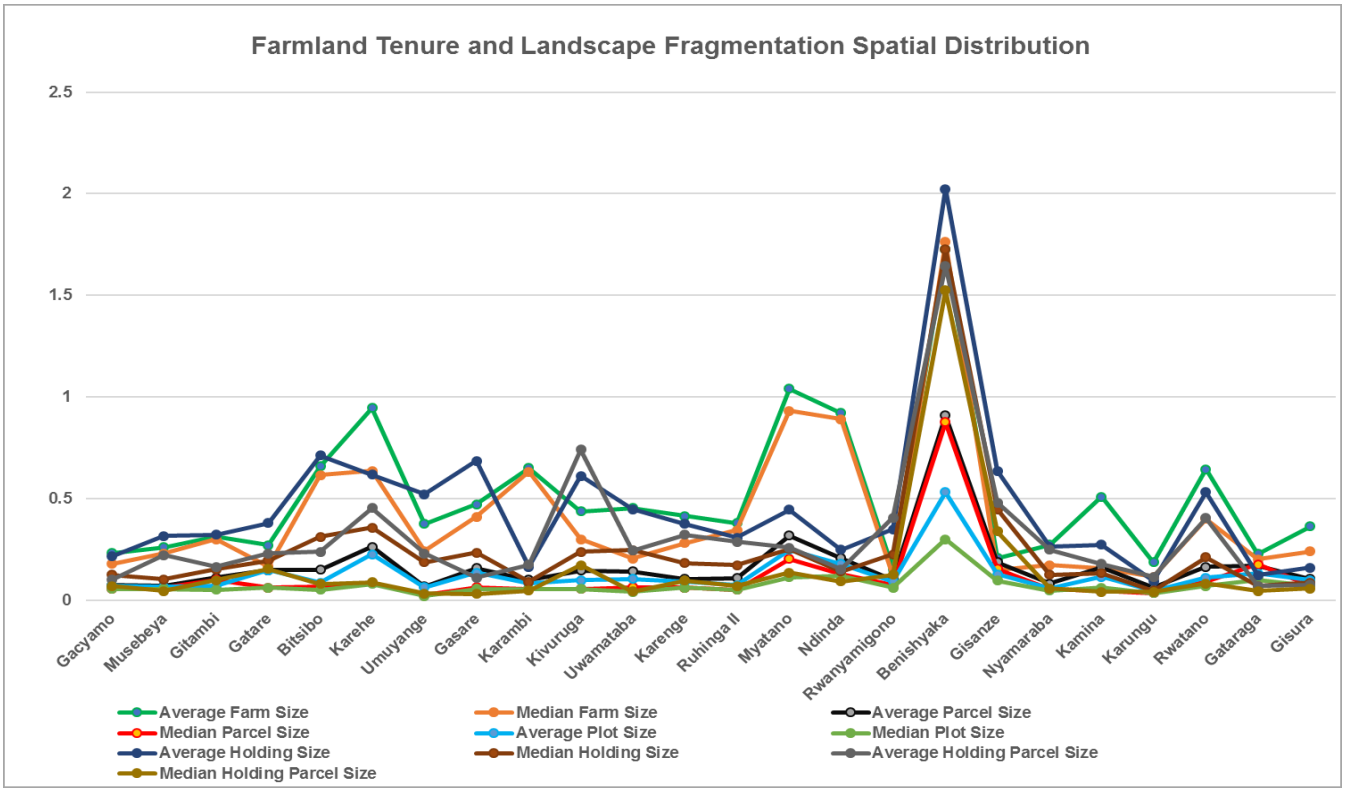

Figure 7. Farmland Tenure and Landscape Fragmentation Spatial Distribution

Source: Visualisation from farm and cadastral-level datasets analysis

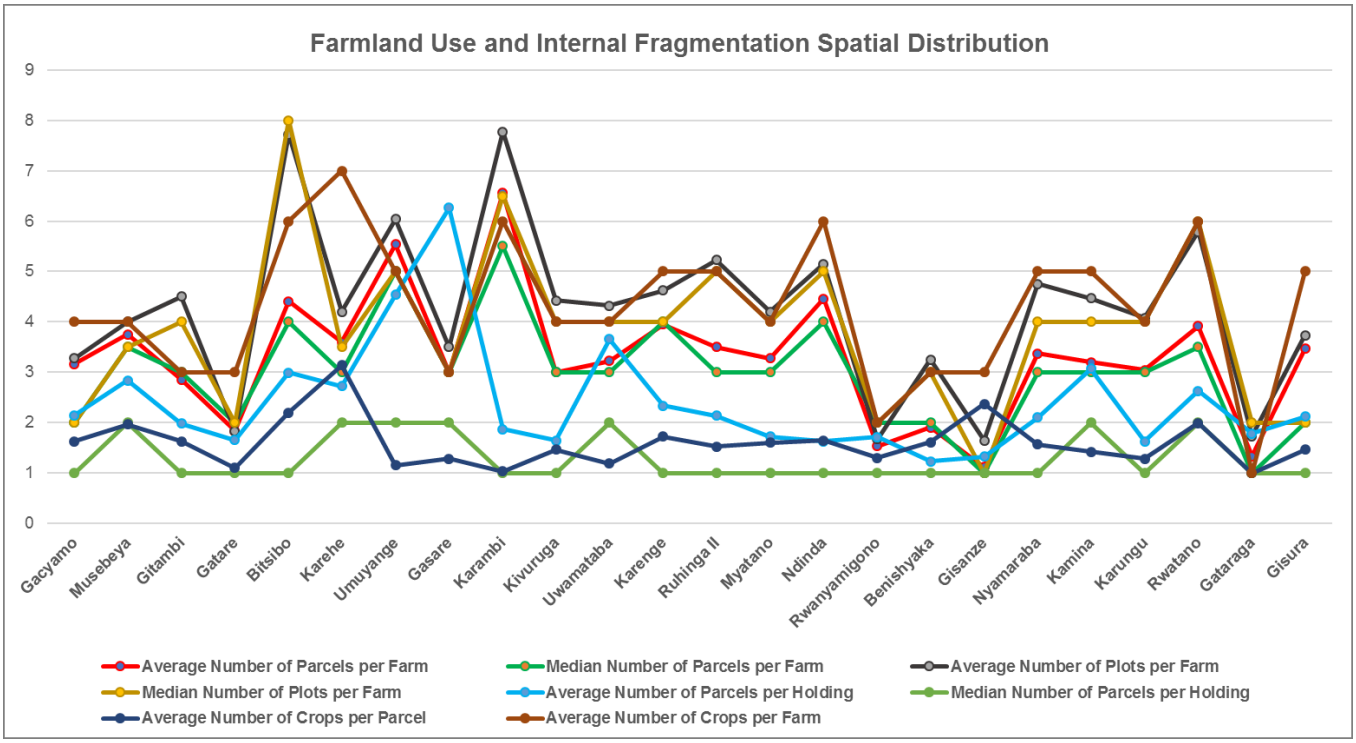

Figure 8. Farmland Use and Internal Fragmentation Spatial Distribution

Source: Visualisation from farm and cadastral-level datasets analysis

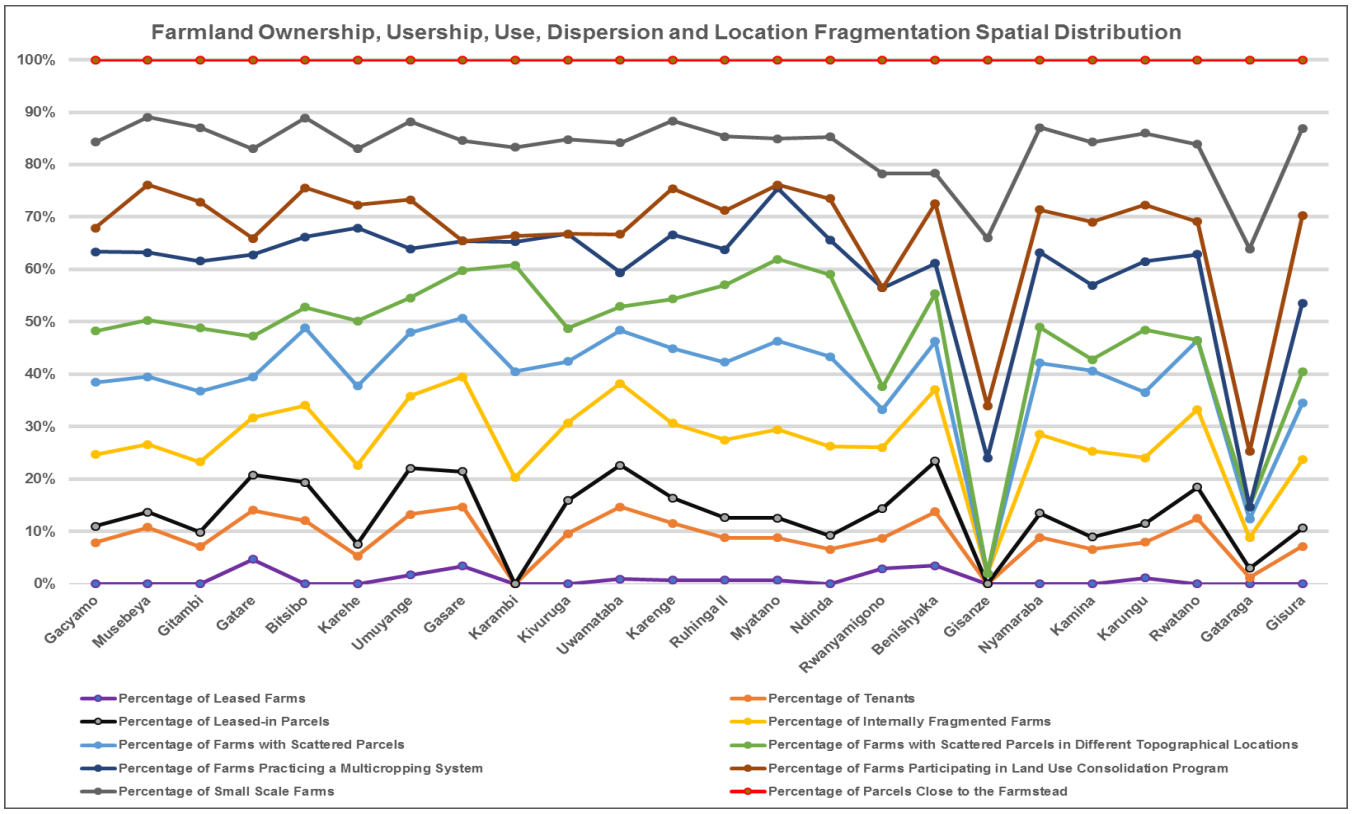

Figure 9. Farmland Ownership, Usership, Use, Dispersion and Location Fragmentation Spatial Distribution

Source: Visualisation from farm-level dataset analysis

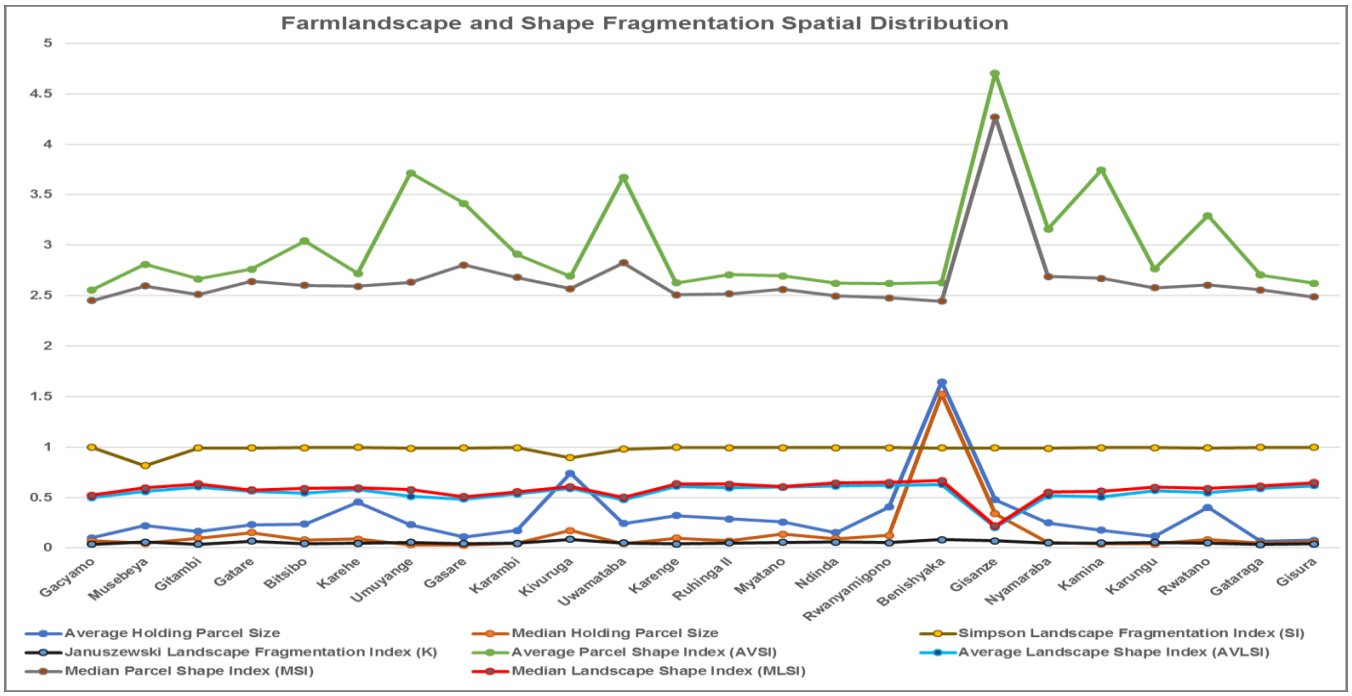

Figure 10. Farmlandscape and Shape Fragmentation Spatial Distribution

Source: Visualisation from cadastral-level dataset analysis

As Table 3 reads, the findings from One-way ANOVA tests of the farm and holding sizes and Crosstabs test of the percentage of small scale farms indicate a presence of Tenure Fragmentation at statistically significant different degrees across all research sites, $F(23,463) = 10.8$, $p < .001$; $F(23, 6506) = 14.98$, $p < .001$; and $X^2(23) = 38.78$, $p < .001$ respectively. Except for Benishyaka and Karehe in Eastern Savana and Central Plateaus AEZs, higher percentages (≥ 70%) of small-scale farms (<1 ha) were found in most of the research sites. Despite the presence of tenure fragmentation in all research sites, as indicated in Table 3 and Figure 7, it tends to increase with altitude since very small mean farm sizes were found in the highlands of northern and western provinces (Karungu, Gataraga, Gacyamo, and Musebeya with 0.187, 0.227, 0.231, and 0.261 ha respectively). In contrast, larger ones were reported in the lowlands of eastern and southern provinces (Benishyaka=1.725 ha, Myatano=1.04 ha, Ndinda=0.92 ha, Karehe=0.945 ha, Bitsibo=0.657 ha, and Rwatano=0.644 ha) with the exceptions of Rwanyamigono (0.152 ha) and Gisanze (0.207 ha), Gatare (0.27 ha), Nyamaraba (0.272 ha), and Karambi (0.65 ha). This finding provides the trends for partial rejection of the null hypothesis (H_{01}), stipulating a significant negative relationship between tenure and landscape fragmentation and topography in the country. Similarly, the findings from the holding sizes indicate the same trends. The mean and median holding sizes were very small in western (Karungu, Karambi, Gisura) and northern (Gataraga, Gacyamo) provinces, while relatively large ones were generally found in eastern (Gisanze, Benishyaka) and southern areas (Gasare, Bitsibo). This trend indicates the prevalence of moderate to very high levels of visible ownership fragmentation in all research sites except in Benishyaka. This same farm size was used to determine the extensive fragmentation aspect (average farm size <0.9 ha), and the results indicate its presence in most of the research sites except for Benishyaka, Myatano, Ndinda, and Karehe.

The usership fragmentation was mainly assessed through Pearson Chi-Square crosstabs analysis of the percentage of leasing farmers or tenants in the study areas compared to the owner-user farmers (farmers using their own parcels), the percentage of fully leased farms and the percentage of leased parcels. The results in Table 3 and Figure 9 indicate a significant difference in the levels of usership fragmentation across research sites and AEZs, $X^2(23) = 30.8$, $p < .001$ for leasing farmers, $X^2(46) = 16.59$, $p < .001$ for fully leased farms, and $X^2(23) = 189.6$, $p < .001$ for leased-in parcels. According to the values of these indicators, usership fragmentation was prevalent in most of the study sites across all AEZs at different levels except in Karambi and Gisanze. It was high in Umuyange, Bitsibo, and Musebeya with 81.81% vs 49.48%, 75% vs 57.42%, and 83.33% vs 22.22% of tenants vs leased-in parcels in Central plateaus of southern province and Buberuka highlands of northern province respectively. Its moderate levels were found in Gatare, Gasare, Kivuruga, Uwamataba, Karenge, Ruhinga II, Benishyaka, Nyamaraba and Rwatano, and low levels to absent in the rest of the study sites.

The comparisons of the numerical metrics (mean and median) of two datasets (farm level vs holding level data) at the farmland block scale through two-sample (independent) *T*-statistical tests were performed to provide additional information on the trends of visible ownership, usership and hidden ownership fragmentation forms. The results indicate significant differences across various research sites and AEZs between the median farm and holding size, $t(23) = 5.59$, $p < .001$, mean farm parcel and holding parcel size, $t(23) = -6.29$, $p < .001$, median farm parcel and holding parcel size, $t(23) = -2.14$, $p = .036$,

mean farm and holding number of parcels, $t(23)$ =5.36, p <.001, and median farm and holding number of parcels, $t(23)$ =13.53, p <.001. However, no significant difference was found between the average (mean) farm and holding size, $t(23)$ =1.73, p =.087. In this regard, to avoid data skewness biases from large governmental parcel holdings, the median was preferred over the mean for this type of comparative test. While the positive differences between farm and holding size as well as farm and holding parcel size metrics confirm the presence of visible ownership fragmentation in the majority of the study sites, the negative differences between these variables and the number of parcels helped to get the insights on the presence of usership and hidden ownership fragmentation forms. Based on the values reported in Table 3, the holding sizes, parcel sizes, and the number of holding parcels (officially recorded in the national land registry) were significantly higher than the sizes and number of parcels at the farm level in Benishyaka and Gisanze in eastern savanna (eastern province) AEZ, Gasare in Congo Nile divide (southern and western province) AEZ, and moderate in Kivuruga of Congo Nile divide respectively, indicating high to moderate levels of hidden and usership fragmentation in these sites.

From the physical fragmentation side, the internal fragmentation form at the farm and parcel levels was assessed through the analysis of the number of parcels and plots per farm, the number of parcels per holding, the percentage of internally fragmented farms, the Simpson and Januszewski fragmentation indices, and the comparison of these metrical indicators from the two datasets at the farmland block (landscape) analysis unit. These same indices were used to analyse the level and distribution of landscape fragmentation across different research sites. The results from ANOVA of both the mean and median number of parcels and plots per farm and crosstabs analysis of the percentage of internally fragmented farms indicate the presence of internal fragmentation across different study sites and AEZs at the farm scale except in Gisanze and Gataraga, and parcel scale except in Gacyamo, Musebeya, Gatare, Rwanyamigono and Gisura at significantly different degrees, $F(23,463) = 8.34$, p <.001, $F(23,463) = 6.39$, p <.001, $F(23,463) = 8.06$, p <.001, $F(23,463) = 7.27$, p <.001, and $X^2(23) = 99.73$, p <.001 respectively. The same trends were somehow revealed by ANOVA results of the mean and median number of parcels per holding, indicating significantly different degrees of internal fragmentation of the holdings across most of the study sites except in Benishyaka and Gisanze of the eastern savana AEZ, $F(23, 6506) = 2.33$, p <.001 and $F(23, 6506) = 4.68$, p <.001 respectively. The objective comparison of the metrics from the two datasets through T-statistical tests of the medians generally indicates significantly higher values at the farm than holding levels (median number of parcels per farm>median number of parcels per holding) except in Gisanze and Gataraga, confirming the above-mentioned prevalence of internal fragmentation in 22 study sites at different degrees, $t(23)$ =13.53, p =.087. These trends were validated by the findings from ANOVA tests of the Simpson and Januszewski indices at both the farm and holding levels, $F(23,463) = 2.56$, p <.001, $F(23,463) = 5.93$, p <.001, and $F(23,14927) = 2.3$, p <.001, $F(23,14927) = 8.63$, p <.001.

According to these findings, the internal fragmentation tends to increase with farm size except for Benishyaka and Gisanze, and the decrease in altitude and vice versa contrary to the tenure fragmentation, since higher internally fragmented farms were found in the highlands of northern, western and southern provinces than in the lowlands of eastern province. From both the farm and holding analysis

levels, as shown in Table 3 and Figure 8, the internal fragmentation was very high (≥ 5 parcels per farm or holding on average, ≤ 0.15 for Januszewski Index, ≥ 0.95 for Simpson Index, and ≥ 80% of internally fragmented farms in the farmland block) in Karambi and Gasare in Congo Nile divide, and Umuyange in central plateaus of the western and southern provinces respectively. In contrast, it was very low or absent (≤ 2 parcels per farm or holding, ≤15% of internally fragmented farms in the land block, ≥ 0.2 for Januszewski Index, and ≤ 0.95 for Simpson Index) in Gisanze (eastern savana) and Gataraga (volcanic summits and high plains) of the eastern and northern provinces respectively. These results are consistent with the theoretical claim of Bentley [111], which posits that small farms in highlands are more internally fragmented than bigger ones in lowlands and explained by the fact that the physical structure and steep slopes of farmlands in highlands limit the possibility to get big continuous parcels. These findings provide the trends for partial confirmation of our research hypothesis (H_{A4}) stipulating the negative relationship between tenure and internal fragmentation in the country. The internal fragmentation at the parcel level (parcel fragmentation) was mainly assessed through the T-test comparison analysis of the metrics of the number of parcels and plots per farm at the farmland block scale. The results show significantly positive differences between the mean and median of these variables, indicating the prevalence of this fragmentation form in 19 research sites at different degrees, $t(486) = -8.96$, $p < .001$, and $t(486) = -7.82$, $p < .001$ respectively. This parcel fragmentation was high in Bitsibo, Rwatano, and Ruhinga II, with the medians of 4, 2.5(≈3), and 2 plots per parcel in the southern and western provinces, respectively.

The parcel and plot size, Simpson and Januszewski indices were particularly used to determine the level of farmland block landscape fragmentation and excessive fragmentation aspect (average parcel size <1 ha), while the ANOVA test was performed to compare the distribution of these metrics across different research sites and AEZs. The results from all these indicators in Table 3 and Figure 10 revealed the presence of very high to excessive levels of landscape fragmentation in all the study sites at statistically different degrees except in Benishyaka (moderate level on the Likert scale), $F(23,1583) = 23.73$, $p < .001$, $F(23,1583) = 7.39$, $p < .001$ for mean and median farm parcel size, $F(23,14927) = 94.14$, $p < .001$, $F(23,14927) = 65.9$, $p < .001$ for mean and median holding parcel size, $F(23,2067) = 12.93$, $p < .001$, $F(23,2067) = 8.66$, $p < .001$ for mean and median farm plot size, $F(23,463) = 2.56$, $p < .001$, $F(23,463) = 5.93$, $p < .001$ for farm level Simpson and Januszewski indices, and $F(23,14927) = 2.3$, $p < .001$, $F(23,14927) = 8.63$, $p < .001$ for holding level Simpson and Januszewski indices respectively. The comparison between the parcel size at the farm and holding levels through T-tests also confirmed this presence of landscape fragmentation in 19 research sites since the holding level parcel size metrics were significantly higher than the farm level ones, $t(23) = -6.29$, $p < .001$ for means and $t(23) = -2.14$, $p = .036$ for medians. From the cadastral dataset view, the landscape was more fragmented in volcanic summits and high plains of the northern province in Gataraga and Gisura with relatively low values for mean and median parcel size (0.069, 0.045 ha and 0.075, 0.057 ha) and K(0.033 and 0.041) and high value of SI (0.997 and 0.997), and less fragmented in Eastern Savana in Benishyaka (1.645, 1.524 ha) for mean and median holding parcel size, and 0.99 and 0.082 for SI and K respectively. However, from the farm-level data, the relatively highest landscape fragmentation was found in Umuyange (0.068 and 0.025 ha, 0.956 and 0.098) and Karungu (0.061 and 0.035 ha, 0.957 and 0.138), while the lowest was also reported in Benishyaka (0.908 and 0.875 ha, 0.958 and 0.178) as shown by the mean and median farm parcel

size, and SI and K values, respectively. These findings are supported by the ones from Clay and Dejaegher [150], which reported a decrease in farm and parcel size with temperature and an increase in altitude and rainfall patterns from five agro-ecological regions of Rwanda. Moreover, they are consistent with the findings of Bentley [111] and Blarel *et al*. [16], which stipulate and empirically proved a negative relationship between farm and parcel size and altitude in Rwanda, mainly explained by the differences in physical and demographic features limiting the availability of suitable arable land in highlands.

The aspect of the distance of the parcels from the farmsteads was used to assess the location fragmentation form. The crosstabs analysis results of the ordinal ranges of the estimated distances indicate that the majority of parcels were located in less than 1 km from the farmstead at statistically significant different degrees across research sites, $X^2(138) = 456.6$, $p < .001$. The results in Table 3 and Figure 9 revealed that except in Gasare (68.3%), the majority (≥70%) of the farm parcels were located at short distances from the farmsteads (≤1km) in most of the study sites, indicating low levels of location fragmentation in these sites, moderate level in Gasare, and its absence (100%) in Rwanyamigono and Gisanze. These facts stipulate the rejection of the theoretical distance issue as justification for consolidation programs in Rwanda. The topographical dispersion index, the percentage of farms with scattered parcels, and the percentage of farms with scattered parcels in different locations were used to analyse the scattering level of the farm parcels or their spatial and topographical dispersion across different research sites and AEZs. The ANOVA test of the dispersion index and crosstabs analyses of the percentages of farms with scattered parcels and scattered parcels in different locations revealed the presence of the spatial dispersion or scattering of the parcels either in the same location or in different locations across most of the study sites except in Gisanze and Rwatano, at statistically significant different levels, $F(23,463) = 3.74$, $p < .001$, $X^2(23) = 22.62$, $p < .001$, and $X^2(46) = 269.8$, $p < .001$ respectively. As displayed in Table 3 and Figure 9, the dispersion was very high in Karambi, Ruhinga II, Musebeya, Gitambi, karambi, Myatano, Ndinda and Karungu, where more than 80% of the farmers had their parcels dispersed in different locations regardless of the agro-ecological zone (Dispersion Index ≥ 0.8), and low to absent in Rwatano where farmers had most of their parcels scattered in one same topographical location (79% of scattering, 0% scattering in different locations, 0.0 for Dispersion Index), Gisanze, Rwanyamigono and Gataraga where the majority of farms were made of single parcels or many contiguous parcels located in the same or one location (<40% of scattering, 20% of scattering in different locations, and 0.5 of Dispersion Index). The rest of the sites recorded moderate values, indicating the moderate levels of topographical location dispersion fragmentation. These findings are closely consistent with the ones from the study of Blarel *et al*.[16], which found a spatial dispersion of the majority of the farm parcels in the same topographical location at short distances from the farmsteads, thereby rejecting the hypothetical topographical location dispersion and distance aspect of fragmentation in three prefectures (provinces) of Rwanda, generally considered as the main justification for farmland consolidation programs.

The use or utilisation fragmentation form of farmland was analysed through the number of crops per parcel (parcel multiculture) and the number of crops per farm from the farm-level dataset. The ANOVA test of these metrics revealed the presence of use fragmentation form at the parcel and farm levels in

most of the research sites except in Gataraga at statistically significant different degrees, $F(23,1583) = 21.3$, $p < .001$, and $F(23,463) = 5.56$, $p < .001$ respectively. The results displayed in Table 3 and Figure 8 indicate a high level of parcel-level use fragmentation (multiculture) in Karehe of Central plateaus AEZ (Mean ≥ 3 crops per parcel), moderate level (Mean≈ 2 crops) in Musebeya, Gacyamo, Gitambi, Bitsibo, Karenge, Ruhinga II, Myatano, Ndinda, Benishyaka, Gisanze, Nyamaraba and Rwatano, and low level (Mean<1.5 crops) in the rest of the study sites. According to these results, the number of crops per parcel tends to increase with the number of plots per parcel and parcel size. From the farm level, the findings indicate a high degree (mean ≥ 5 crops per farm) in Umuyange, Karehe, Bitsibo, Karambi, Karenge, Ruhinga II, Ndinda, Nyamaraba, Kamina and Rwatano to moderate degree (mean≥3<5) of use fragmentation in the remaining 12 study sites except for Rwanyamigono and Gataraga, and tends to increase with the number of parcels per farm and farm size and vice versa. The comparison between the means of the number of crops and the number of parcels per farm was used to back-check this information, and its findings confirm these trends. This information provides insights for the partial verification of the third research hypothesis stipulating a negative relationship between internal and use fragmentation at the parcel level and a positive one at the farm level. Furthermore, it justifies the claim for internal farmland fragmentation as a strategy for crop diversification for household food and nutrition sovereignty and security, climate change adaptation, and agriculture production risk management motives in subsistence economies [1, 3, 4, 16, 32, 37, 64, 86, 87, 89-91, 98, 99, 111].

The shape fragmentation aspect (shape irregularity) was exclusively assessed from the landscape-level cadastral dataset through the Mean Parcel Shape Index (MSI) and Landscape Shape Index (SI). Similar to the landscape fragmentation aspect, the ANOVA test was used to compare the metrics of the levels of this shape fragmentation aspect, and the findings indicated the presence of its high levels at statistically significant different degrees across all the study sites and AEZs, $F(23,14927) = 32.29$, $p < .001$ and $F(23,14927) = 80.94$, $p < .001$ respectively. As shown in Table 3 and Figure 10, the parcel shapes were very highly irregular in Gisanze, Bitsibo, Umuyange, Gasare, Uwamataba, Nyamaraba, Kamina and Rwatano, and high in the rest of the sites. From the key informant interviews, the plausible explanation for this finding is grounded in the unregulated farm landscape subdivision which does not follow any standard geometrical figure in the country. The shape guidelines for such subdivision do not exist in Rwanda. It is randomly done by farmland owners for various land transactions and farming-related purposes.

The pooled national-level values were 0.5 vs 0.4 ha and 0.45 vs 0.25 ha for mean versus median farm and holding sizes; 3.3 (≈3) and 3 parcels per farm for mean and median, 4.2 (≈4) and 3.8 (≈4) plots per farm for mean and median, 2.4 (≈2) and 1.3 (≈1) mean and median parcels per holding; 0.11 vs 0.17 ha and 0.314 vs 0.148 ha for the mean versus median farm parcel size and holding parcel size, 0.126 vs 0.073 ha for the mean versus median plot size; 0.95 versus 0.98 and 0.15 versus 0.05 for Simpson and Januszewski indices at the farm and holding levels respectively; 0.74 for Dispersion Index; 2 vs 4 mean number of crops per parcel and farm; and 2.99 vs 0.55 for the Mean Parcel Shape Index (MSI) and Landscape Shape Index (LSI) respectively. The pooled mean percentages for various additional indicators were 86.13 for small-scale farms; 46.85 for leasing farmers (tenants) and 25.26 for leased-in

parcels; 79.5 for internally fragmented farms; 71.6 for farms with scattered parcels; 49.74 for farms with scattered parcels in different locations; 87.15 for parcels close to the homestead (≤ 1 km); 68.26 for farms under multiculture cropping system and 42,1 for farmers having parcels in LUC program. These values indicate the general trends of very high to excessive levels of landscape, high to extensive levels of tenure (in terms of ownership), high level of shape, moderate levels of internal, dispersion, use and usership, and low level of location fragmentation forms. These findings are consistent with and supported by the existing documented information on farmland fragmentation in Rwanda, which posits that both the demographic, physical (topography and agro-ecology), economic, and socio-cultural features of Rwanda make farmland very densely populated, scarce and diverse, which resulted in the reduction of the farm size to the national average of 0.6 ha often composed of 3 to 4 scattered parcels with 3.2 crops per parcel, thereby increasing farmland fragmentation [14, 21, 39, 41]. According to various research scholars, to address this tenure and landscape fragmentation issues under such farmland scarcity and subsistence economies circumstances, there is a need for policy interventions supporting the efficient use of scarce farmland resources through agriculture intensification and crop diversification programs and farmland saving technologies on small-scale consolidated or internally fragmented farms, strong family planning programs, and the creation of more off-farm employment opportunities in the country, rather than focussing on large scale farming and farmland consolidation options [3, 4, 12, 15, 26, 31, 51, 92, 98, 99, 107, 149].

From the above statistical analyses, 17 farmland fragmentation scenarios were rigorously and deductively identified in 24 research sites. The deduction of this typology of scenarios ignored the low levels of any fragmentation form since they generally do not significantly have any policy implications in terms of farmland fragmentation management. In this regard, during the analysis, a fragmentation form was considered present in a farmland block or research site if it was at a moderate level or higher. Furthermore, the extent aspect was considered in the classification criteria to reflect the extensive and excessive fragmentation forms. The list of these 17 scenarios and their spatial site locations distribution is highlighted below:

- *Visible Ownership, Landscape, Shape, Excessive-Extensive:* ***Gataraga***
- *Visible & Hidden Ownership, Usership, Landscape, Use, Shape, Excessive, Extensive:* ***Gisanze***
- *Visible Ownership, Internal (Farm), Landscape, Dispersion (Scattering), Shape, Excessive:* ***Karehe***
- *Visible Ownership, Usership, Internal (Farm), Landscape, Use, Shape, Excessive, Extensive:* ***Rwanyamigono***
- *Visible Ownership, Internal (Farm), Landscape, Dispersion (Scattering), Shape, Excessive, Extensive:* ***Gisura***
- *Visible Ownership, Usership, Internal (Farm & Parcel), Landscape, Use, Shape, Excessive, Extensive:* ***Rwatano***
- *Hidden Ownership, Usership, Internal (Farm & Parcel), Landscape, Dispersion (Scattering), Use, Shape:* ***Benishyaka***
- *Visible Ownership, Internal (Farm & Parcel), Landscape, Dispersion (Scattering), Use, Shape, Excessive:* ***Myatano, Ndinda***
- *Visible Ownership, Internal (Farm), Landscape, Dispersion (Scattering), Use, Shape, Excessive, Extensive:* ***Gacyamo, Musebeya***
- *Visible Ownership, Internal (Farm & Parcel), Landscape, Dispersion (Scattering), Shape, Excessive, Extensive:* ***Karambi, Kamina, Karungu***
- *Visible Ownership, Usership, Internal (Farm), Landscape, Dispersion (Scattering), Shape, Excessive, Extensive:* ***Umuyange***
- *Visible Ownership, Internal (Farm & Parcel), Landscape, Dispersion (Scattering), Use, Shape, Excessive, Extensive:* ***Gitambi***

- *Visible Ownership, Usership, Internal (Farm), Landscape, Dispersion (Scattering), Use, Shape, Excessive, Extensive:* ***Karenge***
- *Visible Ownership, Usership, Internal (Farm & Parcel), Landscape, Dispersion (Scattering), Shape, Excessive, Extensive:* ***Gatare, Uwamataba***
- *Visible Ownership, Usership, Internal (Farm & Parcel), Landscape, Dispersion (Scattering), Use, Shape, Excessive, Extensive:* ***Bitsibo, Ruhinga II, Nyamaraba***
- *Visible & Hidden Ownership, Usership, Internal (Farm & Parcel), Landscape, Dispersion (Scattering), Use, Shape, Excessive, Extensive:* ***Kivuruga***
- *Visible & Hidden Ownership, Usership, Internal (Farm), Landscape, Location (Distance), Dispersion (Scattering), Shape, Excessive, Extensive:* ***Gasare***

These findings fully test the first research hypothesis, which stipulates a significant spatial and topographical diversity of farmland fragmentation forms, extent and scenarios in Rwanda, since the diversity in forms, extent and scenarios across various research sites was scientifically proven. Moreover, a coexistence of physical and tenure fragmentation forms under different scenarios and socio-spatial analysis levels was found in various research sites and AEZs, which confirms the second research hypothesis stipulating the coexistence of both physical and tenure farmland fragmentation forms at different socio-spatial levels across and within different agro-ecological zones (AEZs) of Rwanda. They also empirically confirm the theoretical findings of Ntihinyurwa and de Vries [64], which stipulate the existence of 40 practical scenarios under various farmland conditions and the coexistence of physical and tenure fragmentation forms in the same area but at different degrees. In the context of Rwanda, this diversity of fragmentation scenarios can be explained by the above-discussed drastic diversity in socio-economic, spatial, demographic, and agro-ecological factors like land quality and quantity, topography or relief (altitude and slope), parent materials (soil type and quality), and temperature and rainfall patterns over short distances as determinants of the variations in farming systems among various regions, which stipulates the hypothetical existence of many more diverse micro agro-ecological and socio-economic zones [16, 33, 40, 150, 151]. The following subsection 2.4.2 classifies these scenarios into few common simple classes and displays their spatial distribution while subsection 2.4.3 empirically tests and models their causal-effects relationships.

2. 4. 2. Farmland Fragmentation Scenarios Classification and Spatial Distribution

In order to reduce the complexity of the above-identified scenarios, five main socio-spatial characteristics of farmland and indicators of farmland fragmentation (physical in terms of landscape and shape, tenure in terms of ownership and usership, internal at both the farm and parcel levels, use at both the parcel and farm levels and the dispersion of the farm parcels) were considered to classify the scenarios into five distinct classes regardless of the study sites and AEZs. Since shape and landscape fragmentation were the most prevalent fragmentation forms in all research sites, they were combined and represented under one indicator of physical aspect, while the usership and ownership fragmentation were represented under the tenure fragmentation form of farmland. The five scenario classes are described below:

- *Physical & Tenure Fragmentation:* Relatively small farms with one or few small irregularly shaped parcels in a small farmland block.

- *Physical-Use-Tenure Fragmentation*: Relatively small farms consisting of one or few small irregularly shaped parcels and multiculture in a small farmland block.
- *Physical-Internal-Use & Tenure Fragmentation:* Relatively small farms with many small irregularly shaped parcels and multiculture in a small farmland block.
- *Physical-Internal-Dispersion & Tenure Fragmentation*: Relatively small farms with many small scattered irregularly shaped parcels in a small farmland block.
- *Physical-Internal-Dispersion-Use & Tenure Fragmentation*: Relatively small farms with many small scattered irregularly shaped parcels and multiculture in a small farmland block.

Figure 11 displays the spatial distribution of the five classes of seventeen identified farmland fragmentation scenarios across research sites and AEZs, while **Figures 12, 13, 14, 15** and **16** illustrate the practical examples of the above-discussed classes of fragmentation scenarios in some of the study sites or farmland blocks. These examples (Gataraga, Gisanze, Benishyaka and Uwamataba) were derived from landscape holding-level cadastral dataset visualisation and serve as practical proxies of the discussed fragmentation scenario classes in this manuscript. For clarity purposes in scenario visualisation, only some portions of the considered research sites (villages) were used as representative farmland blocks since the land block is widely used as the scientific and practical analysis unit of farmland fragmentation scenarios and their management strategies.

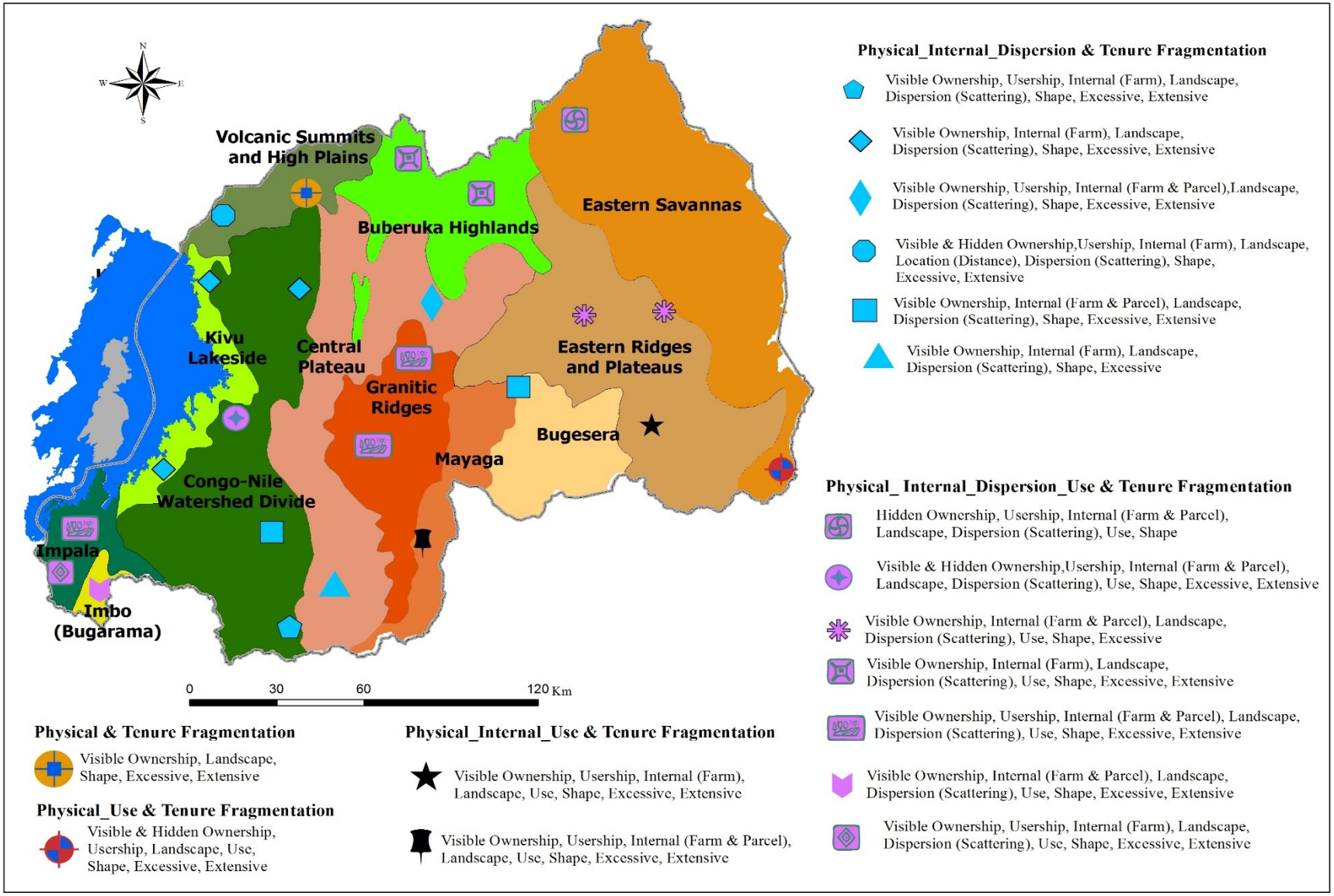

Figure 11. Farmland fragmentation scenarios spatial distribution in 24 research sites and 12 AEZs

Source: Visualisation from farm and cadastral-level datasets analysis

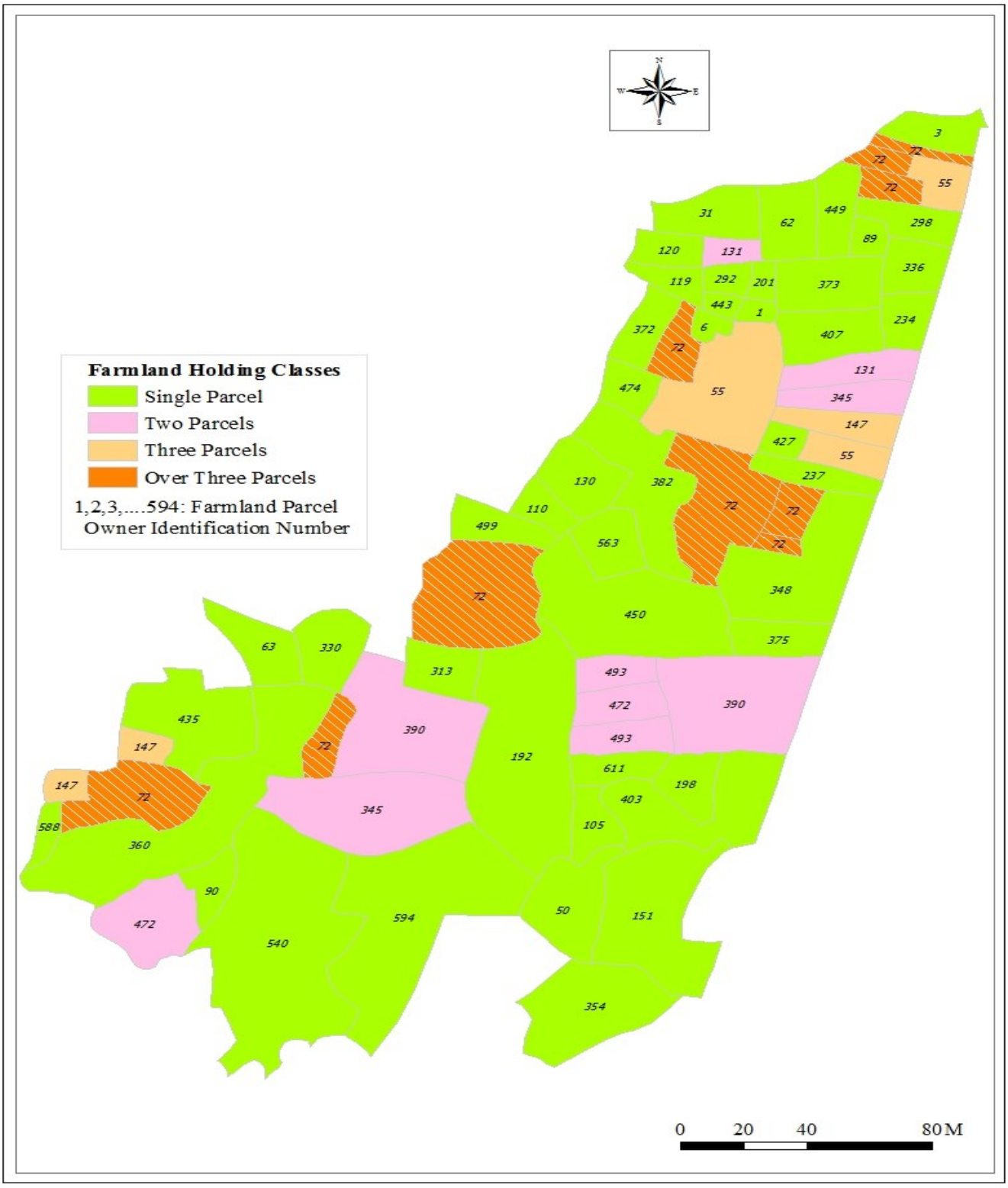

Figure 12. Physical-Tenure & Shape Fragmentation

Source: Visualisation from cadastral-level dataset analysis

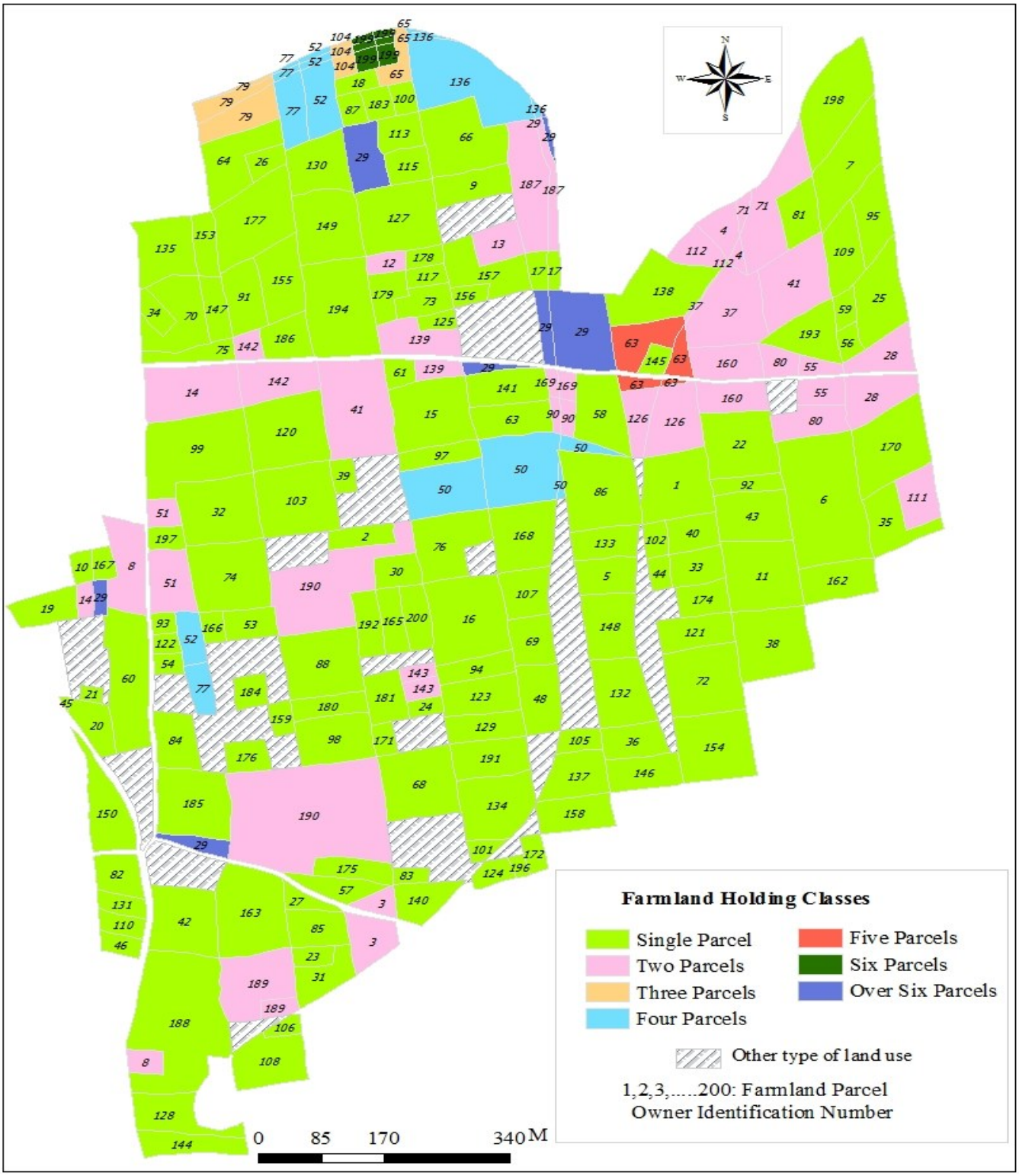

Figure 13. Physical-Tenure-Use & Shape Fragmentation

Source: Visualisation from cadastral-level dataset *analysis*

Figure 14. Physical-Hidden Tenure-Internal-Use & Shape Fragmentation

Source: Visualisation from cadastral-level dataset analysis

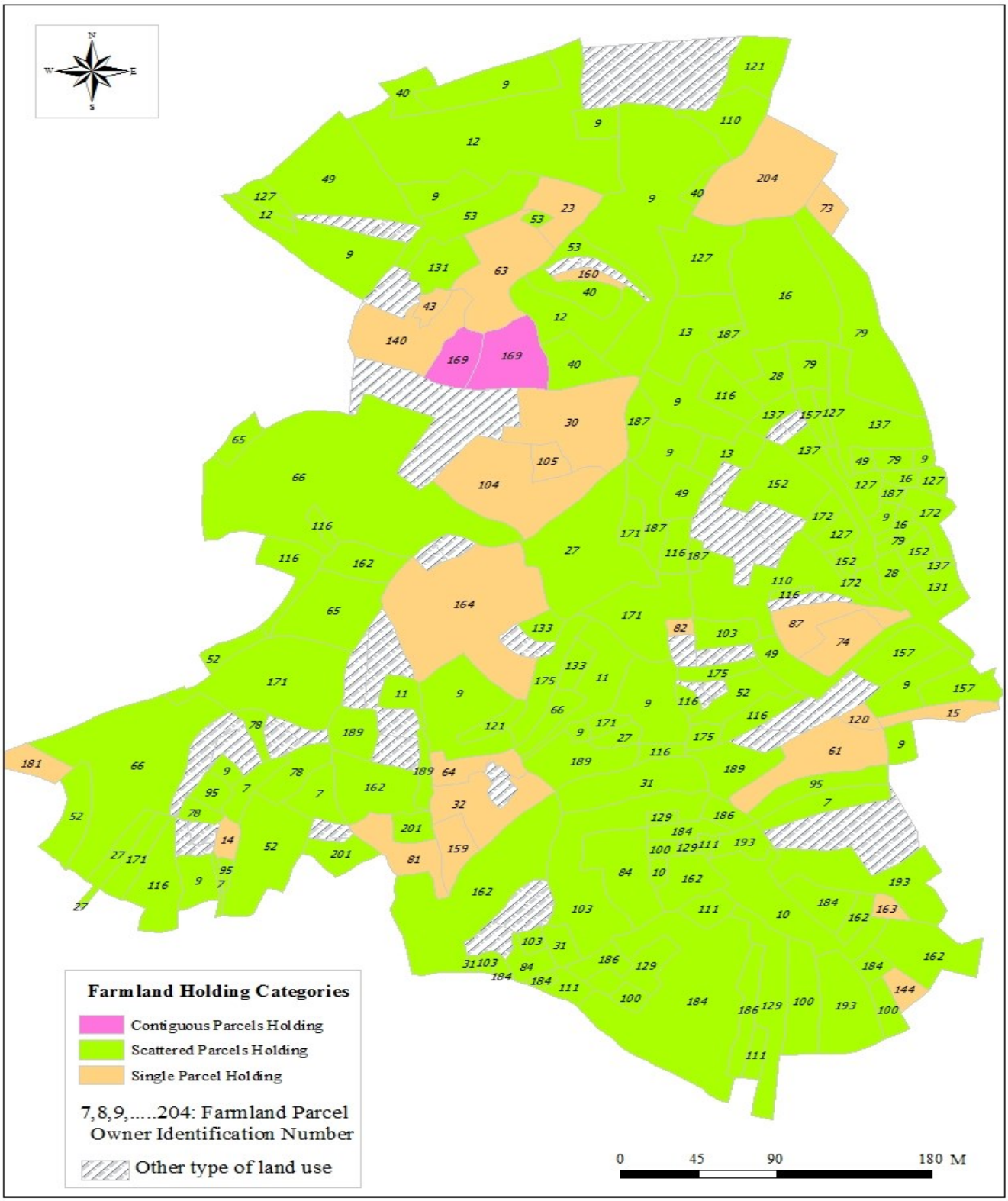

Figure 15. Physical-Tenure-Internal-Dispersion & Shape Fragmentation

Source: Visualisation from cadastral-level dataset analysis

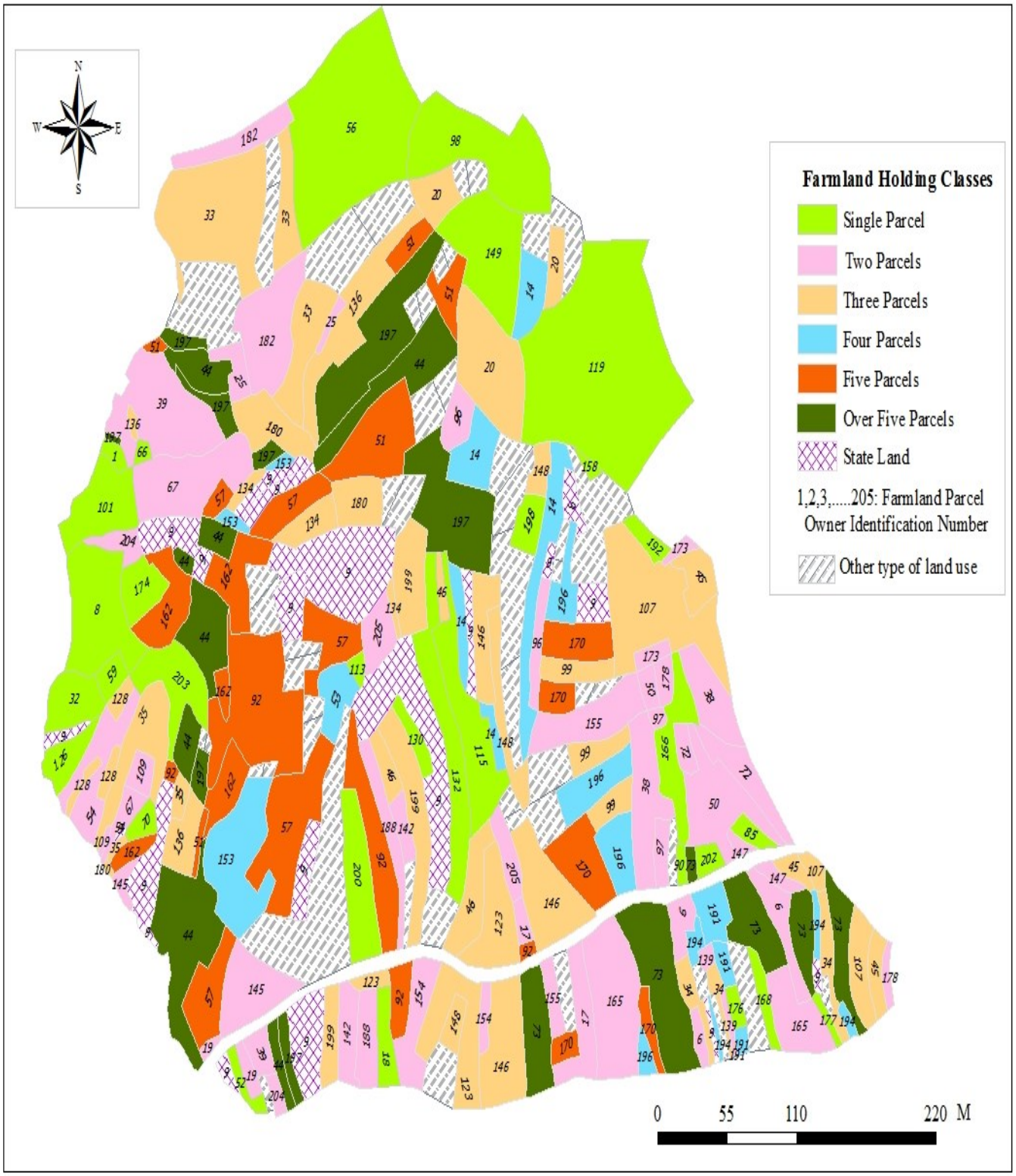

Figure 16. Physical-Tenure-Internal-Dispersion-Use & Shape Fragmentation

Source: Visualisation from cadastral-level dataset analysis

As Figure 11 reads, the five classes of 17 fragmentation scenarios were differently distributed across various research sites and AEZs. In some AEZs, a coexistence of different scenarios in the same AEZ was also identified. This trend confirms the drastic variations in physical, socio-economic, demographic and agro-ecological conditions among and within the 12 AEZs, which explain the hypothetical existence of many more specific micro AEZs in the country [33, 150] and supports our research hypotheses 1 and 2. The scenario classes of *Physical-Internal-Dispersion & Tenure Fragmentation* and *Physical-Internal-Dispersion-Use & Tenure Fragmentation* illustrated in two different land blocks of Uwamataba site (Figures 15 and 16) were the most dominant in the country since they were identified in 20 out of 24 sites in 11 of 12 AEZs. In these sites, the farming system is dominated by many relatively small internally fragmented farms with small scattered irregularly shaped parcels and plots with or without multiple crops per farm or parcel. However, the distance aspect in these scenarios was not a significant and problematic trait since most parcels of the same farm were found to be located in the same topographical location within a radius of less than 1 km, except in the Gasare site. Therefore, as supported by the majority of the key informants, focus group discussions respondents and previous empirical studies of Blarel *et al*. [16], Clay and Dejaegher [150] and Ntihinyurwa *et al*. [32], the scattering of parcels in these scenarios could be linked with the benefits of crop diversification and exploitation of multiple agronomic zones as an agriculture production risk management strategy and agriculture production diversification for food and nutrition sovereignty and security purposes under scarce farmland, climate change vulnerability and lack of off-farm employment conditions.

The *Physical-Internal-Use &Tenure Fragmentation* scenario class was only found in two sites in different AEZs. It is quite similar to the two previously discussed ones except for the aspect of dispersion. Farms in these scenarios are internally fragmented with contiguous irregularly shaped parcels or plots and growing multiple crops. Figure 14 displays a land block in Benishyaka site of Eastern Savana, which illustrates a scenario class of *Hidden Tenure-Physical-Internal-Use & Shape Fragmentation* characterised by moderately big internally fragmented farms with large irregularly shaped parcels and multiple crops. This particular scenario is the only one without the aspect of small sizes, which is explained by its spatial location in flatlands of the least densely populated province of Rwanda and increasing farmland availability and, therefore, large farmland holdings [16, 21, 30, 39, 41, 53, 111]. The *Physical &Tenure Fragmentation* and *Physical-Use-Tenure Fragmentation* Scenario classes characterised by small farms with single small parcels and or without parcel-level multi-cropping illustrated in Figures 12 and 13 were identified in two distinct land blocks of Gataraga in the Volcanic Highlands region and Gisanze in Eastern Savana's lowlands. These two sites share a common feature of high farming population density and the homogeneity of agro-ecological conditions, which explain the small farm sizes with fewer parcels and crops per farm in the case of Gataraga. The information from the key informants and the focus group discussion in Gisanze claimed the immigration of returning Rwandan refugees from Tanzania to be responsible for this unusual particular scenario in the area since they were offered by the Government a small piece of land on which they grow many different crops for household food and nutrition security and survival due to the lack of other off-farm employment opportunities, which increased the farming population density and reduced the farm sizes. These findings about the diversity of fragmentation scenarios imply the diversity of their management strategies and intervention programs, which should be

considered by farmland use policymakers. The following subsection 2. 4. 3 displays the causal-effects relationships among these fragmentation forms and scenarios in the study area.

2. 4. 3. Farmland Fragmentation Causal-Effects: Relationships and Scenarios Modelling

In order to test the relationships among the above-identified farmland fragmentation scenarios and their causes and effects, the research hypotheses 3, 4 and 5 and the null hypotheses 1 and 2, various correlations and regression analyses were performed. The key outputs from these inferential statistical tests are summarized in **Table 4** for Pearson and Spearman correlation tests, **Table 5** for ANOVA test, **Table 6** for Multilinear regression analysis, **Table 7** for Multiple binary regression analysis, **Table 8** for Crosstabs and Pearson Chi-Square statistics tests, and **Table 9** for Multinomial logistic regression analysis results.

Table 4. Pearson correlations results among various farmland fragmentation metrics

Fragmentation Indicators		*Farm size in Ha*	*Number of Parcels per farm*	*Number of Plots per parcel (farm)*	*Av farm parcel size*	*Av farm plot size*	*Parcel size*	*Number of crops per parcel*	*Number of crops per farm*
Farm size in Ha	Pearson Correlation	1	.263**	.350**	.744**	.749**	.867**	.267*	.288*
	Sig. (2-tailed)		.000	.000	.000	.000	.000	.023	.014
	N	487	487	487	487	487	487	487	487
Number of Parcels per farm	Pearson Correlation	.263**	1	.846**	-.179**	-.142**	-.297*	-.022	.755**
	Sig. (2-tailed)	.000		.000	.000	.002	.011	.856	.000
	N	487	487	487	487	487	487	487	487
Number of Plots per parcel (farm)	Pearson Correlation	.350**	.846**	1	-.051	-.132**		.075	.728**
	Sig. (2-tailed)	.000	.000		.263	.004	-.207	.533	.000
	N	487	487	487	487	487	.080	487	487
Parcel size	Pearson Correlation	.867**	-.297*	-.207			487	.199**	-.137
	Sig. (2-tailed)	.000	.011	.080				.000	.252
	N	487	487	487				1607	1607
Number of crops per parcel	Pearson Correlation	.267*	-.022	.075			.199**	1	.458**
	Sig. (2-tailed)	.023	.856	.533			.000		.000
	N	487	487	487			1607	487	487
Number of crops per farm	Pearson Correlation	.288*	.755**	.728**			-.137	.458**	1
	Sig. (2-tailed)	.014	.000	.000			.252	.000	
	N	487	487	487			1607	487	487
Av farm parcel size	Pearson Correlation	.744**	-.179**	-.051	1	.869**			
	Sig. (2-tailed)	.000	.000	.263		.000			
	N	487	487	487	487	487			
Av farm plot size	Pearson Correlation	.749**	-.142**	-.132**	.869**	1			
	Sig. (2-tailed)	.000	.002	.004	.000				
	N	487	487	487	487	487			
Number of farms with parcels scattered in different locations	Pearson Correlation	.168	.479**	.326**			-.071	.312**	.003
	Spearman's rho	.189	.466**	.38**			-.246**	.025	.283**
	Sig. (2-tailed)	.159	.000	.005			.551	.008	.98
		.111	.000	.001			.037	.832	.016
	N	487	487	487			487	487	487
Number of farms practicing the Multicultural system	Pearson Correlation	-.257*	.045	.029			-.322**	.287*	.471**
	Spearman's rho	.209	.135	.059			.310**	.529**	.204
	Sig. (2-tailed)	.029	.707	.810			.006	.014	.000
		.078	.258	.625			.008	.000	.085
	N	487	487	487			487	487	487

***Notes**: **. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed); 0.10 to 0.29: weak positive correlation; -0.10 to -0.29: weak negative correlation; 0.30 to 0.49: moderate positive correlation; -0.30 to 0.49: moderate negative correlation; 0.50 to 1.00: strong positive correlation; -0.50 to -1.00: strong negative correlation.* ***Source**:* Field survey primary data analysis

For the purpose of testing the research hypotheses 3 and 4, the Pearson correlation tests were performed to assess the relationship between the farm size (tenure fragmentation) and the number of parcels/plots per farm (internal fragmentation), the number of crops per parcel and farm (use fragmentation), and the number of farms with scattered parcels in different locations (dispersion fragmentation).

As presented in Table 4, the analysis results revealed a significant but weak positive relationship between the farm size and the number of parcels per farm, [$r(485) = .26$, $p < .001$] and a significant moderate positive relationship between the farm size and the number of plots per farm, [$r(485) = .35$, $p < .001$] indicating a negative relationship between tenure and farm level internal fragmentation forms. Moreover, the same analyses revealed a significant but weak positive relationship between the farm size and the number of crops per parcel, [$r(485) = .28$, $p < .001$] and per farm, [$r(485) = .29$, $p < .001$] indicating a negative relationship between tenure and use fragmentation forms at the parcel and farm levels. They also found a weak positive but not significant relationship between farm size and the number of farms with scattered parcels in different locations [$r(485) = .17$, $p = .159$], which indicates a non-significant negative relationship between tenure and dispersion fragmentation aspects. However, the farm size was significantly but weakly negatively correlated with the number of farms practicing the parcel-level multicultural system, [$r(485) = -.26$, $p = .029$], which indicates a positive relationship between tenure and parcel-level use fragmentation forms of the farmland. These findings confirm the part of our third research hypothesis (H_{A3}) stipulating a significant negative relationship between tenure fragmentation and internal and farm-level use fragmentation forms, and a positive relationship between tenure and parcel-level use fragmentation (multiculture), but scientifically reject the relationship between tenure and dispersion fragmentation as it was not statistically significant. In other words, small farms tend to be less internally fragmented and scattered, and farmers, in this case, choose to grow many crops on the same parcel and vice versa in the case of big farms, for crop and food diversification, household food sovereignty and security, and production risk management purposes [3, 51, 64, 86, 87, 89, 90, 98, 99, 111, 134, 166]. This trend was confirmed by the majority of the interviewed key informants and focus group discussions respondents in this study. Moreover, these results are consistent with the findings of Blarel *et al. [16]* in Rwanda and Ghana, Van Hung *et al.* [143] in Vietnam and support or prove the theoretical position of Ntihinyurwa and de Vries [64], Asiama *et.al* [5], and Van Dijk [142] which stipulate an increase in the number of parcels with farm size and vice versa indicating a negative correlation between internal fragmentation and tenure fragmentation, but disagree with the theoretical argument of Bentley [111] stipulating the opposite by positing that small subsistence farms tend to be more internally fragmented than big farms.

However, the weak relationship between these two fragmentation forms indicates their practical coexistence at different degrees in some research sites under certain conditions, which proves the theoretical assumptions of Ntihinyurwa and de Vries [64]. Furthermore, while the number of parcels per farm was not significantly but very weakly negatively correlated with the number of crops per parcel, [$r(485) = -.02$, $p = .856$], the results indicate its significant strong positive correlation with the number of crops per farm, [$r(485) = .75$, $p < .001$], and its significant moderate positive relationship with the number

of farms containing scattered parcels in different topographical locations, [$r(485) = .48$, $p < .001$]. These findings confirm a part of our fourth research hypothesis (H_{A4}) stipulating a significant positive relationship between internal and farmland use and parcel topographical dispersion fragmentation forms at the farm and farmland block levels, but reject its part stipulating a negative correlation between internal and parcel level farmland use fragmentation forms since this relationship was not statistically significant. Similar findings were previously found by a large number of studies in different study areas, with a common empirical explanation being the internal and parcel topographical dispersion fragmentation forms as farmers' rational choice for crops and food production diversification, exploitation of multiple heterogeneous agro-ecological micro-zones, climate change and production risks management, and household food and nutrition sovereignty and security motives [3, 4, 32, 86, 87, 89, 91, 92, 96, 98, 99].

In order to test the first null hypothesis (H_{01}) of this research, a One-Way ANOVA test was performed to analyse the relationship between parcel size and topography. The results are compiled in **Table 5**.

Table 5. ANOVA comparative relationship between parcel topography and parcel size (*N=1607*)

Parcel topography	N	Parcel size		*Df1*	*Df2*	*F*	*Sig.(≤.05)*
		1	2	2	1604	9.682	.000
Flat slope in a plain or wetland	337	.115					
Steep slope on a hill or mountain	615	.135					
Flat slope on a plateau	655		.185				
Sig.		.241	1.000				

Note: *Alpha = .05. Duncan a, b, c Comparison Method.* ***Source*****:** Field survey primary data analysis

The results in Table 5 indicate a statistically significant difference in the mean parcel sizes among the three topographical categories, $F(2,1604) = 9.68$, $p < .001$. A *Duncan Post Hoc* comparison method was further performed, and these means were grouped into two distinct classes. The mean parcel size on flat slopes of a plain (wetland/lowland) stands in the same group as the mean parcel size on steep slopes of a hill or highland (0.115 vs 0.135 ha), while the mean parcel size on flat slopes on a plateau lies in its distinct group (0.185). From these results, larger mean parcel size was reported on flat slopes of the plateaus, while the smaller ones were recorded on steep slopes of the highlands and flat slopes of the plains or lowlands. Therefore, these findings fail to scientifically reject our null hypothesis and confirm the negative relationship between landscape fragmentation and parcel topographical location as parcel size increases with slope (altitude) and vice versa. This trend could mainly be due to the farming structure in wetlands, where parcels are often subdivided into small pieces to allow the passage of waterways for irrigation and drainage purposes. However, the comparative findings about the farm, holding and parcel sizes across research sites and AEZs in Table 3 indicate the opposite trends since large farm, holding and parcel sizes were reported in the lowlands of the eastern province and small ones in the highlands of the northern and western provinces, which reject our null hypothesis (H_{01}) and confirm a positive relationship between tenure and landscape fragmentation with topography (altitude). The majority of our key informants and the consulted literature linked this pattern with physical, demographic and historical features of the country. As justification, the northern and western provinces of Rwanda have over time recorded higher farming population densities compared to the eastern and southern provinces, and the

availability of suitable arable land in flatlands than in marginal hilly or highlands, which led to high land scarcity in the later than in the former [16, 21, 30, 39, 41, 53, 111].

A Multilinear regression analysis was performed to model the relationship between four main continuous indicators of farmland fragmentation scenarios and their causes, while a multiple binary logistic regression (logit) was used to analyse the same relationship between six identified binary categorical fragmentation scenario classes and their perceived causes in the study area, as a methodological triangulation strategy for validity and reliability checking purposes. The results are summarised in **Tables 6 and 7**, respectively.

Table 6. Summary statistics of Multilinear regression analysis results on farmland tenure and physical fragmentation scenarios causes

Predictor Variables	*Scenario 1 (Farm Size)*		*Scenario 2 (Number of Parcels per farm)*		*Scenario 3 (Number of small scattered parcels per farm)*		*Scenario 4 (Number of tenants)*	
	β(S.E)	*t-value (p-value)*	*β(S.E)*	*t-value (p-value)*	*β(S.E)*	*t-value (p-value)*	*β(S.E)*	*t-value (p-value)*
C_1	-0.234(0.062)***	-3.74 (.000)	0.844(0.212)***	3.985 (.000)	0.844 (0.212)***	3.985(.000)		
C_2	0.068(0.053)	1.293(.196)	0.872(0.522)*	1.671 (.095)	0.872(0.522)*	1.671 (.095)		
C_3			0.569(0.236)**	2.407 (.017)	0.569(0.236)**	2.407 (.017)		
C_4			-2.559(1.426)*	-1.795(.073)	-2.559(1.426)*	-1.795(.073)		
C_5			0.386(0.22)*	1.754 (.08)	0.386(0.22)*	1.754 (.08)	-0.104(0.142)	-.731(.465)
C_6	-0.48(0.077)***	6.251(.000)						
C_7			-0.48(0.247)*	-1.941(.053)	-0.48(0.247)*	-1.941(.053)	0.397(0.709)	.56(.576)
C_8	-0.767(0.051)***	-15.014(.000)						
C_9	-0.235(0.065)***	-3.628(.000)						
C_{10}	0.137(0.14)	.977(.329)						
C_{11}	-0.078(0.12)	-.646(.518)						
C_{12}	-0.169(0.048)***	-3.537(.000)						
C_{14}	-0.01(0.037)	-.28(.78)	-7.722 (2.766)***	-2.792(.005)	-7.722(2.766)***	-2.792(.005)		
C_{15}			-0.47(0.358)	-1.313(.19)	-0.47(0.358)	-1.313(.19)	-0.808(0.502)	-1.609(.108)
C_{16}			0.268(0.308)	0.873 (.383)	0.268(0.308)	0.873 (.383)	0.06 (0.186)	.324(.746)
C_{17}	0.02(0.052)	.388(.698)					-0.23(0.268)	-.86(.39)
C_{18}			-0.323(0.458)	-0.705(.481)	-0.323(0.458)	-0.705(.481)	0.641(0.155)***	4.14(.000)
C_{19}			0.523(0.411)	1.272 (.204)	0.523(0.411)	1.272 (.204)	0.802(0.161)***	4.99(.000)
C_{20}			0.474(0.23)**	2.059 (.04)	0.474(0.23)**	2.059 (.04)	-0.111(0.166)	-.67(.503)
C_{21}			0.13(0.523)	0.249 (.803)	0.13(0.523)	0.249 (.803)		
C_{22}							0.171(0.153)	1.115(.266)
C_{23}			1.951(1.374)	1.42 (.156)	1.951(1.374)	1.42 (.156)		
C_{24}	-0.156(0.052)***	-3.031(.003)	-1.467(0.695)**	-2.11(.035)	-1.467(0.695)**	-2.11(.035)		
C_{25}			-0.531(0.367)	-1.446(.149)	-0.531(0.367)	-1.446(.149)		
C_{26}			-4.182(2.302)*	-1.817(.07)	-4.182(2.302)*	-1.817(.07)		
C_{27}			-0.119(0.503)	-0.237(.813)	-0.119(0.503)	-0.237(.813)		
C_{28}			1.401(0.645)**	2.174 (.03)	1.401(0.645)**	2.174 (.03)	-1.431(0.72)**	-1.988(.047)
C_{29}			-0.303(0.636)	-0.476(.634)	-0.303(0.636)	-0.476(.634)	-0.393(0.309)	-1.27(.205)
C_{30}			0.988(1.405)	0.703 (.482)				
C_{31}	-0.134(0.118)	-1.128(.26)	3.827(1.176)***	3.254 (.001)	3.827(1.176)***	3.254 (.001)		
C_{32}			-0.62(2.162)	-0.287(.774)				
C_{33}			0.723(1.886)	0.384 (.701)	0.723(1.886)	0.384 (.701)		
C_{34}			1.756(0.92)*	1.91 (.057)	1.175(0.516)**	2.276 (.023)		
C_{37}			-2.088(0.417)***	-5.006(.000)	-2.088(0.417)***	-5.006(.000)		
C_{38}			0.83(1.95)	0.426(0.671)	0.83(1.95)	0.426 (.671)		
C_{40}							0.863(0.132)***	6.516(.000)
C_{41}							0.871(0.256)***	3.394(.001)
C_{42}							0.104(0.185)	.563(.574)
C_{43}							0.394(0.318)	1.239(.216)
Farm size			1.288(0.199)***	6.458 (.000)	1.288(0.199)***	6.458 (.000)		
LUC			0.356(0.208)*	1.71 (.088)	0.356(0.208)*	1.71 (.088)	0.312(0.097)***	3.222(.001)
AEZ	0.097(0.033)***	2.924(.004)	0.257(0.19)	1.352 (.177)	0.257(0.19)	1.352 (.177)	0.112(0.084)	1.328(.185)

Site	-0.049(0.016)***	-3.088(.002)	-0.131(0.087)	-1.505(.133)	-0.131(0.087)	-1.505(.133)	-0.057(0.039)	-1.477(.14)
Constant	2.133(0.081)***	26.404(.000)	1.604(0.363)***	4.42(.000)	2.3144(0.477)***	4.848(.000)	0.03(0.129)	.229(.819)
N	487		487		487		487	
R^2(SE)	.641(.36)		.433(1.864)		.435(2.453)		.525 (.944)	
F-Statistic(df)	60.24(14, 472)		3.877 (80, 406)		3.9(80, 406)		27.128 (19, 467)	
p-value	(.000)***		(.000)***		(.000)***		(.000)***	

Notes: *, **, *** denote the significance levels at 0.1, 0.05 and 0.01 respectively. ***β*** stands for regression coefficient and ***t*** for t-statistics. Values in parentheses denote the **standard errors** and ***p***-values respectively. **C1-43** represents perceived fragmentation causes at the farm level. **Scenario 1**: small farms (tenure and landscape fragmentation); **Scenario 2:** internally fragmented farms (internal fragmentation); **Scenario 3:** small scattered and irregularly shaped parcels per farm (internal-dispersion or scattering-landscape and shape fragmentation); **Scenario 4:** leased-in farms and parcels (usership fragmentation). ***Source*:** Field survey primary data analysis.

Table 7. Summary statistics of Multiple binary logistic regression analysis results on perceived farmland fragmentation scenarios causes

Explanatory Variables	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	β(S.E)	***X^2(p-value)***	***β(S.E)***	***X^2(p-value)***	***β(S.E)***	***X^2(p-value)***	***β(S.E)***	***X^2(p-value)***	***β(S.E)***	***X^2(p-value)***	***β(S.E)***	***X^2(p-value)***
C_1	2.53(.97)***	6.82(.009)	6.27(1.09)***	32.6(.000)	9.82(2.73)***	12.9(.000)						
C_2	0.218(1.59)	0.02(.891)	6.39(5.59)	1.3(.253)			9.31(9.91)	0.883(.347)	8.26(13.04)	0.4(.526)		
C_3			5.14(1.12)***	20.7(.000)	9.28(3.92)*	5.6(.018)						
C_4			2.46(4.84)	0.25(.612)								
C_5			5.32(1.11)***	22.6(.000)	-.17(5.86)	0.001(.976)	5.45(2.72)**	4.002(.045)	6.99(1.24)***	31.65(.000)	3.53(1.102)***	10.26(.001)
C_6	3.49(.94)***	13.67(.000)	4.94(1.13)***	19(.000)	8.46(2.68)***	9.9(.002)			8.59(4.4)*	3.75(.053)		
C_7			4.46(1.16)***	14.7(.000)	8.67(3.28)***	6.98(.008)					-.96(8.92)	0.012(.914)
C_8	1.79(.99)*	3.28(.070)										
C_9	2.07(1.02)**	3.87(.049)										
C_{10}									2.08(8.85)	0.055(.814)		
C_{11}	1.224(2.09)	0.34(.559)										
C_{12}	1.75(.938)*	3.5(.061)										
C_{13}									6.76(1.13)***	35.54(.000)		
C_{14}	0.202(1.16)	0.03(.862)	8.08(2.56)***	9.96(.002)	9.35(6.34)	2.17(.140)	1.84(3.89)	0.223(.637)	0.85(11.74)	0.005(.942)	-2.26(5.37)	0.17(.674)
C_{15}			1.8(3.8)	0.22(.635)			-3.37(9.78)	0.119(.73)	6.35(3.68)*	2.97(.084)	0.57(2.16)	0.07(.791)
C_{16}			5.93(3.0)**	3.9(.048)							-.36(2.63)	0.019(.89)
C_{17}							0.86(9.05)	0.009(.924)	-2.94(19.63)	0.02(.881)		
C_{18}			-2.95(5.62)	0.27(.60)								
C_{19}			0.48(8.19)	0.004(.95)								
C_{20}			5.48(1.71)***	10.27(.001)	8.74(3.04)***	8.25(.004)	7.76(2.03)***	14.6(.000)			3.59(0.99)***	13.14(.000)
C_{21}			4.52(2.01)**	5.05(.025)	8.8(4.89) *	3.24(.072)	5.1(1.16)***	19.17(.000)	-2.68(3.61)	0.55(.458)	5.9(1.27)***	21.49(.000)
C_{22}			3.73(2.22)*	2.82(.093)					5.98(2.21)***	7.28(.007)	4.39(1.19)***	13.41(.000)
C_{23}			0.12(3.98)	0.001(.975)	9.8(11.15)	0.77(.379)						
C_{24}	0.903(1.12)	0.65(.419)	8.62(4.63)*	3.46(.063)								
C_{25}			0.29(3.81)	0.006(.939)								
C_{26}			-3.94(7.93)	0.24(.619)								
C_{27}			5.95(4.83)	1.51(.218)	10.32(14.4)	0.51(.474)	10.32(11.1)	0.86(.352)				
C_{28}			0.41(4.79)	0.007(.931)							-5.14(7.29)	0.49(.481)
C_{29}			0.65(10.57)	0.004(.951)	-6.36(36.8)	0.03(.863)					-1.97(3.46)	0.32(.569)
C_{30}			6.16(1.98)***	9.68(.002)	10.96(19.82)	0.3(.58)	6.82(1.1)***	38.43(.000)				

C_{31}	0.73(3.87)	0.036(.85)	-7.08(14.19)	0.25(.618)	11.23(22.6)	0.24(.619)	8.48(3.09)***	7.51(.006)				
C_{32}							3.15(17.82)	0.031(.86)				
C_{33}			10.71(36.66)	0.08(.77)	12.2(36.6)	0.11(.739)						
C_{34}			6.67(5.83)	1.3(.253)	9.81(11.18)	0.76(.38)	-3.37(65.5)	0.003(.959)				
C_{37}			1.27(3.52)	0.13(.719)								
C_{38}			4.94(36.93)	0.01(.894)								
C_{40}											5.67(0.85)***	43.79(.000)
C_{41}											6.96(2.58)***	7.26(.007)
C_{42}											-.33(1.97)	0.03(.866)
C_{43}											6.59(3.102)**	4.52(.034)
Constant	1.79(.436)***	16.86(.000)	-2.83(.42)***	45.4(.000)	58.72(26.7)**	4.8(.028)	13.04(2.45)***	28.1(.000)	25.95(9.043)***	8.24(.004)	14.48(2.38)***	36.8(.000)
N	487		487		487		487		487		487	
NagelkerkeR²	0.95		0.961		0.978		0.973		0.959		0.973	
X^2(df),p-value	185.214(11),	(.000)***	474.5 (28),	(.000)***	581.9(14),	(.000)***	632.405(14),	(.000)***	560.463(11),	(.000)***	636.6(14),	(.000)***
Hosmer & Lemeshow Test p-value	.476		.327		.728		.995		.949		.017**	

Notes: *, **, *** denote the significance levels at 0.1, 0.05 and 0.01 respectively. β stands for regression coefficients in terms of **log odds** and x^2 *for* Wald Chi-square-statistics. Values in parentheses denote the **standard errors** and ***p***-values respectively. **C1-43** denotes perceived fragmentation causes at the farm level. **Scenario 1**: small farms (tenure and landscape fragmentation). **Scenario 2**: small farms with scattered and irregularly shaped parcels (tenure-internal-dispersion or scattering-landscape and shape fragmentation); **Scenario 3**: small farms with contiguous and irregularly shaped parcels (tenure, internal, landscape and shape fragmentation); **Scenario 4**: farms with parcels subdivision into small irregularly shaped plots and multi-cropping (parcel level internal-use-shape and landscape fragmentation); **Scenario 5**: small farms with small irregularly shaped parcels and multi-cropping (tenure-landscape-shape and use fragmentation); **Scenario 6**: leased-in farms and unregistered irregularly shaped parcels (usership-hidden ownership and shape fragmentation).

***Source*:** Field survey primary data analysis

According to the presented results from the multilinear regression analysis in Table 6, all the four models fitted the data well, since the considered independent variables (fragmentation causes) overall highly significantly predicted the variations in the outcome variables (fragmentation scenarios), [$F(14, 472) = 60.24$, $p < .001$, $R^2 = .641$], [$F(80, 406) = 3.877$, $p < .001$, $R^2 = .433$], [$F(80, 406) = 3.9$, $p < .001$, $R^2 = .435$], and [$F(19, 467) = 27.128$, $p < .001$, $R^2 = .525$], for farm size (Scenario 1), number of parcels per farm (Scenario 2), number of small scattered parcels per farm (Scenario3), and the number of farm tenants in a farmland block (Scenario 4) respectively. This shows that the overall considered farmland fragmentation factors significantly explain 64.1 %, 43.3%, 43.5%, and 52.5% of the changes in farm size, number of parcels per farm, number of small scattered parcels per farm, and the number of farm tenants, respectively. Similarly, all the six multiple binary logistic regression analysis models in Table 7 were statistically significant, [$X^2(11, N=487) = 185.21$, $p < .001$], [$X^2(28, N=487) = 474.5$, $p < .001$], [$X^2(14, N=487) = 581.9$, $p < .001$], [$X^2(14, N=487) = 632.4$, $p < .001$], [$X^2(11, N=487) = 560.46$, $p < .001$], [$X^2(14, N=487) = 636.6$, $p < .001$] and the considered perceived fragmentation causes explained 95%, 96.1%, 97.8%, 97.3%, 95.9%, and 93%, (Nagelkerke R^2 =0.95, 0.961, 0.978, 0.973, 0.959, and 0.973) of the changes in farmland fragmentation categorical scenarios for Models 1, 2, 3, 4, 5 and 6 respectively. The Hosmer & Lemeshow tests for the five logit models were not statistically significant (p=.476, .327,.728,.995, .949 respectively), indicating the good fit of these models to the data except in Model 6 (p=.017).

It was found that holding other variables constant, eight farmland fragmentation causes (factors) were highly significantly linked with the variations in farm size and significantly influenced the prediction of the model at different significance levels for multilinear regression analysis, while only five factors in the case of the logit model/Scenario 1 were statistically significant. These include the egalitarian-based partible inheritance/succession principles and land distribution programs among the heirs as part of customary practices (C_1) [β_1 = -.234, p<.001], land scarcity and farmland population density due to uncontrolled population growth and poverty (C_6) [β_6 = -.48, p<.001], lack of Off-farm employment and poverty (C_8) [β_8 = -.767, p<.001], land reforms, individual land tenure system and land market (purchase and sale) (C_9) [β_9 = -.235, p<.001], food production independence (sovereignty) and security and farmland psychology and tenure security (C_{12}) [β_{12} = -.169, p<.001], land sharing, distribution, redistribution and restitution programs (C_{24}) [β_{24} = -.156, p<.001], variations in research sites [β_{site} = -.049, p=.002], and agro-ecological zones (AEZs) [β_{AEZ} = .097, p=.004]. This means that holding all other factors constant, every unit increase in C_1, C_6, C_8, C_9, C_{12}, C_{24} and research sites implies the decrease in farm size by 0.234, 0.48, 0.767, 0.235, 0.169, 0.156, and 0.049 respectively, which indicates a positive relationship between these factors and farmland tenure and landscape fragmentation scenarios in Rwanda. Similarly, the farm size increases by 0.097 with every additional agro-ecological zone, indicating a negative relationship between agro-ecological zones and tenure fragmentation since farmers might expand their farms by acquiring additional parcels in other agro-ecological zones for exploitation of multiple heterogeneous AEZs with diverse agronomic and crops growing conditions. Since only the significant factors were considered for the final model, the resultant reduced tenure and landscape fragmentation model is reflected by the following **Equation 8a**:

$$\boldsymbol{Farm\ size} = 2.133 - 0.234C_1 - 0.48C_6 - 0.767C_8 - 0.235C_9 - 0.169C_{12} - 0.156C_{24} - 0.049Site + 0.097AEZ + 0.36 \quad \textbf{(8a)}$$

From the logit model 1 (Scenario 1), the likelihood of the farms for becoming small (tenure and landscape fragmentation) was statistically significantly associated with C_1 [β_1 = 2.53, p=.009], C_6 [β_6 = 3.49, p<.001], C_8 [β_8 = 1.79, p=.07], C_9 [β_9 = 2.007, p=.049] and C_{12} [β_{12} = 1.75, p=.061]. Simply put, holding all other factors constant, every unit increase in every one of these factors would imply the likelihood of the farms for becoming small (decrease in farm size), thereby increasing tenure and landscape fragmentation forms by 2.53, 3.49, 1.79, 2.007, 1.75 respectively. This relationship is represented by the final logit model displayed in **Equation 9a**:

$$\boldsymbol{Log}\left[\frac{\boldsymbol{number\ of\ small\ farm}}{\boldsymbol{1-number\ of\ small\ farm}}\right] = 1.79 + 2.53C_1 + 3.49C_6 + 1.79C_8 + 2.007C_9 + 1.75C_{12} \quad \textbf{(9a)}$$

From the multilinear regression analysis tests, fifteen factors were found to be significantly linked with the variations in the number of parcels per farm (Scenario 2) and the number of small scattered parcels per farm (Scenario 3), and added significantly to the prediction of the models 2 and 3 respectively at different statistical significance levels. These are C_1 [β_1 = .844, p<.001], intra-familial land related conflicts (C_2) [β_2 = .872, p=.095], land market through the purchase and lease of additional parcels with different irregular shapes for farm expansion (C_3) [β_3 = .569, p=.017], market-oriented agriculture (C_4) [β_4 = -2.56, p=.073], subsistence farming for self-independence in food security (food sovereignty) (C_5) [β_5 = .386, p=.08], poverty of farmers (C_7) [β_7 = .48, p=.053], spatial and topographical diversity(slope) (C_{14}) [β_{14} = -7.72, p=.005], food diversification, climate change adaptation and production risks management strategy through crop diversification in various micro-climatic and agro-ecological conditions or LUC sites (C_{20}) [β_{20} = .474, p=.04], C_{24} [β_{24}= -1.467, p=.035], customary farmland tenure practices (C_{26}) [β_{26}= -4.182, p=.07], marriage and land-based dowry culture (C_{28}) [β_{28}= 1.401, p=.03], erosion control measures including bench and progressive terraces (soil and water erosion control and crops protection against wind and other natural disasters) (C_{31}) [β_{31}= 3.827, p=.001], location and status (structure) of available leasing parcels (C_{34}) [β_{34}= 1.756, p=.057] for model 2 and [β_{34}= 1.175, p=.023] for model 3, relocation for grouped resettlements program (C_{37}) [β_{37}= -2.088, p<.001], farm size [β_{fs}= 1.288, p<.001], and farmland use consolidation (LUC) program participation [β_{LUC}= 0.356, p=.088] for both models 2 and 3 respectively. In both scenario models, the research sites and agro-ecological zones were not among the significant factors [β_{AEZ} =0.257, p=.177] and [β_{Site} =-0.131, p=.133], respectively. In other words, holding other fragmentation factors constant, every unit increase in C_1, C_2, C_3, C_5, C_7, C_{20}, C_{28}, C_{31}, C_{34}, farm size and participation (membership) in LUC program would imply the increase in number of parcels and the number of small scattered parcels per farm indicating internal, dispersion, landscape and shape fragmentation scenarios by 0.844, 0.872, 0.569, 0.386, 0.48, 0.474, 1.401, 3.827, 1.756 and 1.175, 1.288, 0.356 respectively, and their decrease by 2.56, 7.72, 1.467, 4.182 and 2.088 for every unit increase in C_4, C_{14}, C_{24}, C_{26} and C_{37} respectively. The resultant final relationship models are reflected in the following **Equations 8b and c**:

$$\boldsymbol{Number\ of\ parcels\ per\ farm} = 1.604 + 0.844C_1 + 0.872C_2 + 0.569C_3 - 2.56C_4 + 0.386C_5 + 0.48C_7 - 7.72C_{14} + 0.474C_{20} - 1.467C_{24} - 4.182C_{26} + 1.401C_{28} + 3.827C_{31} + 1.756C_{34} - 2.088C_{37} + 1.288\ farm\ size + 0.356LUC + 1.864 \quad \textbf{(8b)}$$

$$\textbf{\textit{Number of small scattered parcels per farm}} = 1.604 + 0.844C_1 + 0.872C_2 + 0.569C_3 - 2.56C_4 + 0.386C_5 + 0.48C_7 - 7.72C_{14} + 0.474C_{20} - 1.467C_{24} - 4.182C_{26} + 1.401C_{28} + 3.827C_{31} + 1.175C_{34} - 2.088C_{37} + 1.288farm\ size + 0.356LUC + 2.453 \quad \textbf{(8c)}$$

From the logit model 2 (Scenario 2), the factors such as C_1 [β_1 = 6.27, p<.001], C_3 [β_3 = 5.14, p<.001], C_5 [β_5 = 5.32, p<.001], C_6 [β_6 = 4.94, p<.001], C_7 [β_7 = 4.46, p<.001], C_{14} [β_{14} = 8.08, p=.002], C_{16} (distance or location of the parcels to the farmstead) [β_{16} = 5.93, p=.048], C_{20} [β_{20} = 5.48, p=.001], C_{21} (micro-climatic and agro-ecological variations leading to the exploitation of multiple and diverse agro-ecological zones and all agriculture seasons) [β_{21} = 4.52, p=.025], C_{22} (climate change adaptation and production risks management strategy) [β_{22} = 3.73, p=.093], C_{24} [β_{24} = 8.62, p=.063] and C_{30} (pathways, natural features, waterways and soil erosion) [β_{30} = 6.16, p=.002] were statistically significantly associated with the likelihood of the farms for becoming small and internally fragmented with small scattered and irregularly shaped parcels (tenure-internal-dispersion-shape and landscape fragmentation).

In the logit model 3 (Scenario 3), significant individual contributions to the prediction of the likelihood of the farms for becoming small and internally fragmented with small contiguous and irregularly shaped parcels (tenure-internal-shape and landscape fragmentation) were made by C_1 [β_1 = 9.82, p<.001], C_3 [β_3 = 9.28, p=.018], C_6 [β_6 = 8.46, p=.002], C_7 [β_7 = 8.67, p=.008], C_{20} [β_{20} = 8.74, p=.004] and C_{21} [β_{21} = 8.8, p=.072]. Similarly, C_5 [β_5 = 5.45, p=.045], C_{20} [β_{20} = 7.76, p<.001], C_{21} [β_{21} = 5.1, p<.001], C_{30} [β_{30} = 6.82, p<.001] and C_{31} [β_{31}= 8.48, p=.006] factors were significantly associated with the likelihood of parcels subdivision into small irregularly shaped plots and parcel level multi-cropping (parcel level internal-use-shape and landscape fragmentation) in scenario 4. In short, holding all other factors constant, every unit increase in every one of these mentioned factors would more likely increase the presence of tenure-internal-shape and landscape fragmentation in a farmland block under scenario 2 by 6.27, 5.14, 5.32, 4.94, 4.46, 8.08, 5.93, 5.48, 5.42, 3.73, 8.62 and 6.16 respectively. Similarly, it would increase tenure-internal-shape and landscape fragmentation under scenario 3 by 9.82, 9.28, 8.46, 8.67, 8.74 and 8.8, respectively, and parcel-level internal-use-shape and landscape fragmentation under scenario 4 by 5.45, 7.76, 5.1, 6.82 and 8.48 respectively. Furthermore, the likelihood of getting small farms with small irregularly shaped parcels and multi-cropping (tenure-landscape-shape and use fragmentation) in scenario 5 was significantly associated with perceived factors of C_5 [β_5 = 6.99, p<.001], C_6 [β_6 = 8.59, p=.053], C_{22} [β_{22} = 5.98, p=.007], C_{13} (efficient use of farmland through the mixture of early maturing crops like sweet potatoes and late maturing ones like cassava for the purposes of increasing crops production and diversification from the profitable complementary combination of crops on a small farm, climate change adaptation, production risks management and household food security (diversity, sovereignty and sustainability) under multi-cropping customs) [β_{13} = 6.76, p<.001], and C_{15} (variations in soil quality and types over short distances) [β_{15} = 6.35, p=.084]. In other words, for every unit increase in C_5, C_6, C_{13}, C_{15} and C_{22} in a farmland block, there is a likelihood of an increase in farmland tenure-landscape-shape and use fragmentation scenario 5 by 6.99, 8.59, 6.76,6.35 and 5.98 respectively. These relationships are mathematically displayed in the final logit models 2, 3, 4 and 5 in the following **Equations 9b, c, d,** & **e**:

$$Log\left[\frac{number\ of\ small\ farms\ with\ scattered\ and\ irregularly\ shaped\ parcels}{1-number\ of\ small\ farms\ with\ scattered\ and\ irregularly\ shaped\ parcels}\right] = -2.83 + 6.27C_1 + 5.14C_3 + 5.32C_5 + 4.94C_6 + 4.46C_7 + 8.08C_{14} + 5.93C_{16} + 5.48C_{20} + 4.52C_{21} + 3.73C_{22} + 8.62C_{24} + 6.16C_{30} \quad \textbf{(9b)}$$

$$Log\left[\frac{number\ of\ small\ farms\ with\ contiguous\ and\ irregularly\ shaped\ parcels}{1-number\ of\ small\ farms\ with\ contiguous\ and\ irregularly\ shaped\ parcels}\right] = 58.72 + 9.82C_1 + 9.28C_3 + 8.46C_6 + 8.67C_7 + 8.74C_{20} + 8.8C_{21} \quad \textbf{(9c)}$$

$$Log\left[\frac{number\ of\ farms\ with\ subdivided\ parcels\ into\ small\ irregularly\ shaped\ plots\ and\ multi-cropping}{1-number\ of\ farms\ with\ subdivided\ parcels\ into\ small\ irregularly\ shaped\ plots\ and\ multi-cropping}\right] = 13.04 + 5.45C_5 + 8.67C_7 + 7.76C_{20} + 5.1C_{21} + 6.82C_{30} + 8.48C_{31} \quad \textbf{(9d}$$

$$Log\left[\frac{number\ of\ small\ farms\ with\ small\ irregularly\ shaped\ parcels\ and\ multi-cropping}{1-number\ of\ small\ farms\ with\ small\ irregularly\ shaped\ parcels\ and\ multi-cropping}\right] = 25.95 + 6.99C_5 + 8.59C_6 + 6.76C_{13} + 6.35C_{15} + 5.98C_{22} \quad \textbf{(9e)}$$

The exploitation of multiple agro-ecological zones with different soil types and qualities (wetlands/lowlands vs highlands) and all agriculture seasons (C_{18}) [β_{18} = .641, p<.001], crops diversification in different (LUC) sites with different priority crops or different agro-ecological zones as production risks management strategy (C_{19}) [β_{19} = .802, p<.001], marriage and land-based dowry culture (C_{28}) [β_{28} = -1.431, p=.047], expansion of the farm for food security (diversity and quantity) and market satisfaction (cheapest and affordable option for small farm expansion for agriculture production and income increase, and household food security purpose) (C_{40}) [β_{40} = .863, p<.001], on-farm employment and farm landlessness (C_{41}) [β_{41} = .871, p=.001], and the participation in LUC program [β_{LUC} = .312, p=.001] factors were significantly related to the variations in the number of tenants in the study area and added significantly to the prediction of multilinear regression model 4. The research sites and agro-ecological zones were not significant determinants of this fragmentation scenario [β_{AEZ} =0.112, p=.185] and [β_{Site} =-0.057, p=.14], respectively. Holding all other factors constant, it was found that every unit increase in C_{18}, C_{19}, C_{40}, C_{41} and participation in the LUC program would lead to the increase in the number of tenants (usership fragmentation) by 0.641, 0.802, 0.863, 0.871, 0.312, and its decrease by 1.431 for every unit increase in C_{28}. The following **Equation 8d** expresses this final relationship model**:**

$$\textbf{Number of farmland tenants} = 0.03 + 0.641C_{18} + 0.802C_{19} + 0.863C_{40} + 0.871C_{41} - 1.431C_{28} + 0.312LUC + 0.944 \quad \textbf{(8d)}$$

The logit analysis model 6 (scenario 6) of this relationship indicated a significant association of C_5 [β_5 = 3.53, p=.001], C_{20} [β_{20} = 3.59, p<.001], C_{21} [β_{21} = 5.9, p<.001], C_{22} [β_{22} = 4.39, p<.001], C_{40} [β_{40} = 5.67, p<.001], C_{41} [β_{41} = 6.96, p=.007] and C_{43} (farmland subdivision restrictions, cooperative farming in land use consolidation (LUC) program for agriculture production and farm income increase, food sovereignty and security, and market facilitation and satisfaction) [β_{43} = 6.59, p=.034] with the likelihood of increasing the leased-in farms and unregistered irregularly shaped parcels (usership-hidden ownership and shape fragmentation) in the study area. Holding all other factors constant, the likelihood of finding usership-hidden ownership and shape fragmentation scenario 6 in a farmland block would increase by

3.53, 3.59, 5.9, 4.39, 5.67, 6.96 and 6.59 for every unit increase in C_5, C_{20}, C_{21}, C_{22}, C_{40}, C_{41} and C_{43} respectively. This resultant final relationship logit model is reflected in the following **Equation 9f:**

$$Log\left[\frac{number\ of\ leased-in\ farms\ and\ unregistered\ irregularly\ shaped\ parcels}{1-number\ of\ leased-in\ farms\ and\ unregistered\ irregularly\ shaped\ parcels}\right] = 14.48 + 3.53C_5 + 3.59C_{20} + 5.9C_{21} + 4.39C_{22} + 4.67C_{40} + 6.96C_{41} + 6.59C_{43} \quad \textbf{(9f)}$$

These findings therefore confirm the fifth research hypothesis (H_{A5}) stipulating a significant positive relationship between C_1, C_6, C_8, C_9, C_{12}, C_{24} factors and farmland tenure and landscape fragmentation forms and scenarios; C_1, C_2, C_3, C_5, C_{13}, C_{14}, C_{20}, and the participation in LUC factors and internal, use and dispersion fragmentation scenarios in farmland; C_{18}, C_{19}, C_{40}, C_{41}, C_{43} and participation in LUC program and farmland usership fragmentation scenario. Furthermore, they support the theoretical fragmentation causal-effects findings of Ntihinyurwa and de Vries [3] and are consistent with the findings of many previous studies on the same topic as discussed in the introductory and theoretical sections of this study. Besides that, these results confirmed and validated in the study area the argument positing that under failed economic incentives, especially in subsistence economies with free but uncertain or imperfect land market, scarce farmland, and lack of off-farm employment conditions like in Rwanda, the farming and urban population growth combined with egalitarian based principles in partible inheritance and land distribution system leads to both physical (landscape, internal, use, dispersion, shape and location) and tenure (ownership and usership) fragmentation. In this situation, since the social value of land outweighs its economic value [3, 119], farmers manifest a very high attachment to land as their only means of subsistence [119]. This leads to many small subsistence farmers and independent farms and parcels in a relatively small area or farmland block, and the desire to increase the number of parcels and plots per farm from the acquisition of contiguous (adjacent) or non-contiguous parcel to meet the food demands of the growing population and family size [3] as found in the majority of our study sites. Furthermore, the land-sharing programs in Rwanda (1994-2012) after the 1994 Genocide against Tutsis left many farms subdivided between their then-owners and former (previous owners returning from exile) nationwide and between big farmers and landless people in the Eastern province. These programs resulted in many small farms (scattered or continuous) and increased land tenure (in forms of ownership and usership in case of absentee non-farmer owners leasing their farms to many tenants), landscape, internal, use and dispersion fragmentation scenarios [3].

In the presence of farmland subdivision and partible inheritance restrictions and policies promoting joint family land ownership and farming like land use consolidation encouraging the monoculture and Article 30 of the outdated law governing land in Rwanda forbidding the subdivision of agricultural land into parcels of less than 1ha [3, 4], the farming population growth was identified as the main significant factor of hidden tenure (ownership and usership) fragmentation forms in case of its hidden undocumented subdivision in four sites of Benishyaka, Gisanze, Gasare and Kivuruga. This hidden subdivision was often triggered by the motives of perceived farmland tenure security (individual use rights) in the form of tenancy or private ownership rights and food independence (sovereignty) for individual food and nutrition security [3]. Furthermore, under heterogeneous socio-spatial and agro-ecological conditions, these subdivision restrictions and LUC program have been found as significant factors of physical farmland fragmentation in terms of internal, use, dispersion and location [1, 3, 120]. In this case, farmers often opt

to acquire additional parcels located in other agro-ecological micro-zones and consolidation sites with different crop growing conditions, which could give them the possibility to diversify their crops for risks and labour management, and food diversity and security purposes [1, 3, 5, 6, 28, 32, 46]. It is argued that the consolidation practices leading to localised mono-cropping systems may push the farmers to acquire other parcels in different sites, which could give them the possibility to grow diverse crops for risks and labour management, and food diversity and security purposes. This feature paradoxically leads to land tenure fragmentation in terms of both visible usership and hidden ownership and physical fragmentation in terms of internal, dispersion, use, and location fragmentation forms (ibid). This farmland subdivision restriction has been removed in the new and current law governing lands in Rwanda since June 2021. However, the use of farmland in accordance with land use consolidation has been enforced as an obligation to all farmers in Article 65 of this law [167], which did not fully solve the farmers concerns. Under the absence of land shape control strategies, natural and artificial drivers leading to the farm landscape subdivision into different irregularly shaped fragments were found as the main significant drivers of farmland shape and internal fragmentation forms and scenarios in this study as theoretically stipulated by Ntihinyurwa and de Vries [3]. However, these causes were found as an external imposition or supply to farmers by the socio-cultural, economic, and natural physical conditions of the country [16, 64, 111, 132].

From the demand side causes of fragmentation, it was found that heterogeneous farmland conditions of the country (diversity in soil qualities and types, slope, microclimates, topography, exposure, crops suitability and growing conditions, and farmland production potentials) and the absence of risks management strategies (agriculture insurance systems, high yielding and resistant crops varieties, crop diseases and pests control measures, and other land saving technologies), the egalitarian principles in land allocation processes (partible inheritance, land sharing, land distribution and restitution, and other land reforms) and farmland market (buying and selling farmland parcels) were revealed as the main significant factors of landscape-internal-dispersion-use and shape fragmentation scenario [3]. The analyses revealed that farmers prefer to have parcels of all grades and classes often scattered in different agro-ecological micro-zones and farming activities across all three agriculture seasons of Rwanda [3, 32, 89, 98], for crop diversification and rotation, crop production and prices risks management, farm expansion and income increase, agrobiodiversity conservation and climate change adaptation, soil fertility management, erosion control (via radical and progressive terraces), and multidimensional food security and sovereignty (food quality, quantity, availability, accessibility and sustainability) purposes [3, 16, 32, 64, 86-92, 95, 96, 98, 111, 145]. Besides these farmers' perceived causes of fragmentation, the immigration and farmland speculation aspects were also emphasised by key informants from key interviews and focus group discussions as the main factors of tenure and landscape, internal and dispersion fragmentation scenarios in some specific areas of the country characterised by relatively low levels of land scarcity and land psychology (economic farmland value> social farmland value) like in the Eastern Province of Rwanda.

2. 4. 4. Farmland Fragmentation Perceived Scenarios Categories Prediction Models

In order to test the second null hypothesis (H_{02}) of this study, Pearson Chi-Square Contingency Table Analyses (Crosstabs) tests were performed to compare the perceived effects-based categories of four main theoretical farmland fragmentation scenarios across different research sites and AEZs. Multiple regression analysis tests were conducted to model the predictors (determinants) of the classification of these fragmentation scenarios into three unordered categories: Beneficial, Problematic, and Problematic-Beneficial. The classification of the effects of fragmentation scenarios into three rather than two categories is grounded in the possible hypothetical coexistence of beneficial and problematic fragmentation forms under one scenario. The results from these statistical tests are summarised in Tables 8 and 9, respectively.

Table 8. Summary statistics of Crosstabs analysis and Chi-Square tests of perceived farmland fragmentation effects-based categories (N= 487) and farmland loss through boundaries in hectares (N=14951)

Fragmentation Scenarios classes	Fragmentation Categories	AEZ	Buberuka Highlands		Bugarama (Imbo)	Bugesera	Central plateau			Congo Nil Divide				Cyangugu Backside (Impala)		Eastern Ridges &Plateau			Eastern Savana		Granitic Ridge	Kivu lakeside		Mayaga	Volcanic summits & high plains		Descriptive metrics		Significance level (p ≤ .05)	
		Research Sites (Villages)	Gacyamo	Musebeya	Gitambi	Gatare	Bitsibo	Karehe	Umuyange	Gasare	Karambi	Kivuruga	Uwamataba	Karenge	Ruhinga II	Myatano	Ndinda	Rwanyamigondo	Benishyaka	Gisanze	Nyamaraba	Kamina	Karungu	Rwatano	Gataraga	Gisura	Total	Mean	X^2/F(p-value)	Cramer's V
Scenario 1	Problematic	Frequency	6	19	25	20	33	12	17	15	20	15	1	20	20	25	19	12	12	9	24	22	15	22	28	22	433			
		Percentage	30	86.4	100	100	100	100	100	100	100	100	5.6	100	95.2	100	100	100	48	69.2	100	100	100	91.7	100	100		88.9	321.99 (<.001)	.575
	Beneficial	Frequency	0	2	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0	6			
		Percentage	0.0	9.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	0.0	4.8	0.0	0.0	0.0	4.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0		1.2		
	Problematic-Beneficial	Frequency	14	1	0	0	0	0	0	0	0	0	16	0	0	0	0	0	12	3	0	0	0	2	0	0	48			
		Percentage	70	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	88.9	0.0	0.0	0.0	0.0	0.0	48	23.1	0.0	0.0	0.0	8.3	0.0	0.0		9.9		
Scenario 2	Problematic	Frequency	7	3	10	14	13	7	14	2	0	7	4	5	8	13	2	3	4	3	1	1	12	0	20	12	165			
		Percentage	35.0	13.6	40.0	70.0	39.4	58.3	82.4	13.3	0.0	46.7	22.2	25.0	38.1	52.0	10.5	25.0	16.0	23.1	4.2	4.5	80.0	0.0	71.4	54.5		33.9	148.13 (<.001)	.567
	Beneficial	Frequency	0	11	15	6	20	5	3	10	20	6	2	15	13	7	16	9	5	2	17	21	3	18	8	7	239			
		Percentage	0.0	50.0	60.0	30.0	60.6	41.7	17.6	66.7	100	40.0	11.1	75.0	61.9	28	84.2	75.0	20.0	15.4	70.8	95.5	20.0	75.0	28.6	31.8		49.1		
	Problematic-Beneficial	Frequency	13	8	0	0	0	0	0	3	0	2	12	0	0	5	1	0	16	8	6	0	0	6	0	3	83			
		Percentage	65.0	36.4	0.0	0.0	0.0	0.0	0.0	20.0	0.0	13.3	66.7	0.0	0.0	20.0	5.3	0.0	64.0	61.5	25.0	0.0	0.0	25.0	0.0	13.6		17.0		
Scenario3	Problematic	Frequency	13	11	10	14	13	7	14	4	0	8	9	5	8	16	2	3	10	6	7	1	12	5	20	13	211			
		Percentage	65	50	40	70	39.4	58.3	82.4	26.7	0.0	53.3	50	25	38.1	64	10.5	25	40	46.2	29.2	4.5	80	20.8	71.4	59.1		43.3	97.18 (<.001)	.447
	Beneficial	Frequency	7	11	15	6	20	5	3	11	20	7	9	15	13	9	17	9	15	7	17	21	3	19	8	9	276			
		Percentage	35	50	60	30	60.6	41.7	17.6	73.3	100	46.7	50	75	61.9	36	89.5	75	60	53.8	70.8	95.5	20	79.2	28.6	40.9		56.7		
Scenario 4	Problematic	Frequency	4	2	5	11	13	6	4	0	0	4	0	4	4	1	0	0	1	1	0	0	4	1	17	9	91			
		Percentage	20	9.1	20	55	39.4	50	23.5	0.0	0.0	26.7	0.0	20	19	4	0.0	0.0	4	7.7	0.0	0.0	26.7	4.2	60.7	40.9		18.7	285.53 (<.001)	.541
	Beneficial	Frequency	2	12	20	9	20	6	13	9	16	9	5	16	11	22	6	12	5	4	14	22	11	10	7	8	269			
		Percentage	10	54.5	80	45	60.6	50	76.5	60	80	60	27.8	80	52.4	88	31.6	100	20	30.8	58.3	100	73.3	41.7	25	36.4		55.2		
	Problematic-Beneficial	Frequency	14	8	0	0	0	0	0	6	4	2	13	0	6	2	13	0	19	8	10	0	0	13	4	5	127			
		Percentage	70	36.4	0.0	0.0	0.0	0.0	0.0	40	20	13.3	72.2	0.0	28.6	8	68.4	0.0	76	61.5	41.7	0.0	0.0	54.2	14.3	22.7		26.1		
N (Number of farms)			20	22	25	20	33	12	17	15	20	15	18	20	21	25	19	12	25	13	24	22	15	24	28	22	487			
Farmland loss in HA			3.758	2.079	4.895	1.795	5.288	4.186	2.262	4.047	2.418	1.585	3.305	4.217	2.721	2.833	1.848	2.612	2.826	2.211	2.721	2.233	1.253	3.502	3.814	2.458	70.877	2.953	92.88 (<.001)	
Percentage of Farmland loss			3.8	3.19	2.93	2.67	2.36	2.49	3.14	3.26	4.35	1.84	3.44	3.05	3.18	2.41	3.14	2.73	0.99	1.69	3.39	3.84	5.33	2.56	4.74	4.57		2.76		
N(Number of farmland parcels)			942	567	996	285	918	721	608	1096	609	227	760	835	574	444	376	458	171	268	622	630	388	658	1116	682	14951			

Notes: **Scenario Class 1**: Small farms (tenure and landscape fragmentation) and multi-cropping (Use fragmentation). **Scenario Class 2**: Small farms with small scattered and irregularly shaped parcels (tenure-internal-dispersion(scattering)-landscape and shape fragmentation); **Scenario Class 3**: Small farms with contiguous and irregularly shaped parcels (tenure-internal- landscape and shape fragmentation); **Scenario Class 4**: Big internally fragmented farms with large scattered and irregularly shaped parcels (internal-dispersion(scattering) and shape fragmentation). ***Source*:** Field survey primary data analysis

The reported results in Table 8 indicate a statistically significant strong relationship (association) between fragmentation categories and location (research site and AEZ) in all the four scenarios and statistically significant differences among the three effects-based fragmentation categories across different sites and AEZs, [X^2(46) = 321.99, *Cramer's V*=.575*, p* <.001], [X^2(46) = 148.13, *Cramer's V*=.567*, p* <.001], [X^2(23) = 97.18, *Cramer's V=.447, p* <.001] and [X^2(46) = 285.13, *Cramer's V*=.541*, p* <.001] for Scenarios 1, 2, 3, and 4, respectively.

On average, farmland fragmentation scenario 1 (small farms with multi-cropping) was perceived by the majority of farmers as more problematic than beneficial and problematic-beneficial (*MP*=88.9% vs 1.2% and 9.9%). The scenarios 2, 3 and 4 with the aspect of internal fragmentation and/or scattering of parcels in the farm were considered as more beneficial than problematic and problematic-beneficial for various socio-spatial, economic and agro-ecological motives, (*MP*= 49.1% vs 33.9% and 17%) for scenario 2, (*MP*= 56.7% vs 43.3%) for scenario 3, and (*MP*= 55.2% vs 18.7% and 26.1%) for scenario 4 respectively. It was found that these differences were not identical across various research sites and AEZs, which explains the variations in the categorisation of the scenarios with location and local conditions. With the exceptions of Gacyamo (30%), Uwamataba (5.6%) and Benishyaka (48%), the majority of farmers in the rest of the research sites perceived farmland tenure and landscape fragmentation scenario 1 as problematic (≥ 70%) mainly for the barriers to the economies of scale effects regardless of the homogeneity or heterogeneity of local conditions. In these three exceptions, scenario 1 was perceived simultaneously as more problematic-beneficial than problematic or beneficial. In this scenario, the perceived negative or detrimental effects of fragmentation far outweigh the positive or beneficial ones. On the other hand, under micro-diverse and heterogeneous agro-ecological conditions, the internal and dispersion fragmentation aspects of either small or big farms in scenarios 2, 3 and 4 were perceived by the majority of farmers (≥ 50%) as beneficial in Musebeya, Gitambi, Bitsibo, Gasare, Karambi, Karenge, Ruhinga II, Rwanyamigono, Nyamaraba, Kamina, and in scenarios 2 and 3 in Rwatano and Ndinda respectively. This perception was explained as farmers' rational choice for the aspects of crop diversification, exploitation of multiple micro-agro-ecological zones, climate change adaptation, production and market risk management and household food security. For quite similar rational reasons plus the aspect of small size and distance-related adverse effects, scenarios 2 and 4 were perceived as both problematic and beneficial by the majority of farmers (≥ 54%) in Gacyamo, Uwamataba, Benishyaka and Gisanze. However, the majority of farmers (≥ 50%) in Gatare, Karehe, Myatano, Gataraga, and Gisura perceived scenarios 2, 3 and 4 as more problematic for the small-sized farms' inefficiency and distance-related production costs, and similarly in Kivuruga, Umuyange, Karungu for scenarios 2 and 3 for small farms inefficiency consequences.

A deep assessment of the disadvantages of farm landscape fragmentation beyond the perceptions of farmers and key informants was performed from the landscape-level cadastral dataset via the computations of the estimated size (area) of farmland loss through boundaries. This was calculated as the product of the total length of the boundary and the estimated standard width of the boundary in farmland in Rwanda (0.3m). The results show that approximately 70.877 Ha (2.76%) of farmland in all research sites (2.95 Ha per site on average) were lost via the subdivision of farmland. The performed

ANOVA test revealed statistically significant differences in farmland loss through boundaries among various study sites, $F(23,14927) = 92.88$, $p < .001$. The highest percentages of loss were recorded in the highlands of Gataraga (M=4.74%) and Gisura (M=4.57%) of Volcanic summits and high plains AEZ in the Northern province, while the lowest were found in the lowlands of Bensishyaka (M=0.99%) and Gisanze (M= 1.69%) of Eastern Savana of Rwanda.

From these findings, it can be concluded that the perceived positive effects of farmland fragmentation under scenarios 2, 3, and 4 slightly outweigh its negative ones. These results support the first part of the second null hypothesis (H_{02}) and fail to reject it since they do not provide enough evidence of the superiority of negative impacts of farmland fragmentation over the positive ones in the study area, but reject its second part as a statistically significant association between research sites (location) and perceived farmland fragmentation categorisation decision indicating differences in categories and their predictors across various research sites and local conditions was found. In order to assess the specific determinants (predictors) of this perceived categorisation, a multinomial regression analysis for the four separate scenarios was conducted, and the results for the four models are summarised in **Table 9**.

Table 9. Summary statistics of Multinomial logistic regression models of farmland fragmentation scenarios classification factors

Explanatory Variables		**Model 1** ***(PTF Scenario)***		**Model 2** ***(PIDF Scenario)***		**Model 3** ***(PITF Scenario)***		**Model 4** ***(IDF Scenario)***	
		β(S.E)	***OR(p-value)***	***β(S.E)***	***OR(p-value)***	***β(S.E)***	***OR(p-value)***	***β(S.E)***	***OR(p-value)***
PE_1				3.64(2.12)***	37.96(.000)			3.92(2.35)***	50.38(.000)
PE_2				1.056(1.06)***	2.87(.002)	2.44(1.606)***	11.52(.000)	2.616(0.51)***	13.68(.000)
PE_3				1.69(0.66)**	5.45(.011)				
PE_4				0.411(0.66)	1.508(.533)				
PE_5		5.58(1.44)***	266.44(.000)	2.94(1.958)***	18.87(.001)	-3.114(1.51)***	0.044(.000)		
PE_6				-0.86(0.668)***	0.424(.007)	-4.57(1.59)***	0.01(.000)	-0.996(0.36)***	0.37(.007)
PE_7		2.599(0.44)***	13.45(.000)	1.68(0.65)***	5.38(.000)				
PE_8				1.518(1.59)	4.56(.341)			-0.182(0.25)	0.83(.474)
PE_9				-2.13(1.55)**	0.119(.045)			-1.407(0.62)**	0.24(.025)
PE_{10}				-4.038(443.4)	0.018(.993)				
PE_{11}		6.73(1.46)***	842.07(.000)						
PE_{12}		-0.63(0.14)***	0.531(.000)						
PE_{14}		-0.586(0.387)	0.557(.131)						
PE_{15}		0.987 (0.18)***	2.68(.000)						
BE_1				6.05(3.22)***	424.4(.000)			5.411(2.27)**	223.8(.017)
BE_2				0.402(2.2)	1.49(.855)	2.89(0.87)***	18.15(.000)	-0.413(0.14)***	0.66(.005)
BE_3				1.04(1.78)***	2.83(.000)				
BE_4								0.802(0.21)***	2.23(.000)
BE_5				0.365(5.16)**	1.44(.011)	2.78(0.67)***	16.13(.000)	1.29(0.24)***	3.63(.000)
BE_6				0.711(3.86)	2.03(.854)	-5.128(1301.64)	0.006(.997)		
BE_7				-0.18(2.741)**	0.83(.017)				
BE_8				0.302(4.18)	1.35(.942)	-2.503(954.75)	0.082(.998)	-1.342(0.16)***	0.26(.000)
BE_9				1.66(2.048)***	5.27(.000)			1.972(0.27)***	7.18(.000)
BE_{10}				-0.235(02.54)***	0.79(.000)	0.166(0.501)	1.18(.740)	1.183(0.14)***	3.26(.000)
BE_{11}				0.536(1.77)***	1.71(.000)	5.29(0.72)***	200.21(.000)	1.154(0.15)***	3.17(.000)
BE_{12}				2.079(1.85)***	7.99(.000)			4.092(0.33)***	59.88(.000)
BE_{14}				0.17(2.108)	1.18(.936)				
Farm size		-0.114(0.138)	0.89(.409)	0.186(0.215)	1.204(.387)	2.52(0.77)***	12.44(.001)	-0.453(0.16)***	0.63(.005)
Number of parcels		0.01(0.111)	1.01(.929)	-0.149(0.053)***	0.86(.005)	-1.79(0.313)***	0.167(.000)	-0.076(.027)***	0.92(.005)
LUC		-1.59(0.76)**	0.203(.036)	0.147(52.61)	1.15(.992)	-3.93 (1.329)**	0.02(.049)	0.531(0.17)***	1.7(.003)
Multi-cropping						1.96(0.904)**	0.14(.030)		
AEZ	***(p-value)***		(.000)***		(.000)***		(.992)		(.000)***
	AEZ1	1.45(0.498)***	4.26(.004)					4.015(0.43)***	55.41(.000)
	AEZ2	1.18(.431)***	3.27(.006)					1.022(0.47)**	2.78(.030)
	AEZ3	1.27(.501)**	3.57(.011)						
	AEZ4	0.97(0.46)**	2.64(.034)						
	AEZ5	0.051(0.44)	1.05(.909)	-0.807(0.47)*	0.446(.089)				
	AEZ6	1.14(0.42)***	3.13(.007)					3.114(0.36)***	22.5(.000)
	AEZ7	-0.187(0.43)	0.83(.661)					4.318(0.67)***	75.02(.000)
	AEZ8	1.094(0.45)**	2.98(.015)						
	AEZ9	0.53(0.39)	1.69(.185)						
	AEZ10	1.25(0.41)***	3.51(.002)	1.25(0.41)***	3.51(.001)			1.746(0.53)***	5.73(.001)
	AEZ11	0.198(0.36)	1.22(.585)					-0.995(0.41)**	0.37(.017)
	AEZ12	1.25(0.41)***	3.51(.002)					0.746(0.53)***	5.73(.001)

Site	***(p-value)***		(.000) ***		(.009)***		(.849)		(.000) ***
	Site1	-0.383 (0.47)***	0.68(.002)					-0.58(0.49)***	.56(.000)
	Site2	0.555(0.395)***	1.74(.005)						
	Site3	1.8(1.25)***	6.07(.004)					3.22(0.56)***	25.05(.000)
	Site4	2.69(0.8)***	14.79(.000)						
	Site5	0.029(0.45)***	1.03(.000)						
	Site 6	3.16(0.64)***	23.6(.001)					2.079(0.47)***	7.99(.000)
	Site7	0.33(0.47)***	1.39(.000)					2.17(0.47)***	8.8(.000)
	Site8	1.13(0.55)**	3.11(.039)						
	Site9	1.667(0.53)***	5.29(.000)	-3.64(0.973)***	0.026(.000)			2.506(0.86)***	12.25(.004)
	Site10	1.94(0.64)***	7.01(.002)					3.023(0.99)***	20.55(.002)
	Site11	-0.26 (0.55)***	0.77(.000)					-2.55(0.45)***	0.08(.000)
	Site12	1.13(0.66)***	3.12(.001)					4.49(0.87)***	89.19(.000)
	Site13	0.826(0.55)***	2.28(.000)						
	Site14	0.438(0.37)***	1.55(.001)					2.65(0.95)***	14.18(.000)
	Site15	0.49(0.39)**	1.64(.002)					-0.33(1.21)***	0.06(.005)
	Site16	1.134(0.55)**	3.11(.039)					2.83(0.96)***	1.39(.000)
	Site17	-0.428(0.514)***	0.405(.000)					-1.57(0.63)**	0.21(.013)
	Site18	0.5(0.707)***	1.65(.002)					-1.35(0.45)***	0.26(.003)
	Site19	0.97(0.94)***	2.64(.000)						
	Site20	1.18(0.39)***	3.26(.000)					1.45(0.57)**	4.27(.011)
	Site21	1.39(1.05)***	4.03(.001)	2.77(0.567)***	16.03(.000)			1.38(1.5)***	4(.000)
	Site22	0.756(0.62)***	2.13(.001)						
	Site23	1.183(0.39)***	3.26(.002)					4.038(0.36)***	56.74(.000)
	Site24	0.33(0.473)***	1.39(.001)						
Constant		-65.02(4.001)***	(.000)	-16.65(0.942)***	(.000)	36.19(1.41)***	(.000)	26.85(1.35)***	(.000)
N	***Problematic***	433		165		211		91	
	Beneficial	6		239		276		269	
	Problematic & Beneficial	18		83				127	
	Total	487		487		487		487	
Nagelkerke Pseudo R^2		0.996		0.948		0.982		0.993	
X^2(df), p-value		376.97(34)	(.000)***	846.47(100)	(.000)***	642.03 (39)	(.000)***	945.45(88)	(.000) ***
Pearson X^2 (p-value)		0.001 (1)		150.77(1)		31.361 (1)		10.858 (1)	

Notes: *, **, *** denote the significance levels at 0.1, 0.05 and 0.01 respectively. ***β*** stands for regression coefficients in terms of **log odds** and ***OR*** for Odds ratios or Exp(B). Values in parentheses denote the **standard errors** and ***p***-values respectively. **Problematic (1)**, **Beneficial (2)**, **Both problematic and beneficial (3 and reference category)** indicate the outcome categories. **PE1-16** denotes the perceived problematic or negative fragmentation effects while **BE1-18** indicates the perceived beneficial or positive fragmentation effects at the farm level. **Model 1**: Small farms (tenure and landscape fragmentation) and multi-cropping (Use fragmentation). **Model 2**: Small farms with small scattered and irregularly shaped parcels (tenure-internal-dispersion-landscape and shape fragmentation); **Model 3**: Small farms with contiguous and irregularly shaped parcels (tenure-internal-landscape and shape fragmentation); **Model 4**: Big internally fragmented farms with large scattered and irregularly shaped parcels (internal-dispersion and shape fragmentation). ***Source*****:** Field survey primary data analysis

As reported in Table 9, all the four multinomial logistic regression analysis models were statistically significant, [X^2(34, N=487) = 376.97, p < .001], [X^2(100, N=487) = 846.47, p < .001], [X^2(39, N=487) = 642.03, p < .001], [X^2(88, N=487) = 945.45, p < .001]. This indicates that the perceived fragmentation effects and other external factors significantly and accurately predicted the categorisation of farmland fragmentation scenarios into three categories (Beneficial, Problematic, Problematic-Beneficial) compared to the intercept-only models by farmers. These factors explain 99.6%, 94.8%, 98.2% and 99.3% of the changes in farmland fragmentation scenarios categorisation (Nagelkerke *Pseudo* R^2 =0.996, 0.948, 0.982 and 0.993) for Models 1, 2, 3 and 4 respectively. The Pearson Chi-square of the goodness- of-fit tests in all models were not statistically significant ($p=1$ in all four scenarios), indicating the good fit of these models to the data. The reference category to which the other two categories were compared was the third category (Problematic-Beneficial) in models 1,2 and 4, and problematic in model 3 that did not have the third category from the farmers' perceptions.

From the model 1, the results indicate that the likelihood of tenure-landscape-use fragmentation scenario 1 for being categorised by farmers as problematic was statistically significantly associated with its consideration by farmers as a barrier to the economies of scale, farm efficiency and income, climate change and natural shocks risk management, professional or market-oriented farming and household development (PE_5) [β_5 = 5.58, OR=266, p<.001], egalitarian-based land distribution among heirs through inheritance (insufficient farm to the heirs) which results in land ownership related conflicts and the risks of landlessness (PE_{15}) [β_{15}= 0.987, OR=2.68, p<.001], and parcel fallow and crops rotation leading to costly intensive cultivation/overuse of farmland which reduces soil fertility status and increases its degradation (P_{12}) [β_{12}=-0.63,OR= 0.53 p<.001]. Furthermore, this likelihood was statistically significantly associated with the perception of this scenario as the driver of household food and nutrition insecurity through increase in food security uncertainty and hunger (low food quantity, diversity, quality, accessibility and sustainability) and risks of losing the whole crops production in case of extreme weather and natural shocks (PE_7) [β_7= 2.59,OR=13.45, p<.001], and low farm income leading to permanent poverty and risks of multi-cropping for food security (diversity and sustainability) and leaving the farming sector with struggles for finding additional on-farm or off-farm employment for survival (PE_{11}) [β_{11}= 6.73, OR= 842, p<.001]. Similarly, the membership or participation of the farm in LUC program [β_{LUC}= -1.59, OR=0.203, p=.036], the AEZ [p<.001], and the study site location of the farm [p<.001] were also found as statistically significant predictors of this model. This means that holding all other factors constant, the scenario of small farms growing multiple crops is 266, 2.68, 842, and 13.45 times more likely to be considered as problematic than problematic-beneficial under the conditions of its perception by farmers as a barrier to PE_5, PE_{15}, and driver of PE_7 and PE_{11} respectively. Similarly, this scenario is 0. 53 and 0.203 times less likely to be perceived as problematic than problematic-beneficial in case of PE_{12} and the participation of the farmer in monoculture based LUC program as a barrier to crop diversification in different LUC sites with heterogeneous agro-ecological conditions for production risk management, climate change adaption and household food security motives, respectively. This fragmentation scenario in model 1 was statistically significantly more likely to be perceived as problematic in the majority of the study sites, except in Gacyamo [β_{site1}= -0.383, OR=0.68, p=.002], Uwamataba [β_{site11}= -0.26, OR=0.77, p<.001] and

Benishyaka [β_{site17}= -0.428, *OR*=0.405, *p*<.001] where it was less likely perceived as problematic but more as problematic-beneficial. This final relationship model is specified in the following **Equation 10a**:

$$Log\left[\frac{number\ of\ small\ farms\ with\ \ multi-cropping\ as\ Problematic}{number\ of\ small\ farms\ with\ multi-cropping\ as\ Problematic}\right] = -65.02 + 5.58PE_5 + 2.59PE_7 + 6.73PE_{11} - 0.63PE_{12} + 0.987PE_{15} - 1.59P_{LUC} - 0.38Gacyamo + 0.55Musebeya + 1.8Gitambi + 2.69Gatare + 0.029Bitsibo + 3.16Karehe + 0.33Umuyange + 1.13Gasare + 1.66Karambi + 1.94Kivuruga - 0.26Uwamataba + 1.13Karenge + 0.82RuhingaII + 0.43Myatano + 0.49Ndinda + 1.13Rwanyamigono - 0.42Benishyaka + 0.5Gisanze + 0.97Nyamaraba + 1.18Kamina + 1.39Karungu + 0.75Rwatano + 1.18Gataraga + 0.33Gisura \quad \textbf{(10a)}$$

The likelihood of the tenure-internal-dispersion-landscape-shape fragmentation scenario in model 2 for becoming more problematic than problematic-beneficial was statistically significantly associated with its perception by farmers as a barrier to agricultural mechanisation through irregular shapes, small parcel and plot sizes, boundaries and absentee owners (PE_2) [β_2= 1.056, *OR*=2.87, *p*=.002], and PE_5 [β_5= 2.94, *OR*=18.87, *p*=.001]; and the driver (factor) of high farm (agriculture) production costs (travel costs and labour supervision costs) and low farm income (PE_1) [β_1= 3.64, *OR*=37.96, *p*<.001], farmland boundaries related conflicts (PE_3) [β_3= 1.69, *OR*=5.45, *p*=.011], and PE_7 [β_7= 1.68, *OR*=5.38, *p*<.001]. The likelihood of this scenario for being considered more beneficial than problematic-beneficial was significantly associated with its perception by farmers as a driver (factor) of agriculture production diversification and exploitation of soil agro-ecological diversity through suitability-based crop diversification as production risks management and food security achievement strategy (BE_1) [β_1= 6.05, *OR*=424.4, *p*<.001], household food independence/sovereignty and security in forms of accessibility, diversity and sustainability (BE_3) [β_3= 1.04, *OR*=2.83, *p*<.001], climate change adaptation strategy (BE_9) [β_9= 1.66, *OR*=5.27, *p*<.001], erosion control, fallow and crop rotation for soil fertility management (BE_{11}) [β_{11}= 0.536, *OR*=1.71, *p*<.001], exploitation of multiple/diverse agro-ecological zones and all agriculture seasons (BE_{12}) [β_{12}= 2.079, *OR*=2.99, *p*<.001]; and the conditions of high costs of defragmentation like in highlands (BE_5) [β_5= 0.365, *OR*=1.44, *p*=.011].

In contrast, under the conditions of the consideration of this scenario as a factor of wastage/loss of land through boundaries and related conflicts (PE_6) [β_6= -0.86, *OR*=0.424, *p*=.007], an obstacle to timely farming and labour management through very tiring and time consuming farming activities leading to lease-out and the abandonment of distant parcels (PE_9) [β_9=-2.13, *OR*=0.119, *p*=.045], increase in the number of parcels per farm [β_{NP}= -0.149, *OR*=0.86, *p*=.005], factor or strategy of farmland ownership and use related conflicts management (BE_7) [β_7= -0.18, *OR*=0.83, *p*=.017], and agrobiodiversity conservation (BE_{10}) [β_{10}= -0.235, *OR*=0.79, *p*<.001], it was 0.424, 0.119 and 0.86 times less likely to be perceived as problematic than problematic-beneficial, and 0.83 and 0.79 times less likely beneficial than problematic-beneficial, rather the opposite respectively. The research sites and AEZs variables were also statistically significantly associated with the categorisation (*p*<.001 in both cases), indicating that the location of the farm determined the perceived choice of the category. This scenario was statistically significantly 0. 026 times less likely to be considered problematic in Karambi [β_{site9}= -3.64, *OR*=0.026, *p*<.001] in Congo Nile

Divide Watershed AEZ5 [β_{AEZ5}= -0.807, *OR*=0.446, *p*=.089] and 16.03 times more likely to be problematic in Karungu [β_{site21}= 2.77, *OR*=16.03, *p*<.001] in Kivu lakeside AEZ10 [β_{AEZ10}= 1.25, *OR*=3.51, *p*=.001]. The farm size, participation in LUC program and the parcel level multi-cropping system fell short of statistical significance and, therefore, not statistically significant determinants of the categorisation of this scenario (*p*>.1). This final relationship model is expressed in the following **Equations 10b$_{1\&2}$:**

$$Log\left[\frac{number\ of\ small\ farms\ with\ \ small\ scattered\ irregularly\ shaped\ parcels\ as\ Beneficial}{number\ of\ small\ farms\ with\ \ small\ scattered\ irregularly\ shaped\ parcels\ as\ Beneficial}\right] = -16.65 + 6.05BE_1 + 1.04BE_3 + 0.365BE_5 + 1.66BE_9 + 0.536BE_{11} + 2.079BE_{12} - 0.18BE_7 - 0.235BE_{10} \quad \textbf{(10b}_1\textbf{)}$$

$$Log\left[\frac{number\ of\ small\ farms\ with\ \ small\ scattered\ irregularly\ shaped\ parcels\ as\ problematic}{number\ of\ small\ farms\ with\ \ small\ scattered\ irregularly\ shaped\ parcels\ as\ Problematic}\right] = 19.23 + 3.64PE_1 + 1.05PE_2 + 1.69PE_3 + 2.94PE_5 - 0.86PE_6 + 1.68PE_7 - 2.13PE_9 - 0.149P_{NP} - 3.64Karambi + 2.77Karungu \quad \textbf{(10b}_2\textbf{)}$$

The tenure-internal-landscape-shape fragmentation scenario in model 3 mainly indicated by farms with small contiguous parcels was significantly more likely to be perceived as beneficial than problematic under the conditions of its consideration by farmers as a factor of crop intensification and diversification, agriculture production and market diversification for household food security and income increase, climate change adaptation, and food production and market imperfections risks management (BE_2) [β_2= 2.89, *OR*=18.15, *p*<.001], facilitation of agricultural mechanisation due to the contiguity of irregularly shaped small plots and parcels, boundaries and absentee owners (PE_2) [β_2= 2.44, *OR*=11.52, *p*<.001], facilitation of BE_{11} [β_{11}= 5.29, *OR*=200.21, *p*<.001], BE_5 [β_5= 2.78, *OR*=16.13, *p*<.001], bigger farm sizes [$\beta_{farm\ size}$= 2.52, *OR*=12.44, *p*<.001], and parcel level multi-cropping system in the farm [$\beta_{multi\text{-}culture}$= 1.96,*OR*=0.14, *p*=.030]. On the other hand, this likelihood significantly decreased where farmers perceived this scenario 3 as a barrier to PE_5 [β_5= -3.114, *OR*=0.044, *p*<.001] and PE_6 [β_6= -4.57, *OR*=0.01, *p*<.001]; membership of the farm in LUC program [β_{LUC}= -3.93, *OR=0*.02, *p*=.049]; and in conditions of the increase in the number of parcels per farm [β_{NP}= -1.79, *OR*=0.167, *p*<.001], and therefore considered as problematic. Neither of the AEZs and the research sites were significant determents in this model (*p*>.1). This final relationship model is specified in the following **Equation 10c:**

$$Log\left[\frac{number\ of\ small\ farms\ with\ \ small\ scattered\ irregularly\ shaped\ parcels\ as\ Beneficial}{number\ of\ small\ farms\ with\ \ small\ scattered\ irregularly\ shaped\ parcels\ as\ Beneficial}\right] = 36.19 + 2.89BE_2 + 2.78BE_5 + 1.66BE_9 + 5.29BE_{11} + 2.44PE_2 - 3.114PE_5 - 4.57PE_6 + 2.52B_{farm\ size} + 1.96B_{multi-culture} - 3.93B_{LUC} - 1.79B_{NP} \quad \textbf{(10c)}$$

The likelihood of internal-dispersion and shape fragmentation scenario in model 4 indicated by big internally fragmented farms with large scattered and irregularly shaped parcels for being considered more beneficial than problematic-beneficial was significantly associated with its perception by farmers as a factor of the increase in farm income, household food and nutrition security (diversity, quantity, sustainability, availability, acceptability and sovereignty) and market satisfaction from the surplus (BE_4)

[β_4= 0.802, *OR*=2.23, *p*<.001], exploitation of multiple/diverse agro-ecological zones and all agriculture seasons (BE_{12}) [β_{12}= 4.09, *OR*=59.88, *p*<.001], BE_1 [β_1= 5.41, *OR*=223.8, *p*=.017], BE_9 [β_9= 1.972, *OR*=7.18, *p*<.001], BE_{10} [β_{10}= 1.183, *OR*=3.26, *p*<.001], BE_{11} [β_{11}= 1.154, *OR*=3.17, *p*<.001]; and under the situations of BE_5 [β_5= 1.29, *OR*=3.63, *p*<.001] and membership or participation of the farm in LUC program [β_{luc}= 0.531, *OR*=1.7, *p*<.001]. On the other hand, its likelihood of perception as problematic than problematic-beneficial was significantly associated with increase in its perception as a factor of PE_1 [β_1= 3.92, *OR*=50.38, *p*<.001] and PE_2 [β_2= 2.61, *OR*=13.68, *p*<.001]. In the situations of the consideration of this scenario as a factor of PE_6 [β_6= -0.996, *OR*=0.37, *p*=.007] and PE_9 [β_9=-1.407, *OR*=0.24, *p*=.025], the increase in farm size [$\beta_{farm\ size}$= -0.453, *OR*=0.63, *p*=.005] and the number of parcels per farm [β_{NP}= -0.076, *OR*=0.92, *p*=.005], it was 0.37, 0.24, 0.63 and 0.92 times less likely to be perceived as problematic than problematic-beneficial. Where perceived as a factor of BE_2 [β_2= -0.413, *OR*=0.66, *p*=.005] and strategy for labour and production risks management in agriculture through farm employment (BE_8) [β_8= -1.34, *OR*=0.26, *p*<.001], it was 0.66 and 0.26 times less likely beneficial than problematic-beneficial, hence categorised as both problematic and beneficial.

Both the AEZ and research site spatial locations were statistically significant predictors of the categorisation in this model 4 (*p*<.001). This fragmentation scenario would be statistically significantly more likely perceived as beneficial in Gitambi [β_{site3}= 3.22, *OR*=25.05, *p<.001*], Karehe [β_{site6}= 2.07, *OR*=7.99, *p<.001*], Umuyange [β_{site7}= 2.17, *OR*=8.8, *p<.001*], Karambi [β_{site9}= 2.5, *OR*=12.25, *p<.001*], Kivuruga [β_{site10}= 3.02, *OR*=20.55, *p<.001*], Karenge [β_{site12}= 4.49, *OR*=89.19, *p<.001*], Myatano [β_{site14}= 2.65, *OR*=14.18, *p<.001*], Rwanyamigono [β_{site16}= 2.83, *OR*=1.39, *p<.001*], Kamina [β_{site20}= 1.45, *OR*=4.27, *p=.011*], and Karungu [β_{site21}= 1.38, *OR*=4, *p<.001*], problematic in Gataraga [β_{site23}= 4.03, *OR*=56.74, *p*<.001], and problematic-beneficial in Gacyamo [β_{site1}= -0.58, *OR*=0.56, *p<.001*], Uwamataba [β_{site11}= -2.55, *OR*=0.08, *p*<.001], Ndinda [β_{site15}= -0.33, *OR*=0.06, *p<.001*], Benishyaka[β_{site17}= -1.57, *OR*=0.12, *p=.013*] and Gisanze [β_{site18}= -1.35, *OR*=0.26, *p<.001*]. This final relationship model is expressed in the following **Equations 10d$_{1\&2}$**:

$$\boldsymbol{Log}\left[\frac{\textbf{number of big farms with large scattered irregularly shaped parcels as Beneficial}}{\textbf{number of big farms with large scattered irregularly shaped parcels as Beneficial}}\right] = -1.316 + 5.41BE_1 - 0.413BE_2 + 0.802BE_4 + 1.29BE_5 - 1.34BE_8 + 1.942BE_9 + 1.183BE_{10} + 1.154BE_{11} + 4.09BE_{12} + 0.531B_{luc} - 0.58Gacyamo + 3.22Gitambi + 2.079Karehe + 2.17Umuyange + 2.506Karambi + 3.023Kivuruga - 2.55Uwamataba + 4.49Karenge + 2.65Myatano - 0.33Ndinda + 2.83Rwanyamigono - 1.57Benishyaka - 1.35Gisanze + 1.45Kamina + 1.38Karungu \quad \textbf{(10d}_1\textbf{)}$$

$$\boldsymbol{Log}\left[\frac{\textbf{number of big farms with large scattered irregularly shaped parcels as Problematic}}{\textbf{number of big farms with large scattered irregularly shaped parcels as Problematic}}\right] = 26.85 + 3.92PE_1 + 2.61PE_2 - 0.996PE_6 - 1.407PE_9 - 0.453P_{farm\ size} - 0.076P_{NP} + 4.038Gataraga \quad \textbf{(10d}_2\textbf{)}$$

These findings confirm the fifth research hypothesis (H_{A5}) and support the theoretical farmland fragmentation scenarios-causal-effects relationships of Ntihinyurwa and de Vries [3] and the findings of various research scholars on this topic as discussed in the introductory and theoretical sections of this study. These results are also similar to the ones from the majority of previous research scholars that reported the aspect of small farms and parcel sizes as the main problematic side of farmland tenure and landscape fragmentation scenarios. These scholars linked the aspect of small farm and parcel sizes with the obstacle to economies of scale, farm and agriculture production efficiency, parcel fallow and crop rotation, the factor of the waste of productive arable land through boundaries, farmland boundaries related conflicts, and household food and nutrition insecurity in subsistence economies and farmland scarcity conditions in many Sub-Sahara African countries [3, 10, 64, 68, 72, 78-85, 101, 168, 169]. Similarly, they reported the aspect of distance from internal-location and dispersion fragmentation scenarios as problematic for its linkage with the increase in agriculture production costs [3, 10, 64, 68, 72, 78-85, 101, 168, 169].

In the conditions of subsistence or semi-subsistence economies characterised by farmland and capital scarcity, high farmland population density, subsistence agriculture, failed economic incentives, imperfect market (for labour, agricultural inputs and food), higher social land value than its economic one, the absence of risks management strategies and off-farm employment opportunities, abundant farm labour (high farming population density), and heterogeneous socio-spatial and agro-ecological conditions, farmers generally choose to have their own small farms made of small heterogeneous contiguous farmland parcels and plots or scattered in different locations [3, 4, 32]. This preference is often for the motives of individual farmland tenure security (ownership and use), land ownership and use-related conflicts management, labour use and weather shocks management, and self-sufficiency or independence in the production of diversified food basket to meet the nutritional requirements and food preferences as the cheapest strategy to meet the household food security [3, 4, 32]. This is exactly the situation found in the case of Rwanda in this study, which was recently found by some other empirical studies in sub-Saharan Africa, such as Rao [98] and Kadigi *et al.* [90] in Tanzaniza, Ndip et al. [99] in Cameroun, Knippenberg *et al.* [91] and Cholo *et al*. [86] in Ethiopia. Despite its adverse effects on farm efficiency and income, farmland tenure fragmentation in these conditions is therefore considered a source of employment for household members and a positive factor of agricultural production and perceived farmland tenure security [3, 16], as confirmed by the patterns from key informants interviews and focus groups discussion sessions.

In some parts of the country where farmland is relatively abundant and heterogeneous, land scarcity is less problematic, and production risk management strategies are absent or limited, farmers prefer to have parcels of all grades and classes often scattered in different agro-ecological micro-zones and all agriculture seasons. This was justified as their rational choice for exploitation of diverse crop growing conditions and farmland production potentials, crop diversification and rotation, climate change adaptation, soil fertility management, agrobiodiversity conservation, crop production and prices risks management and multidimensional household food and nutrition sovereignty and security under internal-dispersion and use fragmentation scenario, which is consistent with the literature claim on the positive

aspect of farmland fragmentation [3, 16, 32, 64, 86-92, 95, 96, 98, 111, 145]. The popular argument stipulating the ability of small internally fragmented farms with scattered parcels to mitigate the adverse effects of farmland fragmentation by reducing the labour costs, including the supervision and employment costs through high labour use intensity and high labour per land ratio under imperfect labour market conditions [3, 111, 148, 149] is therefore supported by the findings of this study. Similarly, these farms were found to buffer or compensate for the adverse effects of the small size aspect of small farms in terms of crop production diversification for household food sovereignty and security motives.

Furthermore, the participation in the LUC program in heterogeneous and climate change-vulnerable areas was found problematic for small subsistence and poor farmers with small single contiguous or scattered parcels in the same LUC micro-agro-ecological zone since they do not have similar alternatives as big farmers for farm expansion in other LUC sites with different priority crops for risks management, household food security and farm income increase. In this situation, small farmers often opt for hidden multi-cropping (parcel-level use fragmentation) to compensate for the benefits of crop diversification lost through a monoculture-based LUC program. This finding supports similar previous findings from various studies on LUC which reported it to be more performant in marchlands and lowlands than in highlands and profitable for big farmers with many scattered parcels at the expense of small farmers, and the outperformance of the benefits of improved intercropping system over the ones from LUC based mono-cropping system in terms of household food security and risks management insurance mainly due to the market imperfections [28, 31, 37, 44, 48, 52]. These studies strictly recommended the support of mixed farming systems or the conservation of beneficial farmland fragmentation scenarios as a promising solution for agricultural production and household food security concerns [28, 31, 37, 44, 48, 52]. This is in line with the wish of the majority of farmers, who prefer the option of operating big farms with big or small scattered parcels in different agro-ecological micro-zones. As explained by key informants and supported by the literature, under such circumstances and where the Rwandan Government recently introduced agriculture insurance schemes for some priority food crops like maize, Irish potatoes, wheat, rice and pepper, and other legumes to support and complement the controversial LUC program, farmers and agriculture policymakers seek to maximise the returns through scarce factors (land and capital) rather than abundant factors (labour), by improving farming technologies through land saving strategies such as agricultural insurance, high yielding crops varieties and different agriculture intensification programs to increase the farm efficiency and meet the food needs of the growing population [3, 111, 146, 147]. In contrast, the claim supporting the theory of diseconomies of scale which stipulates a negative relationship between farm size and farm output, and the competitiveness of small farms over big ones [3, 11, 12, 16, 51, 52, 148, 149] is however not supported in this case study as it fell short of enough and robust scientific evidence to prove it from the used data. This needs rigorous comparative studies of the performance of small-scale and big farms in terms of socio-economic, spatial and agro-ecological aspects.

Simply put, these findings indicate a paradoxical coexistence of problematic farmland tenure and landscape fragmentation as a barrier to farm efficiency, income, economies of scale, farmland loss through boundaries and land-related conflicts and household food insecurity, and beneficial physical

(internal, use, dispersion and location) and tenure fragmentation for the motives of individual farmland tenure security (ownership and use), land ownership and use related conflicts management, labour use and weather shocks management, and self-sufficiency or independency in production of diversified food basket to meet the nutritional requirements and food preferences (food sovereignty) as the cheapest strategy to meet the household food security [3, 4, 32]. Therefore, under the existing agro ecological, socio-spatial, demographic, and economic conditions of the country, in the absence of farmland expansion options within the fixed national administrative boundaries due to its scarcity, the government of Rwanda should consider this paradoxical (beneficial and problematical) diversity of fragmentation scenarios (physical and tenure) in its various agriculture development strategies and policy interventions. This would support its transformation from subsistence farms towards commercial ones by prioritising agriculture intensification programs and farmland-saving technologies on small internally fragmented farms in agro-ecologically heterogeneous areas and creating more off-farm employment opportunities in relatively homogeneous agro-ecological conditions to reduce the number of small inefficient farms and facilitate their consolidation into big efficient farms through farmland banking programs, rather than focussing on farmland expansion and scale economies through generalised consolidation programs. Furthermore, this could support the government to meet its long-term economic transformation plans from a subsistence economy towards a middle-income economy by 2035 and a high-income economy by 2050 in the Vision 2050, the Sustainable Development Goals (SDGs 1, 2, 12, 13 and 15) in the UN agenda 2030 [170] reflected in its short term strategies and plans like the First National Strategy for Transformation with the main targets and goals of boosting the national agriculture production to meet the food demands of the ever-increasing population (NST1 2018–2024) [6, 21, 23, 28, 39, 41, 109].

Moreover, besides the enforcement of already introduced agriculture insurance schemes and farmland banking interventions, multi-cropping based cooperative farming and voluntary parcel exchange and kitchen gardens, the promotion of the growth of diversified high value, yielding and climate change resistant crop varieties, and farmland market legal enforcement (formalisation) to prevent informal farmland transaction and speculation and facilitate farmland leasing and voluntary farmland consolidation programs stipulated by the National Agriculture Policy (NAP 2017-2030) [21] through Strategic Plan for Agricultural Transformation (PSTA4 2018–2024), and the protection of potential agricultural land stipulated by the National Land Use and Development Master Plan (NLUDMP 2020-2050) [23] and National Land Policy [22], there is a need for improvement of the suitability of marginal lands for farming exploitation, enforcement and legalisation of the family planning programs, promotion of climate-smart and resilient agriculture practices, and the options of leasing and buying farmland in neighbouring countries for farm expansion. This would provide sustainable alternative solutions for farmland fragmentation management and overcome the above-discussed LUC program weaknesses. If no serious actions are undertaken, the growing pressure on farmland for food and energy production, human settlements and shelter, and biodiversity conservation purposes for climate change adaptation will continue to worsen its scarcity issues and limit the potential for reducing tenure fragmentation aspect, thereby hindering the achievement of the governmental long term goals and targets for food demands and preferences of the growing population, household food and nutrition security [6, 23, 32, 41, 53], and keeping the poverty level of the country among the highest in the world [29].

2. 5. Conclusions and Recommendations

Drawing from the theoretical socio-spatial, economic, physical and agro-ecological diversity of 12 agro-ecological zones of Rwanda, this study adopted a mixed methods research approach to empirically test the theoretical farmland fragmentation scenarios of Ntihinyurwa and de Vries [64] and Ntihinyurwa and de Vries [3], and extend the studies of Blarel *et al*. [16] and Ntihinyurwa *et.al*. [32] which hypothetically stipulate the diversity and the coexistence of both tenure and physical beneficial and problematic farmland fragmentation scenarios in the Rwandan context. The main aim was a comprehensive analysis of all possible socio-physical farmland fragmentation forms and their causal-effects relationships, as well as modelling the scenario predictors from household-level surveys and cadastral datasets as pioneering country-level research in this domain. The findings of this study are fivefold and support most of the study hypotheses:

First, the study data ANOVA, T-tests and Pearson Chi-Square Contingency Table (Crosstabs) analyses identified a typology of seventeen farmland fragmentation scenarios grouped into five distinct classes across the 24 research sites from 12 AEZs, which confirms the significant spatial and topographical diversity of farmland fragmentation forms, extent and scenarios in Rwanda stipulated by the first research hypothesis (H_{A1}). ***Second***, through these analyses, the coexistence of both physical and tenure, problematic and beneficial farmland fragmentation forms at different degrees under different scenarios and socio-spatial analysis levels was found in various research sites and AEZs, which confirms the second research hypothesis (H_{A2}) and the theoretical findings of Ntihinyurwa and de Vries [3, 64]. The pooled values indicate the general trends of very high to excessive levels of landscape, high to extensive levels of tenure (in terms of ownership), high level of shape, moderate levels of internal, dispersion (scattering), use and usership, and low level of location (distance) fragmentation forms at statistically significant degrees across research sites and AEZs. This diversity of fragmentation scenarios was explained by the drastic diversity in socio-economic, spatial, demographic, and agro-ecological factors like land quality and quantity, topography or relief (altitude and slope), parent materials (soil type and quality), and temperature and rainfall patterns over short distances behind the variations in farming systems among various regions, which stipulates the existence of many more diverse micro agro-ecological and socio-economic zones than the currently documented ones.

Third, the correlation analyses identified and confirmed a significant but weak negative relationship between tenure fragmentation and internal and farm-level use fragmentation forms and a positive relationship between tenure and parcel-level use fragmentation (multiculture), but statistically rejected the positive relationship between tenure and dispersion fragmentation stipulated by the third research hypothesis (H_{A3}). It was found that small farms tend to be less internally fragmented and scattered, and farmers, in this case, choose to grow many crops on the same parcel and vice versa in the case of big farms for crops and food diversification, household food sovereignty and security, and production risk management purposes. The same analyses identified and confirmed a significant positive relationship between internal and farmland use and parcel topographical dispersion fragmentation forms at the farm and farmland block levels, but rejected a statistically significant negative relationship between internal and parcel level farmland use fragmentation forms claimed by the fourth research hypothesis (H_{A4}).

Moreover, a Duncan post hoc comparison analysis of homogeneity of groups identified a statistically significant negative relationship between landscape fragmentation and parcel topographical location as parcel size was found to increase with slope and vice versa mainly due to the farming structure in wetlands characterised by small pieces of parcels to allow the passage of waterways for irrigation and drainage purposes. However, the comparative findings about the farm, holding and parcel sizes across research sites and AEZs indicated a positive relationship between tenure and landscape fragmentation with topography (altitude) since large farm, holding and parcel sizes were found in lowlands of the eastern province and small ones in highlands of the northern and western provinces which reject the first null hypothesis (H_{01}) of this study.

Fourth, the Pearson Chi-Square Contingency Table (Crosstabs) analyses and Multinomial logistic regression analyses did not find enough evidence to confirm the superiority of negative impacts of farmland fragmentation over the positive ones in the study area, thereby failing to reject the first part of the second null hypothesis (H_{02}) and confirming the empirical findings of Ntihinyurwa *et al.* [32] and Blarel *et al*. [16] that reject the broad perception of farmland fragmentation inefficiency and problematic connotation *per se* in Rwanda. However, these analyses found a statistically significant association between research sites (location) and perceived farmland fragmentation categorization decision, indicating differences in categories and their predictors across various research sites and local conditions, which rejects the second part of the second null hypothesis (H_{02}) of this research in the study area.

Fifth, the multilinear and multi-logistic regression analyses revealed that a combination of various semi-subsistence socio-spatial, natural physical, and politico-economic conditions of the country indicated by farmland and capital scarcity, high farmland population density, subsistence agriculture, failed economic incentives, free but uncertain or imperfect market (for land, agricultural inputs and food), higher social land value than its economic one, climate change vulnerability, limited risks management strategies and off-farm employment opportunities, abundant farm labour, heterogeneous socio-spatial and agro-ecological aspects, presence of farmland subdivision and partible inheritance restrictions and policies, land reforms and sharing programs, participation in LUC program, individual farmland tenure aspect and egalitarian based principles in partible inheritance and land distribution system were statistically significantly linked with a coexistence of both beneficial and problematic farmland tenure-landscape-internal-dispersion-use and shape fragmentation predominant scenario in the country. This scenario was found as farmers choice and/or external imposition by these factors for individual perceived farmland tenure security (ownership and use), land ownership and use related conflicts management, labour use and weather shocks management, farm employment for household members, crops diversification and rotation, crops production and prices risks management, farm expansion and income increase, exploitation of all multiple agro-ecological zones and all three agricultural seasons, agrobiodiversity conservation and climate change adaptation, soil fertility management, erosion control and self-sufficiency or independency in production of diversified food basket to meet the nutritional requirements and food preferences (food sovereignty) as the cheapest strategy to achieve the household multidimensional food security, despite its statistically significant adverse effects on farm efficiency and income, economies of scale, farmland loss through boundaries (approximately 2.76% on average), crops

rotation and fallow, and factor of land related conflicts and household food insecurity. This finding is consistent with and confirms the part of stipulations of the fifth research hypothesis (H_{A5}) and the theoretical farmland fragmentation scenarios of Ntihinyurwa and de Vries [3].

However, the distance aspect considered as a critical determinant of the classification of internal-location and dispersion fragmentation scenario as problematic for its linkage with farm production costs and justification for land consolidation programs was not a statistically significant factor since most parcels of the same farm were found to be located in the same topographical location within a radius of less than 1 km except in Gasare site. In some specific areas of the country, like in the Eastern Province, characterised by relatively abundant and heterogeneous farmland, low levels of land scarcity and land psychology (economic farmland value> social farmland value) and absence of/or limited production risk management strategies, the historical immigration patterns, farmland market and farmland speculation aspects were also emphasised as the main factors of problematic tenure and landscape fragmentation scenarios for their linkage with farm inefficiency and household food insecurity. Similarly, these aspects were also pinpointed as factors of beneficial internal-dispersion and use fragmentation scenarios as farmers preference to have farms composed of parcels of all grades and classes often scattered in different agro-ecological micro-zones and all agriculture seasons for exploitation of diverse crops growing conditions and farmland production potentials, crops diversification and rotation, climate change adaptation, soil fertility management, agrobiodiversity conservation, crops production and prices risks management and multidimensional household food and nutrition sovereignty and security and subject for conservation. This confirms the theoretical claim of Ntihinyurwa and de Vries [3] and a part of the fifth research hypothesis (H_{A5}).

In relatively homogeneous socio-spatial and agro-ecological conditions, higher farmland population density and scarcity, absence of risk management strategies and off-farm employment, participation in LUC program, and social land attachment like in the volcanic region of the northern province of Rwanda, the predominant tenure and landscape (physical) fragmentation scenario was statistically significantly linked with adverse effects on farm efficiency and income, the economies of scale, farmland loss through boundaries, land ownership related conflicts and the risks of landlessness, household food security and poverty, crops rotation and fallow, farmland over-use and quality degradation and climate change risk management capacity, and therefore mainly perceived as problematic subject for defragmentation. Therefore, the popular argument for farmland fragmentation conservation stipulating the ability of small, internally fragmented farms with scattered parcels to mitigate the negative effects of farmland fragmentation is supported by the findings of this study. This claim argues that small internally fragmented farms reduce the labour costs (the supervision and employment costs) through high labour use intensity and high labour per land ratio under imperfect labour market conditions and buffer (compensate) the adverse effects of the small size aspect in terms of crops production diversification for household food sovereignty and security, farmland tenure security, and climate change adaptation and risks management motives. This argument also applies in situations when the costs for defragmentation outperform the ones for consolidation programs. In contrast, the literature claim supporting the theory of diseconomies of scale, which stipulates a negative relationship between farm size and farm output and the

competitiveness of small farms over big ones, is, however, not supported in this case study as it fell short of enough and robust scientific evidence to prove it from the used data.

Although this study was conducted in a relatively wide area covering all the twelve officially recognised national level agro-ecological zones of the country using a large set of comprehensive scientifically valid methods for farmland fragmentation scenarios analysis and modelling, its findings are limited to the considered 24 research sites level for which the sample was statistically representative and cannot, therefore, be generalized to the national level, considering the macro-diversity and drastic variations of socio-spatial, physical, pedological, demographic, economic, and micro-agro-ecological conditions of the country. However, they can be replicated and generalized to other areas with conditions similar to the study sites. Furthermore, although the study widely modelled the farmland fragmentation scenarios causal-effects relationships, it did not statistically assess the specific moderating effects of the research site and AEZ on the individual variables in these models, as one of the methodological limitations. Therefore, the implications of these findings to farmland management policy, practitioners, science and further research are threefold:

Firstly, the diversity of fragmentation scenarios and the paradoxical coexistence of their polarized (beneficial and problematic) effects under specific local conditions imply the diversity and the localization of their management strategies and intervention programs, which should be considered by farmland use policymakers. Therefore, in the absence of farmland expansion options due to its scarcity, off-farm employment opportunities, and dominance of social attachment to land with subsistence agriculture as the main source of food, and the ever-growing population density under subsistence economic conditions of the country, there is a need for a paradigm change in farmland management and use policies and interventions design processes. This shift should concern the reverse from the focus on market-oriented agriculture expansion on large-scale consolidated farms for scale economies towards an emphasis on policy perspective supporting small-scale farms for efficient use of scarce farmland resources like agriculture intensification and crop diversification programs and farmland saving technologies on small-scale consolidated or internally fragmented farms, strong family planning programs to cut the population growth below a certain threshold, and creation of more off-farm employment opportunities to facilitate existing localised farmland banking interventions. Furthermore, the national generalization of farmland fragmentation management strategies should be strictly avoided.

Secondly, this study provides policy guidance for farmland fragmentation management, which could support the government of Rwanda in making scientifically informed decisions towards the achievement of its sustainable development goals and targets reflected in UN-SDGs (1.4; 2.1, 2, 3, 4 and 5; 12.2; 13.1; and 15.3, 4, 5 and 9) in the framework of the agenda 2030, and the national vision 2050. This can be done by devising suitable socio-spatial sustainable farmland fragmentation management interventions tailored to specific localized fragmentation scenarios, the needs and concerns of local farmers and local conditions, and therefore narrow the gap between research and policy making in the field of farmland fragmentation management in Rwanda and other countries with quite similar conditions.

Thirdly, considering the heterogeneous local social, demographic, economic, physical and agro-ecological conditions, predominance of subsistence and rain-fed hillside agriculture, high incidence and vulnerability to climate change consequences and natural and weather shocks in the study area, and the identified diverse typology of farmland fragmentation scenarios despite the existence of farmland fragmentation combat strategies like land use consolidation and its supporting programs for food security purposes, this study questions the suitability of these strategies and interventions and inductively hypothesises their insufficiency and irrelevancy, a positive relationship between farmland fragmentation and household food security, and the unsuitability of modern government-led farmland consolidation programs for the management of the identified farmland fragmentation scenarios in the country. Thus, it recommends and underscores the need for a comprehensive critical performance and relevance analysis of these strategies and interventions with regard to farmland fragmentation and multidimensional food security nexus in the country; rigorous comparative study of the performance and competitiveness of small-scale and big farms in terms of socio-economic, spatial and agro-ecological aspects; the suitability analysis of farmland consolidation models; and the modelling of Fit-for Rwanda theoretical farmland fragmentation management strategies tailored to specific and localized fragmentation scenarios and their empirical test in the country as further research calls.

3. Concluding Remarks

3. 1. Key Findings and Implications on Land Management Scientific Domain and Policy

Being a farmland management research project, this dissertation contributes to the broad land management scientific domain in various ways by answering some unanswered research questions, providing alternative solutions to policy dilemmas on farmland size, tenure, use, shape and spatial location fragmentation management concerns, and generating new consolidated scientific knowledge on these matters. It narrows the knowledge gap in widely recognised components of land management such as land tenure and land use management, land development, land dispersion management, land quality and quantity management, land shape and boundaries management, land administration and governance, land value and economy management, land-related conflicts management, and land policy for the motives of multidimensional food security, farmland tenure security, and sustainable farmland related development Goals (SDGs 1,2, 12,13, and 15) of the UN-Agenda 2030. By explicitly generating a substantive explanation of different farmland fragmentation scenarios [64] to answer the first research question (***RQ1***), the conditions under which they become defective or beneficial [3] to answer the second research question (***RQ2***), and proposing the suitable potential strategies for their sustainable management under various specific circumstances [4] as an answer to the third research question (***RQ3***) and their empirical test in the context of Rwanda, this dissertation contributes to the existing knowledge on farmland management including its administration, policy and governance as tools of land management science.

First, contrary to the conventional insights in land fragmentation, this study posits new ontologies and epistemologies of farm and parcel as a fundamental basis for describing, measuring and controlling parcel fragmentation, farm fragmentation and farmland fragmentation. By describing fragmentation as a natural and socio-economic phenomenon that occurs at different spatial levels (parcel, farm, land block and landscape), the study suggests drawing its conceptualisation and derived forms and scenarios from the existing relationship between land parcel (object) and people (subject) in land management paradigms on the one hand, and from the naturally fragmented landscape characteristics (land quality, soil type, size, location, shape, and topography) on the other hand [64]. Since this relationship is the synonym of land tenure often defined at the parcel level, which is the basic unit of land administration, it dictates the existence of physical, social (tenure), and economic fragmentation forms at the parcel and farmland block levels as subject for various land use management interventions which capture the variety and dynamics of farmland fragmentation scenarios as suitable solutions to address local farmland fragmentation paradoxical concerns [64]. Therefore, by proposing this approach, this dissertation significantly contributes to the scientific knowledge extension in land administration and governance and informs land use policy as land management tools.

Second, the development of the relationship models between farmland fragmentation scenarios, food security and farmland tenure security extends the existing debate and knowledge about farmland fragmentation and defragmentation and multiple UN sustainable development goals and targets (SDGs 1.4; 2.1, 2, 3, 4 and 5; 12.2; 13.1; and 15.3, 4, 5 and 9) nexus, versus the global trends towards market-

oriented agriculture on either fragmented or consolidated farmland [3, 4]. Contrary to the existing popular and global logic favouring market-oriented agriculture often combined with agriculture expansion on big consolidated farms to achieve food security and reduce the problematic farm fragmentation-based inefficiency, this dissertation rejected the broad perception of farmland fragmentation inefficiency and problematic connotation *per se* in Rwanda and provides new approaches and novel knowledge about the necessity of the variety of farmland management instruments to address particular farmland fragmentation scenarios to achieve these SDGs of ending hunger, malnutrition, and poverty through sustainable agriculture production in the framework of the agenda 2030, since not all farmland fragmentation scenarios are problematic. These SDGs stipulate the equal distribution, ownership, access, security, and control of land resources among all the heirs (SDGs 1.4; 2.3), sustainable management and efficient use of natural resources including land (SDG 12.2), the diversification of crops in different fragmented and scattered areas with diverse growing conditions as an adaptive strategy (climate-smart or resilient agriculture) to the ongoing new global challenging realities of climate change (SDGs 2.4, 5; 13.1) to end hunger and malnutrition resulting from food insecurity (SDG 2.1, 2, 3, 4, 5), and the agrobiodiversity and ecosystems conservation through the protection of their natural habitats on land (SDG 15.3, 4, 5, 9) [3, 4]. Since these SDGs-specific targets capture and converge with the main sustainable land management goals of tenure security, sustainable land use and climate change adaption and mitigation, the generated knowledge shedding light on the policy decision-making process about farmland use either in fragmented or consolidated forms, therefore contributes to the improvement and facilitation of farmland policy as a tool of land management scientific domain. Moreover, this research stands among the first research projects reconciling sustainable farmland management-related development goals and sustainable farmland fragmentation management as a novel contribution to land management science.

Third, by informing and guiding the decisions of policymakers and land managers, practitioners, research scholars and the general scientific community for the devise of suitable policies and tools for the best management of local farmland fragmentation scenarios, this dissertation extends the existing knowledge about farmland management as a component of land management scientific domain. Furthermore, by adopting a mixed methods research approach and pragmatic research paradigm to generate new consolidated theoretical models on farmland fragmentation scenarios management and their empirical test in a specific case study context, this research stands as the very first of this kind, reconciling various fragmented positions on farmland fragmentation management. It, therefore, serves as a critical information base for future studies narrowing the existing knowledge gap in the scientific domain of farmland management.

3. 2. Research Limitations

As a result of a long research process, this dissertation has undergone various external and internal limitations in methodology, scope, and content. First, the field data collection phase was seriously affected and delayed by the travel restrictions in the country during the critical COVID-19 pandemic period. This significantly affected the scope, the content and the financial support of this dissertation. Due to these temporal limitations from the pandemic, financial and other personal familial health

considerations, the third theoretical model calling for the development of Fit-for Rwanda sustainable farmland fragmentation management models was not exhaustively empirically tested in this dissertation. This test stipulated an empirical analysis of the relationship between identified farmland fragmentation scenarios and food security in the study area, a critical performance and relevance analysis of these strategies and interventions with regard to farmland fragmentation and multidimensional food security nexus in the country, a suitability analysis of various farmland defragmentation models in the context of Rwanda, and the development of Fit-for Rwanda theoretical models of farmland fragmentation management strategies tailored to specific and localised fragmentation scenarios within the doctoral research scope.

In the same respect, the focus group discussion data collection activity was (for example) methodologically limited by the COVID-19 pandemic control measures forbidding physical meetings of more than ten people, which resulted in the selection of small groups of 5 to 10 farmers. Furthermore, this study was not able to test the widely disputed claim supporting the theory of diseconomies of scale that stipulates a negative relationship between farm size and farm output, and the competitiveness of small farms over big ones in the context of Rwanda, as it fell short of enough and robust scientific evidence to prove it from the used data. This needed a rigorous comparative study of the performance of small-scale and big farms in terms of socio-economic, spatial and agro-ecological aspects using large-scale cross-sectoral panel data, which was practically not possible within this limited dissertation scope.

3. 3. Future Research Implications: Towards fit-for Rwanda Sustainable Farmland Fragmentation Management Models

Being a theoretical-empirical problem-oriented research type, this research can be replicated in other countries with similar farmland fragmentation management policy dilemmatic concerns and paradoxes as the ones identified in Rwanda. This means that the three developed theoretical models can be tested in any country experiencing farmland fragmentation management issues to inform the policies. Hence, this research calls for further tests of these models in other countries, mainly but not limited to Sub-Saharan African countries. **Figure 17** connects this doctoral research scope and its derived further post-doctoral research implications in Rwanda.

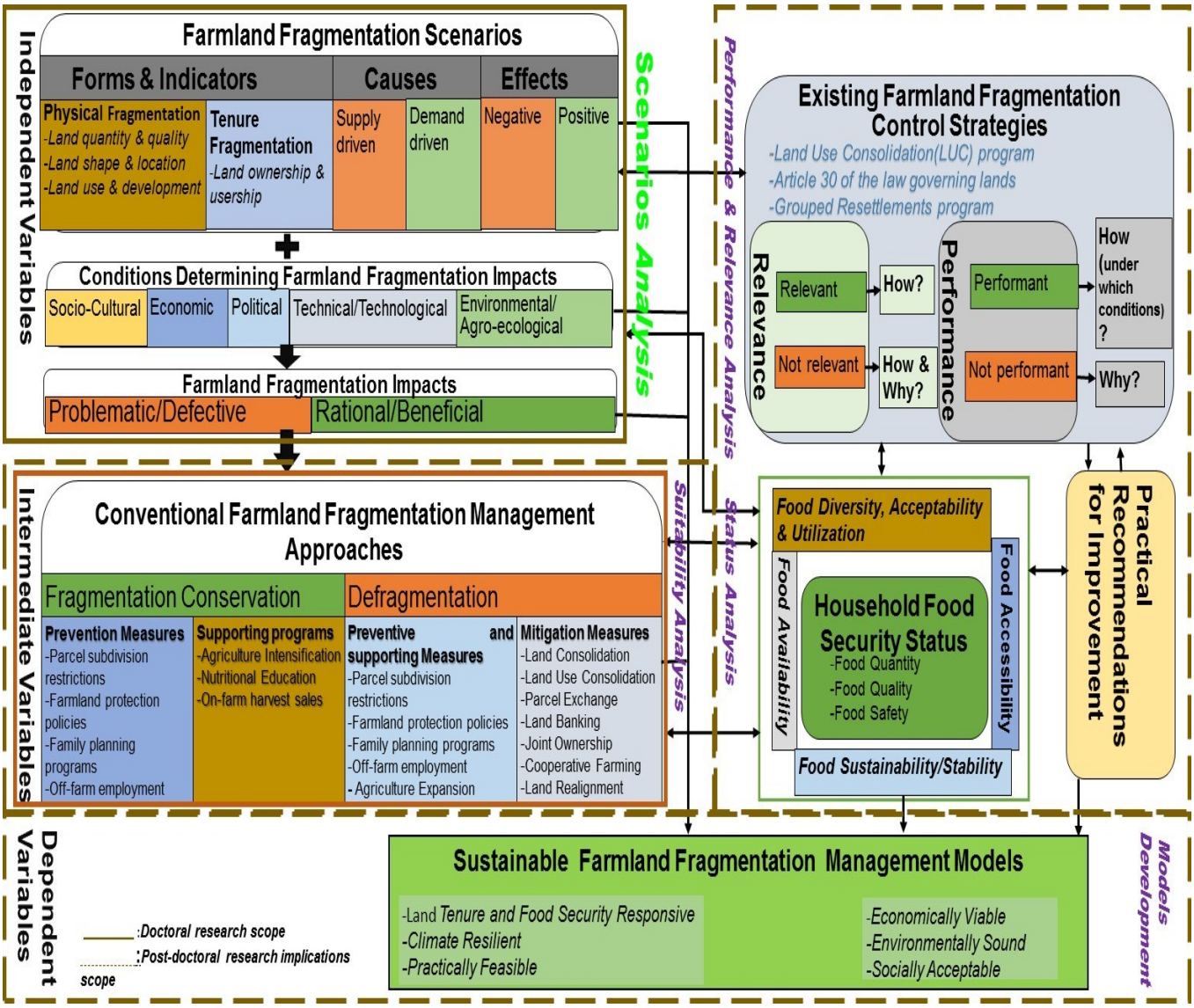

Figure 17. Fit-for Rwanda sustainable farmland fragmentation management models Post-doctoral research framework

Considering the heterogeneous local social, demographic, economic, physical and agro-ecological conditions, the predominance of subsistence and rain-fed hillside agriculture, the high incidence and vulnerability to climate change consequences and natural and weather shocks in the study area, and the identified diverse typology of farmland fragmentation scenarios despite the existence of farmland fragmentation combat strategies like land use consolidation and its supporting programs for food security purposes, this study questions the suitability and performance of these strategies and interventions in the country. Consequently, it inductively hypothesises their insufficiency and irrelevancy, a positive relationship between farmland fragmentation and household food security, and the unsuitability of modern government-led farmland consolidation programs for the management of the identified farmland fragmentation scenarios in the study area.

Therefore, this doctoral research recommends the test of the third theoretical model of Ntihinyurwa and de Vries [4] from this thesis in the context of Rwanda via the following set of further research calls:

- A comprehensive critical performance and relevance analysis of existing farmland fragmentation combat strategies and interventions with regard to multidimensional food security and farmland tenure security nexus in the country.
- A rigorous comparative study of the performance and competitiveness of small-scale and big farms in terms of socio-economic, spatial and agro-ecological aspects, and the suitability analysis of farmland consolidation models using large-scale cross-sectoral primary and panel data.
- The modelling of Fit-for Rwanda theoretical farmland fragmentation management strategies tailored to specific and localised fragmentation scenarios and local conditions.
- Empirical test of the developed models in the form of pilot projects in Rwanda.

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Appendices

Appendix 1 (A1). The Positive Impacts of Farm Land Fragmentation in Rwanda

Abstract

Land fragmentation and land consolidation are two interrelated concepts of land management. The dominant discourse is that fragmented land ownership and land use tend to be ineffective and unwanted, and land consolidation is then a solution to this quandary. Not surprisingly, in countries such as Rwanda, the majority of the governmental strategies highlight the negative effects of fragmentation. However, the effects of land fragmentation have been dual. Its positive side has often been overlooked by policy makers and the research community. Therefore, this study investigates to which degree one can benefit from farmland fragmentation, especially in the context of food security at the household level and of climate change vulnerability. The goal of this article is to expand the current land fragmentation discourse and describe in which context specific types of land fragmentation may be just as sustainable as opting for land consolidation. The guiding hypothesis hereby is that there is a high level of fragmented land ownership yet, that physical (location, use, internal, shape and value) fragmentation acts as a risk management strategy which positively impacts the nutritional balance for food quality and food sustainability as components of food security. Conceptually, land fragmentation can be seen from multiple lenses. It can be seen as a land use concept (emphasizing variation in manner of agricultural production, variety of crops, frequency of harvesting, etc.). It can also be seen as a geodetic concept (emphasizing variation in shape and size of parcels on the one hand, and variation in land ownership on the other hand). Additionally, it can be seen as a spatial planning and intervention concept (emphasizing the urgency and need for order, structure and alignment of space). In our article we look at fragmentation (and the variation thereof) in all these three ways. If within an area, the utilization, ownership, leasehold, shape, size and location of parcels and spatial policies vary more than average (as compared to a similar area), then we consider it a fragmented landscape. Once we find a case of such a landscape, then we are able to investigate why and/or under which conditions (and by which drivers) this 'fragmented' landscape has emerged and what are the implications. This is the main question under investigation in this research. The research relies on a mixed methods research approach via household surveys with 98 random respondents in Gashora sector, Bugesera district, Eastern province of Rwanda. The data collection included further 7 key informants' interviews, a focus group discussion, field observations of current plot sizes and land uses, and the review of the existing literature on the topic. The findings indicate that a high level of fragmentation exists, both in terms of land ownership (visible and hidden) and physical landscape. The dominant reasons are that land users perceive this as an effective risks management strategy which would positively affect food quality, food sustainability and food security. Multiple land holdings with different shapes in different locations allow farmers to grow multiple crops with different adaptation capacities in different growing conditions (soil type, slope, microclimate variations, etc.). Furthermore, fragmentation seems to help reduce land ownership and use related conflicts despite its negative impacts on agriculture production efficiency, especially the loss of land through boundaries and the increase in boundaries related conflicts. Unlike previous studies on land fragmentation, we posit that environmental and agricultural policies should take both negative and positive impacts of land fragmentation into account equally as sustainable and resilient solutions, given the right circumstances and contexts, especially for vulnerable and food insecure areas in Rwanda.

Keywords: land fragmentation; impact assessment; climate resilience; food security

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1. Introduction

Both the unique topography and high population densities have contributed to a fragmented landscape in Rwanda. With a current population density of 462 people per km^2 (NISR, 2015) combined with decreasing land availability due to fast urbanization, complex settlement and farming opportunities due to a mountainous and hilly geomorphology, and an increasing risk of erosion due to climate change, fragmented landscapes and fragmented land tenure has gradually increased in Rwanda. Due to the increasing competition and pressure of the growing population to meet their basic needs for food, energy and shelter on limited land resources in Rwanda, land has become a contested asset, scarce in nature and containing many competitive interests. That is why land management is a must. Generally, land fragmentation has negatively affected agricultural production and food quantity. However, in Rwanda, whether land fragmentation is only causing negative effects is strongly debated Kathiresan and MINAGRI (2012), Konguka (2013); GoR (2014); Musahara et al. (2014). Most governmental reports and current strategies such as the Land Use Consolidation (LUC) Program, Article 30 of the Law Governing Lands in Rwanda view land fragmentation as negative, and do not see any positive sides to it. On the other hand, there is no comprehensive knowledge concerning the circumstances under which land fragmentation derives significant negative or positive effects. Neither is there sufficient knowledge on the causes and implications of different kinds of land fragmentation.

Since the majority of the population (more than 72%) lives off subsistence agriculture (NISR, 2015), the effects of land fragmentation are always linked to the volume of agriculture production, thereby dividing the Rwandan research community. Research by GoR (2004), Musahara and Huggins (2006), Kathiresan and MINAGRI (2012), Ntirenganya (2012 cited in USAID, 2014), Mbonigaba and Dusengimana (2013) consider that land fragmentation has a negative impact on food security. The question is to which extent land fragmentation, either in the form of a deliberate or a gradual land intervention can be considered as a “responsible land management” practice (de Vries and Chigbu, 2017: 68). The argument is that land fragmentation can be expressed as both a fragmentation of use and ownership. The agriculture production tends to be small at all scales due to this fragmentation through the reduction of its efficiency at the national level, since the yield per HA is small when agriculture is done on small plots far away from the residence, as a result of which production costs are high. They also advance the idea that land fragmentation reduces the size of land under cultivation through the loss or wastage of some areas and farm sizes under boundaries.

Chigbu and Kalashyan (2015: 10) warn that land consolidation should not be about “a mere reallocation of parcels to remove effects of fragmentation” as fragmentation is not always a problematic issue. This explains why Konguka (2013) finds land fragmentation to have positive impacts on food security, since it acts as a protection strategy against environmental risks such as change in weather patterns, by diversifying different crops in different locations. Konguka (2013) advances the idea that holding different plots in different areas with different soils, slopes, micro-climatic variations sustain the agriculture production at the household level within the subsistence agriculture all over the year, thereby supporting the nutritional balance as a component of food security. This goes in line with the Sustainable

Development Goals (SDGs 2, 13 and 15) which stipulate the focus on the climate smart agriculture, requiring the use of multiple crops with different adaptation capabilities on small plots spread in different areas, rather than the widely known market-oriented agriculture on big farms often promoting the monoculture.

Coping with this very complex issue needs a sound knowledge about the level, forms and causes of land fragmentation along with all its effects, and the components of food security at both national and household levels and their relationships. Unfortunately, prior to the lack of key knowledge and the literature gap about the above problem, the majority of the governmental programs to tackle it, including the Farm Land Use Consolidation (LUC) program and the prohibition of the subdivision of agricultural land which could result in parcels less than 1HA (GoR,2013),have been recently found to be inefficient, ineffective and non-participatory, since they are only oriented towards coping with farm land use and ownership fragmentation and act as a bridge of climate change towards food insecurity through the quite imposed monoculture. Hence, there is a need to prepare sustainable and climate resilient solutions to the above problem by considering the harmonization of environmental and agriculture policies which require the consideration of both negative and positive impacts of land fragmentation.

Therefore, this study investigates to which extent assumed or perceived positive impacts of land fragmentation play a role in the decisions of individual farmers and the decisions of governmental agencies as a whole. The issue of fragmentation is connected to the attributes of food security related decisions and effects at household level in Rwanda. Once the correlations of fragmentation and food security features are evident, it is possible to propose the alternative sustainable solutions to address land fragmentation problem and adapt the current negative discourse. Unlike previous researches on the topic in Rwanda, this article assesses the level, different forms, and causes of land fragmentation and shows their effects focusing on the positive ones on different dimensions of food security in terms of food quantity, food quality, food sustainability and food availability, using the case study of Gashora sector in Bugesera district. The research assumes that there is a high level of land ownership, use, shape, value, internal and location fragmentation, which act as risks management strategy thereby positively impacting on the nutritional balance for food quality and food sustainability as components of food security. The findings of this study will assist the government of Rwanda to develop appropriate country context specific and climate resilient policies and coping strategies to the problems of land fragmentation and food insecurity, and achieve its national sustainable development goals. This article focuses only on farm land fragmentation and food security at the household level.

This article is structured as follows: First, we conceptualise land fragmentation and food insecurity. Next, we describe the positive and negative implications of land fragmentation. Then, we present the applied data collection and data analysis methodology to achieve the study objectives. Finally, we present and interpret our empirical findings, respond to the main research question about the conditions, causes and effects of land fragmentation, and present recommendations for practitioners and for further research.

2. Theoretical perspective

2. 1. The concept of land fragmentation: forms, characteristics, causes and measurements

There is no single commonly agreed definition of land fragmentation. Bentley (1987) defines it as the scattering of farmland, McPherson (1982) as a situation where there are many numbers of plots spatially separated, with the same owner. King and Burton (1982) characterize land fragmentation as a basic rural spatial problem whereby farms are poorly organized at different locations across an area. These conceptualizations focus however only on dispersed land owners and dispersed plot locations held by single owners without considering the variety in size, use and shape of the respective plots. Sundqvist and Lisa (2006) give a more concrete definition adapted from FAO (2003), which considers land fragmentation as a situation where a farming household possesses several non-contiguous land plots, often scattered over a wide area. They view it as a spatial concern with the spatial characteristics like the farm size, the number of land parcels belonging to the farm, the size and shape of land parcels, the size distribution of plots and the spatial distribution of plots. For de Vries (2016), the most common interpretation of land fragmentation relates to physical aspects of fragmentation, i.e. holdings with a large number of small parcels scattered over a considerable area. In this regard, Sabates-Wheeler (2002) has shown land fragmentation as a multidimensional phenomenon with four dimensions such as: (1) physical fragmentation, (2) social fragmentation, (3) activity fragmentation and (4) ownership fragmentation. The same author argues that the physical fragmentation may imply any one or a combination of the following: (i) non-contiguous land parcels that are owned and tilled as a single enterprise; (ii) parcels that are distant from the owner's homes or from each other; or (iii) ownership of very small parcels.

There are different methods of measuring land fragmentation. They include the Global Land Fragmentation Index (Demetriou et al., 2013), the Januszewski index (janusi), the Simpson index (Simpsi) and the Simmons fragmentation index(Simmons,1988), among others. Each of these methods have different meanings and the absence of a real standard objective measure make it hard to decide if a farm is too fragmented or not fragmented at all. When comparing all those globally recognized measurement methods, land fragmentation is generally focusing on measurements of the physical shape and distribution of parcels, i.e. by determining the number of owners per a given land unit, area, region or land block (ownership fragmentation), the size of household landholding, the number of plots per household or farm, respective sizes of plots, their shapes, uses and their spatial distribution or locations from the household homestead along with their values in some cases. We can refer to this as physical fragmentation.

Generally, the forms of land fragmentation should be linked with each of the characteristics of land, such as its ownership, size, use, shape, value and location since their causes and effects also vary from type to type. However, most of the literature ignores the land location, value and shape fragmentation when analysing the impacts and causes of land fragmentation in general, which in turn leads to the development of broad and non-appropriate coping policies and strategies. King and Burton (1982); Bentley (1987), Van Dijk (2003a, b) cited in Hartvigsen (2014,2015a, b), Sundqvist and Lisa (2006); Sklenicka et al. (2014), and Hiironen et al. (2016) have limited the existing types of land fragmentation to

the fragmentation of land ownership; land use; within a farm (or internal fragmentation); and separation of/discrepancy between ownership and use fragmentation. According to Van Dijk (2003a, b) cited in Hartvigsen (2014,2015a, b), land ownership fragmentation refers to the situation where the ownership of agricultural land is split between many owners of small and often badly shaped parcels (when there are many land owners on a small land block). For them, land use fragmentation refers to the number of users of lands which are not their own lands. This is generally considered as the number of tenants in the European land fragmentation and consolidation literature. Land is considered to be fragmented in use when there are many users on it. However, in the general context, land use fragmentation has to do with the actual use of land (whenever there are more than one land uses on a single farm or plot). This does not have anything to do with the number of users, since one user or owner can have multiple uses on a farmland. For this reason, the number of users can refer to a different type of fragmentation which is **Usership fragmentation** merely associated with **Ownership fragmentation** depending upon whether the users are using their own lands or not. In this article, the term land use fragmentation in the sense of land utilization fragmentation will be followed. Internal fragmentation is understood as the fragmentation within a farm (whenever a farm or household land holding is split into many small non-contiguous plots often scattered in different locations at long distances from the homestead and between the parcels). Separation of ownership and use involves the situation where there is a discrepancy between ownership and use, often shown by small number of land owners who use their lands. For Van Dijk (2003a, b), the reduction of land fragmentation occurs when the number of owners and/or users declines, the number of parcels per farm falls, and the share of owners that use land themselves raises.

Hartvigsen (2014,2015a, b) argues that land fragmentation and land consolidation policies in Eastern and Central European countries were more concerned with land ownership and land use fragmentation. Drawing on Demetriou et al. (2013), he introduces a new form of fragmentation known as a **Hidden fragmentation** in ownership and use, when there is a co-ownership of a family land by many family or household members. Each household member tends to ask for his own part for individual use based on his use and food preferences. This has been found in countries like Bulgaria and Albania, and is likely to exist in Rwanda as well, as there is a restriction of the subdivision of family land with sizes less than 1 ha, and the encouragement of its co-ownership. He also referring to the studies of McPherson (1982) introduced the notion of **Excessive fragmentation**, which he defined to exist if the number of parcels in a farm exceeds its size. As an example, a 20 ha farm would be excessively fragmented if it consisted of more than 20 parcels (McPherson, 1982). He further refers to Bentley (1987) when mentioning that **Extensive fragmentation** exists when the parcels become so small that they are not economically viable which could often result in land abandonment. Recent studies conducted by Muchová (2017) in Slovakia, and Janus et al. (2018) in Poland introduced new more flexible approaches of calculating land fragmentation, but all of them were more oriented towards defending the benefits and the need for land consolidation projects both in case of physical and ownership fragmentation. Janus et al. (2018) have emphasized on the importance of aggregation of parcels or plots belonging to the same owner as it happens in land consolidation. They developed different parcel aggregation indexes which do only consider the number of plots belonging to the same owner before and after aggregation (after elimination of the boundaries) when calculating physical land fragmentation indicators through the so

called phenomenon of neighbourhood of plots. This method does not show land fragmentation indicators to be considered and their calculations, neither gives any attention to land ownership fragmentation. On the other hand, Muchová (2017) gives more details on the calculation of land ownership fragmentation by considering multiple criteria like the number of owners per land unit area, the number of plots per unit land, the number of co-owners per parcel, the size of land, the size of plots, the average number of plots, average size of plots, average number of co-owners and different ratios, although his approach does also not consider some physical fragmentation features (uses and shapes of parcels). It however brings in a new idea of considering both external ownership fragmentation and internal ownership fragmentation (co-ownership) when preparing or evaluating land consolidation projects. Therefore, in this article, we use the above mentioned characteristics of land (ownership, size, use, shape, value and location), and split land fragmentation into two main forms such as: **Land ownership fragmentation** and **Physical land fragmentation** (land use, land value, land location, land shape and internal fragmentations). Land usership fragmentation will be often combined with land ownership fragmentation. Although there are no standard measurable indicators combining all the above forms besides the subjective and somehow incomplete indexes, the number of owners in a given land block, the number of household members (ownership fragmentation), the size of household land holding, the number of plots per household, the sizes of respective small plots and their averages, the shapes of those plots, their uses and their local distributions (physical fragmentation) have been considered.

According to King and Burton (1982); Hartvigsen (2014), there are four causes of fragmentation: (1) socio-cultural (inheritance laws, marriage, dowry culture); (2) economic (land market, land transactions); (3) physical (soil qualities, topography, location, shapes, etc); and (4) operational (land reforms, land policies, infrastructures development). Bizimana et al. (2004) advance the causes of land fragmentation to be mainly linked with the inheritance culture and laws, land reforms including land redistribution, restitution and land sharing programs in different countries after the conflicts, and the increasing population growth on limited, stable and scarce land resources. The urbanization and increasing land markets also have been found to put a lot of pressure on land parcels, thereby increasing their continuous subdivision. The variations in land qualities (soil types, slopes, microclimates, topography, etc) associated with the Egalitarian principles during inherence and land reform processes have also been over time pointed out by different researchers like Keeler and Skuras (1990); Tan et al. (2006), Sklenicka and Salek (2008), Hristov (2009); Platonova et al.(2009); Sikor et al. (2009); Sklenicka et al. (2014); Ciaian et al.(2015) and Sky (2015), as one of the main causes of both physical and ownership fragmentation. According to these authors, the Egalitarian principle applied in many countries like Greece, China, Albania and Rwanda throughout the inheritance and land reform processes stipulates the distribution of land among all the heirs in qualitative and quantitative equal shares. All the members receive the pieces of land of the same sizes, same qualities from all locations and all classes and grades. They believe that lands are different and diverse in physical properties (flat, mountainous, various soil fertility status, etc), locations (far from the homestead, close to the house, close or far from irrigation facilities and roads, etc), types (arable land, grassland, etc), with different production potentials and suitability classes or grades. Therefore, family members prefer to have lands of all grades or classes through inheritance, land reforms, and land market, which leads to the subdivision of lands into small

pieces scattered in different locations with various uses, thereby increasing the land ownership and physical fragmentation explained above. The marriage and dowry culture in some countries also exacerbates/worsens this problem, when the female household members get married and dislocate to the places located far away from their parcel shares in family lands. The subsistence motive reasons have been also advanced by some authors like Ciaian et al. (2015) as factors of diversification when family members with different reasons prefer to have different heterogeneous lands with different crops suitability for their crops diversification to meet their various dietary preferences. For the land market, most of the people prefer to buy additional lands of different qualities often located far away from their own farmed lands and homestead as it has been found difficult to get additional parcels contiguous and close to their already farmed own lands, thereby leading to the physical fragmentation (location and use). From the above literature considerations, it can be concluded that the forms of land fragmentation cause others (Ownership and/or usership fragmentation induce physical fragmentation and vice versa). Table A1/Appendix A in appendices section summarizes the attributes of land fragmentation in the literature and its implications.

In summary, from the above mentioned Table A1, we consider an area fragmented if we find the following characteristics in the physical, socio-economic and institutional landscape: The number of owners/users exceeds the size of land block in a given area (more than 10 owners in 10 ha), the average household land holding is less than 1 ha, more than 50% of households are composed of more than the average number of household members or co-owners, more than 50% of households have more than 2 plots with irregular shapes (not rectangular, squares) located in more than 2 different places in more than 500 m far from the homestead, with more than 2 uses (various crops in cropland, grassland, etc), heterogeneous land qualities (steep and flat slopes, mountainous and plain topography, wetlands and dry lands, fertile versus non-fertile soils, sandy soils versus clay soils, etc), existence of Egalitarian principles in inheritance, land sharing and redistribution programs, domination of subsistence agriculture, absence of land consolidation practices in the area. We also consider that land is excessively fragmented if the number of parcels or plots exceeds the size of household landholding. The hidden land use and ownership fragmentation is considered when the average number of co-owners /household members is more than 2. We categorize the level of fragmentation to be low if the values are far below the average, medium if the values equal to or are around the averages and high if the values are far higher than the averages.

2. 2. Positive and negative implications of land fragmentation

The effects of land fragmentation are generally viewed as negative, even though some studies find that not all the forms of land fragmentation are a problem. Bizimana et al. (2004); Sundqvist and Lisa (2006), consider land fragmentation as an obstacle to agricultural productivity and modernization. It is a major threat to efficient production system due to the fact that continuous subdivision of farms leads to small sized land holdings that may be hard to economically operate. The concepts of land fragmentation and food security have been always separated from the climate change, and linked with the agriculture production with the focus on the negative impacts of farm land fragmentation. However, land, whether

fragmented or consolidated in any form, remains a fundamental asset for food security. Although popular logic is that land consolidation (especially due to increasing farm size) has direct positive effect on increasing food production, this only makes sense when food security is viewed from the lens of quantity. Nevertheless, food security is much more than quantity of food production. It has the quality, and food access perspectives which are achievable even under land fragmentation scenarios (Maxwell and Smith, 1992; FAO, 1996; Ellis, 2000; Pinstrup-Andersen, 2009; Manjunatha et al.,2013; Van der Molen,2017). FAO (1996) from World Food Summit (WFS) in November 1996 defines **Food Security** as a status, "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life", and vice-versa for **Food Insecurity**. This definition stipulates the four aspects of food availability, food accessibility, as well as quantity and quality, through which food security should be measured at both national, regional, household and individual levels. Whenever one of these four aspects is not fulfilled or met, people may suffer from hidden hunger. The household food security is the application of this concept to the family level, with individuals within households as the focus of concern. Despite the provisions of the FAO definition of food security, in Rwanda, only food quantity at the national level is focused on, when measuring and showing the status of food security in the country, living behind the other aspects like food quality and food sustainability, and overlooking the household level. This leads to the formulation of non-climate resilient or inappropriate and irrelevant coping strategies. This argument is supported by the Rwanda National Food and Nutrition Plan 2013–2018 which recognizes that despite the major economic and poverty reduction progress, improvements in nutrition and household food security remains a foundational issue (GoR, 2014). Furthermore, the evidence based correlation between various forms of land fragmentation and the aspects of food security at household level with more focus on the climate change effects seems to be somehow overlooked by the Rwandan research community and policy makers. FAO studies (2003) show that some forms of land fragmentation (like land location and use fragmentation) can act as environmental risks management strategy by growing different crops in different growing conditions which positively impact on the nutritional balance for food quality and food sustainability at the household level. This article follows this later theory stipulating the harmonization of environmental and agriculture policies which requires the consideration of both negative and positive impacts of Farm Land Fragmentation (FLF) with the focus on food security at the household level, and the correlation of the two concepts in the study area to get the current picture of causal and effects relationships.

Land fragmentation has advantages when it comes to reducing the risk of total crop failure on the variety of soil and growing conditions. Many different types of plots allow farmers access to land of different qualities when it comes to soil, slope and micro-climatic variations. Land fragmentation can be a measure to increase food security in the context of climate change. Ciaian et al. (2015) have found that land fragmentation stimulates significantly more diversification for subsistence farm households than for market-oriented households in Albania. They have advanced that the consolidation policies that relocate and enlarge plots would have a significant impact on reducing agricultural production diversification and that land fragmentation contributes to the food security improvement by increasing the variety of foodstuffs produced by subsistence farm households. For them, the more the differences, diversity or

heterogeneity in land and soil qualities with various suitability classes and production potentials, the more the crops diversification and food stuffs diversity, the higher the nutritional balance, the higher the food quality and sustainability, the higher the food security. King and Burton (1982); McPherson (1982); Bentley (1987); Keeler and Skuras (1990), Van Dijk (2003a, b), Tan et al. (2006), Van Hung et al. (2007), Sklenicka and Salek (2008); Hristov (2009); Platonova et al. (2009); Sikor et al. (2009); Demetriou et al. (2013), have all emphasised on the importance of land fragmentation in heterogeneous communities with varying land and soil conditions, when farmers find land fragmentation as desirable for social and environmental reasons. It acts against the total harvest loss risks spreading (through disease, hail, droughts, floods and other natural disasters) and factor for diversification in various soils and growing conditions. They also find it as a tool for equal distribution of resources through the Egalitarian principles. Furthermore, this group of authors find land fragmentation to preserve biodiversity as opposed to land consolidation in some countries and cases.

Different authors including McPherson (1982); Sabates-Wheeler (2002); Sundqvist and Lisa (2006); Sklenicka et al. (2014); Hartvigsen (2013, 2014, 2015a, b), Hiironen et al. (2016); de Vries (2016); Muchová (2017); Janus et al. (2018), believe that fragmented land holdings or small scattered plots in different locations increase transport costs, supervision costs, and time consuming, lead to the loss of land area through boundaries and the boundaries related conflicts and disputes, and hamper the mechanization of agriculture and the development of irrigation and drainage infrastructures within the farms thereby hindering the modernization of agriculture. Land fragmentation also limits the growth of more profitable crops on big farms on profit of the less profitable crops on small plots, and costly to alleviate. For this, these authors in their studies tend to defend the need for, and relevancy of land consolidation practices against this negative land fragmentation phenomenon, though some of them do recognise some of its social and environmental advantages above mentioned. Finally, it is noticed that banks are sometimes unwilling to take small and scattered land holdings as collateral, which prevents farmers from obtaining credit to make investments. This in turn negatively affects the quantity of agriculture production and food quantity as a component of food security. This position has been supported and found out by different authors and studies, including the recent one conducted by Sundqvist and Lisa (2006) in Vietnam, which has shown a negative relationship between land fragmentation and agriculture production.

On the other hand, different FAO land tenure studies (2003) show that land fragmentation is not a problem when fragmented land is a risk management strategy. Sundqvist and Lisa (2006) state that even though policy makers often point out the drawbacks of fragmentation, there is no consensus that fragmentation is strictly a negative phenomenon. Bentley (1987 cited in Sundqvist and Lisa, 2006) argues that the harm caused by fragmented land holdings is overrated and that the farmers own views often are neglected by policy makers. Fragmented land reduces the risks of the farmers by giving them the opportunity to grow a variety of crops beyond the world top four crops of wheat, rice, maize and potatoes in a variety of soils and growing conditions. For them, many different plots located in different areas allow farmers to access land of different qualities when it comes to soil, slope, micro-climatic variations etc. Fields with high yields in one year may in the following year generate much lower yields, thus several

plots of the same crop also spread out the risk. In addition, a holding with several plots facilitates crop rotation and the ability to leave some land in fallow.

In reality, the Rwandan land is highly fragmented due to its high population density. About 36 % of the households own 6% of the farm lands (with an average of 0.11 ha); 30% of households own 24% of farm lands (with an average of 0.6 ha) while 24% of households own 70% of farm lands (with an average of 2 ha), besides a certain number of more than 10% of landless households. The national average holding of 0.76 ha is generally divided over 4 –5 small plots, often in multiple locations. Such multiple holdings are valued by Rwandans since they can diversify their crop production across different locations and thus provide protection against natural risks and unbalanced nutrition even though it has been shown to lead to low agriculture productivity (Kathiresan and MINAGRI (2012)). According to Jayne et al. (2003 cited in GoR, 2004; Bizoza and Havugimana, 2013; Musahara et al., 2014), almost a half of the farms are small with less than 0.3 ha (45.8%) with more than 83 percent of farms being smaller than 0.9 ha as the FAO economically viable farmland size to sustain a family, since more than 50% of farming families have less than 0.70 ha. Though the studies of ECA (2004) have shown that the average sizes of farms in Africa are normally between 0.4 and 6 ha, in densely populated countries like Rwanda, this average goes below 0.5 ha. However, the forms and the extent of such fragmentation are neither yet well-known nor documented. For this, different programs embarked on to overcome this problem are broadly established regardless of the forms of land fragmentation referred to. No distinction between **Ownership fragmentation, Internal fragmentation, Location fragmentation** and **Use fragmentation** of the land has been shown when establishing the objectives of the LUC program for coping with land fragmentation in general, while they are different. It looks like LUC is oriented towards reducing land use fragmentation rather than land ownership, internal, location and size fragmentation. Konguka (2013) has shown how fragmented land has some benefits associated with scattered pieces of landholdings at different locations with varying soils and ecological characteristics. He argued that varieties of soils enable a farmer with a large number of small parcels to grow a wider variety of crops in comparatively small areas, thereby reducing overreliance on a limited number of crops species that can be disastrous when disease strike or pests threaten to wipe out an entire harvest. Blarel et al. (1992) argued in their study in Ghana and Rwanda that fragmentation of farmland is not as inefficient as generally perceived. They supported this view by arguing in favour of fragmentation as a tool for the management of risk, seasonal bottlenecks and food insecurity (Abubakari et al., 2016). This helps to withstand the effects of climate change in different risks prone areas like Rwanda, leading to the sustainable production of the diversity of crops the whole year, thereby increasing the nutritional balance for food quality and food sustainability as components of food security.

In summary, land fragmentation is considered good when farms are composed of many small plots located in different places with varying soils, growing conditions, topography, crops suitability and production potentials. In addition, it is relevant when it is combined with the presence of Egalitarian principles in land reforms and inheritance cultures, and climate change prone areas, high number of household members, domination of desired subsistence agriculture for crops diversification, risks management, food security, and tenure security. Therefore, if we find these elements in a case area, we

consider it as a good fragmentation. Land fragmentation is considered bad if there are many owners on a small land unit, with many small parcels with irregular shapes and different uses, scattered over large distances from the homestead in a more homogenous area (homogenous topography, homogenous soils and growing conditions) with less vulnerability to climate change risks, leading to reduction in agriculture production efficiency, land related conflicts and loss/wastage of land through boundaries. Therefore, if we find these elements in a case area, we consider it as a bad fragmentation.

3. Methodology

3. 1. Research approach and design

A Mixed Methods Research Approach was chosen for this study. Creswell et al. (2003, 2011 and 2014) note that this kind of approach gives the chance to rely on different methodologies and convergent data collection and analysis techniques which gives a better understanding of the problem and enables better solutions. Therefore, we used both household surveys about the forms and level (information about the parcel/land holding sizes, shapes, locations, uses, number of owners/users and co-owners), causes and implications of land fragmentation especially on food security as a quantitative non-experimental research design for quantitative primary data, and national data set analysis (information about parcel sizes, ownership, uses, values) for quantitative secondary data. A case study analysis of Gashora sector in Bugesera district through key informants' interviews, focus groups discussions, field observations and document review for qualitative primary and secondary data collection about the land uses, land and soil types, agro-climatic conditions, parcel shapes, causes and effects of land fragmentation was also used as part of this design. This design facilitated the authors to collect both primary and secondary data simultaneously as shown on Figure.1 below.

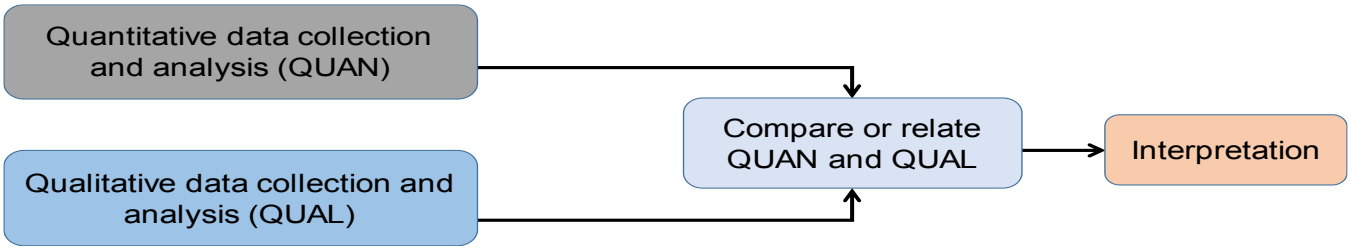

Figure 1A1. Convergent parallel mixed methods research design

Source: Authors adapted from Creswell (2014)

The choice of the above case study was driven by the fact that in the past, this sector as well as the whole Bugesera district has experienced a problem of food insecurity due to factors like land use changes, changes in weather conditions leading to prolonged droughts and changes in rainfall patterns, despite the relatively higher farm sizes in the Eastern province and the homogeneous topography of the region as compared to other parts of Rwanda. Recently, there has been increasing reduction in farm sizes, and the number of plots per land owner, and reduction in food insecurity in the district at the household level. This situation is attributed to the recent increases in population density associated with the existing customary practices of Egalitarian based inheritance, along with the desire to have plots in different growing conditions associated with the encouragement of the exploitation of swamps for

agricultural purposes. These characteristics have been identified as some of the reasons (e.g. egalitarian based inheritance and desire to have plots in different growing conditions) for the increases in food security in Rwanda (Blarel etal., 1992; Huggins, 2012; Kathiresan and MINAGRI, 2012; Musahara et al., 2014). This raises questions concerning the homogeneity of ownership and use combined with the ever changing agro ecological conditions as the main drivers of food insecurity in the past (Rwanda National Food and Nutrition Plan 2013–2018; NISR, 2015). Therefore, studying the impacts of land fragmentation in a such area which has experienced the two opposite and changing scenarios at different times has been thought by the authors to give the best picture of the increasing land fragmentation and its impacts, rather than other more topographically heterogeneous regions where no significant changes in fragmentation and food security statuses and their drivers have been questioned, even though the authors plan to extend the same study to other regions of the country to get the more complete and general picture of the situation at the national level.

3. 2. Research methods

Open and closed-ended questions (through questionnaire administration and semi-structured interviews) for household survey were used to collect the information about the parcel/land holding sizes, shapes, locations, uses, number of owners and co-owners for the level and forms of land fragmentation, and the causes and implications of land fragmentation especially on food security as primary quantitative data. The unstructured key informants' interviews with open questions along with the field observations and focus groups discussions have been used for primary qualitative data collection about the land uses, land and soil types, agro-climatic conditions, parcel shapes, causes and effects of land fragmentation in 5 cells of Gashora sector, Bugesera district, Eastern province of Rwanda. The choice of all the five cells was not for the comparison purpose, but for the data variability for validity and reliability purposes. The random sampling method along with the purposive one have been used for the selection of 98 respondents representing more than 15% of the total number of households in the sector for the household survey from the simplified formula of Glenn (1992) appropriate for the small homogenous case studies, and 7 key interviews with 7 key respondents (5 cell agronomists, 1 sector agronomist, 1 sector land manager) respectively for the primary data collection. This technique of household survey in the assessment of the impacts of land fragmentation which uses the number of plots per household, their sizes, uses and shapes for physical fragmentation, and the number of owners/users in a given land unit area and co-owners per landholding for land ownership fragmentation, their causes and effects has been used by many different previous similar studies in Rwanda, Uganda, Vietnam, and Europe. Sundqvist and Lisa (2006) have used it when analysing the impacts of land fragmentation on agriculture productivity in Northern Vietnam, Hiironen et al. (2016) have used it to evaluate land fragmentation in agriculture areas in Finland, Muchová (2017) has used it to assess land ownership fragmentation by multiple criteria in Slovakia, and Janus et al. (2018) have used it when introducing a new approach to calculate land fragmentation indicators considering the adjacent plots in Poland. The Triangulation and Back-checking techniques were used to check the validity and reliability of the collected data, and chosen for their wide use in mixed studies like this one. The information about the level of land fragmentation was obtained

through the calculations of different averages about the sizes and ownership through the following different ratios and sums.

Formulae	Formulae Legend
1.*Nlo*$= \sum_{i=1}^{n} loi$	Where, ***n***: The number of observations
2.*Nco*$= \sum_{i=1}^{n} coi$	***lo***: land owners/households under survey
3.*Np*$= \sum_{i=1}^{n} pi$	***co***: number of co-owners per households' land holding (households' members) under survey
4.*Nploc*$= \sum_{i=1}^{n} ploci$	***p:*** number of plots per households' land holding under survey
5.Td$= \sum_{i=1}^{n} di$	***ploc*****:** number of plot locations per households' land holding under survey
6.*Slb*$= \sum_{i=1}^{n} si$	**s:** sizes of land parcels/plots under survey in ha
7.*AvNp*$= Np/Nlo$	**d:** distances of plots from the homesteads under survey in km
8.*AvHlhs*$= Slb/Nlo$	***Nlo:*** Number of land owner*s*
9.*Avps*$= Slb/Np$	***Nco*****:**Total number of co-owners (Household members) per land block in the study area
10.*AvNco*$= Nco/Nlo$	***Np*****:** Total number of plots in the study area or per land block
11.*Avpsco*$= Slb/Nco$	***Nploc*****:**Total number of plots locations in the study area
12.*Avpd*$= Td/Np$	***Td*****:** Total plots distances from the homesteads(in Km)
13.*AvNploc*$= Nploc/Nlo$	***Slb*****:** Size of farm or a land block in the study area (in ha) ***AvNp*****:** Average number of plots per owner ***AvHlhs:*** Average household land holding size (in ha) ***Avps*****:** Average plot size in the study area(in ha) ***AvNco*****:** Average number of co-owners (Household members) per land holding

Source: Authors (2018), compiled from the reviewed literature

The number of plots per household, the number of household members and the household's landholdings were obtained through the household survey interviews and land titles. A correlation diagram was used to show the relationships among different causes of land fragmentation in the study area. Both descriptive statistics and text description were used to analyse quantitative and qualitative data. The implications of land fragmentation from the perceptions of household members and key informants in the study area have been plotted against the aspects of food security in order to assess their relationships and answer the main research question (hypothesis). Table B1/Appendix B in appendices section shows the matrix summarizing the data collection and analysis methods.

4. Results

4. 1. Forms and level of land fragmentation in Gashora sector

The forms and the level of land fragmentation came from combining the household survey (interviews and land titles checking) with the documentation (National data set analysis), and field observations data. Table 1, Figures. 2a, b & c present different indicators of both ownership and physical land fragmentation.

Table 1A1. Forms and level of land fragmentation in Gashora sector

Indicators	Values	% of Respondents /Observations	Type of Fragmentation		Level of Fragmentation
Total available land area in Gashora Sector (in ha)	≈4500	-	**Land ownership fragmentation**	**Visible fragmentation**	Very high (Excessive)
Total number of Households in Gashora sector	5522	-			
Size of land block under survey (Slb) (in ha)	41.5	-			
Number of households/land owners/users under survey (Nlo)	98	-			
Number of household members/co-owners under survey (Nco)	610	-		**Hidden fragmentation**	Very high (Excessive)
Average number of co-owners (Household members) per land holding (AvNco)	6	-			
Total Number of plots	432	-	**Physical land fragmentation**	**Internal and location fragmentation**	Very high (Excessive)
Average household land holding size (AvHls) (in ha)	0.4	-			
Average number of plots per owner/user (AvNp)	4.4	-			
Average plot size (Avps) (in ha)	0.1	-			
Average plot size per co-owner (Avpsco) (in ha)	0.07	-			
Number of plot locations	**1 location**	10			
	≥2 locations	90			
Average number of plot locations (AvNploc)	3	-			
Estimated distances of plots from the homestead (Espd) (in km)	≤0.5	23			
	0.5-1	58			
	≥ 1	19			
Average distance of plots from the household homesteads (Avpd) (in km)	0.8	-			
Production potentials of plots(Land qualities)	**Homogeneous**	26		**Value fragmentation**	High
	Heterogeneous	74			
Uses of plots	**Monoculture**	62		**Use fragmentation**	Low
	Multiculture	38			
Shapes of plots	**Irregular**	71		**Shape fragmentation**	High
	Regular	29			

***Source*:** Authors (2018), from household survey

Besides the indicators in Table 1, the level of physical land fragmentation can be proved by the percentages of respondents evidencing the number of plots per household/land owner or land user (Figure. 2a), their respective sizes (Figure. 2b) and uses (Figure. 2c) and shapes. The level of land use fragmentation is shown by different use types such as agriculture, residential, commercial, forestry and different farming systems (Monoculture of the priority crops versus the Multi-cropping) within agriculture use as shown in Figure. 2c and the above Table 1. It has been obtained through the household survey (interviews and land titles checking) and field observations. The level of land shape fragmentation has been obtained by checking the spatial parts of land titles for each parcel during the household survey and through different field observations in the study area. It is shown by the Regular (with a well identified geometric Figure like rectangular and square) and Irregular (with no known or identified geometric Figure, not rectangular nor square) forms as shown in the above Table 1. For this purpose, more than 200 land parcels were checked. The majority of the surveyed parcels (90%) and the land titles were categorized as agriculture land as also confirmed in the field observations.

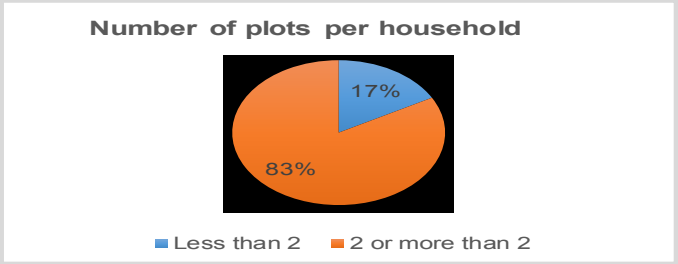

Figure 2a: Number of plots per household

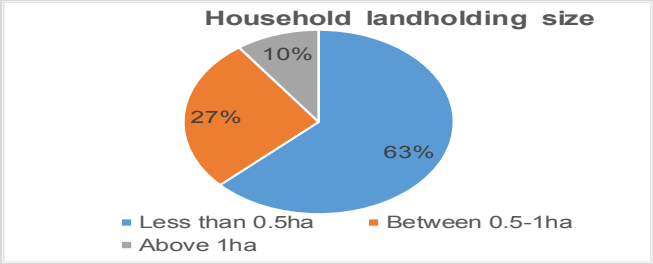

Figure 2b: Size of household landholding

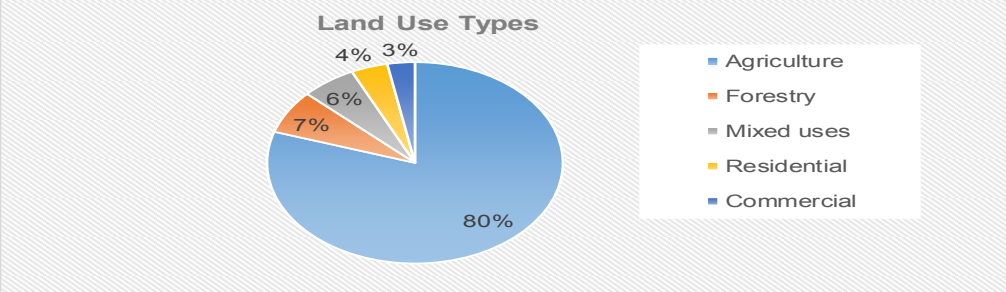

Figure 2c: Land use types in Gashora sector

Figure 2A1. Household landholding size, number of plots and their uses

Source: Authors (2018), from household survey

4. 2. Causes/ driving forces of land fragmentation in Gashora sector

The causes of land fragmentation are shown by the perceptions of households' respondents about the ways of their land acquisition in the study area, and the ones from the key informants about the driving forces of land fragmentation along with the focus group discussions with 2 different groups of farmers and community leaders, and the review of the existing literature as shown on the Table 2 and 3 below.

Table 2A1. Means of land acquisition in Gashora sector

Land acquisition in Gashora sector	Frequencies(F)	Percentages (%)
Inheritance/succession	37	38
Ascending partition	26	27
Purchase (formal& informal transactions)	23	23
Others (donations, land sharing program, diverse soil qualities, topography, agro climatic conditions etc)	12	12
Total	98	100

***Source*:** Household survey

Table 3A1. Driving forces of land fragmentation in Gashora sector

Driving forces of land fragmentation in Gashora sector	Frequencies(F)	Percentages (%)
Inheritance, succession and marriage	7	100
Land related conflicts	5	71
Land market(formal and informal transactions)	6	86
Others (donations, land sharing program, land redistribution, variability of agro ecological conditions like soil type, slope, biodiversity conservation, etc)	7	100
Total	7	100

Source: Key informants' interviews, focus group discussions & literature

The information from the focus group discussions and the review of the existing literature have revealed the increasing population growth on stable and scarce land resources combined with the traditional inheritance cultural practices (Egalitarian customary principles), the land reforms including the land sharing and redistribution programs, informal land transactions leading to the subdivision of parcels of less than 1 ha, and the variability of agro ecological conditions to cope with the effects of climate change(long droughts), as the key driving forces of land fragmentation in Gashora sector.

4. 3. Effects/Implications/Impacts of land fragmentation

The effects of land fragmentation in Gashora sector are summarized in Table 4 and Figure 3

Table 4A1. Effects of farmland fragmentation in Gashora sector

Forms of Land Fragmentation		Effects of Land Fragmentation	Frequencies(F)	Percentages (%)
Land Ownership Fragmentation		*Loss/wastage of land through boundaries*	7	100
		Increase in land ownership &Boundaries related conflicts	7	100
		Decrease in yields of priority crops(Agriculture production)	5	71
		Increase in Land Tenure Security (LTS) and reduction in ownership related conflicts	7	100
Physical Land Fragmentation	**Land Use Fragmentation**	*Decrease in yields of priority crops (Agriculture production)*	5	71
		Increase in land use related conflicts	6	86
		Environmental Risks Management Strategy (ERMS)	6	86
		Increase of the nutritional balance through multiple crops(crops diversification)	6	86
	Internal Land Fragmentation	*Obstacle to mechanization, irrigation and drainage infrastructures*	7	100
		Risks management strategy(diseases and pests spreading control, droughts and floods control)	7	100
		Increase in food security through crops and food stuffs diversification(Output or agricultural production variation)	7	100
		Loss/wastage of land through boundaries and increase in boundaries related conflicts	5	71
		High transaction and production costs (given the waste of time to get to the parcels)	4	57
	Land Location and Value Fragmentation	**Increase of the nutritional balance through variety of crops and different growing conditions(Soil, slope, micro climate, etc)**	6	86
		Environmental Risks Management Strategy (ERMS) through different growing conditions (Soil, slope, micro climate, etc), biodiversity conservation	7	100
		Decrease in agriculture production efficiency (High production costs and time), abandonment of some productive plots due to high transport costs	6	86
	Land Shape Fragmentation	**Environmental Risks Management Strategy(ERMS) through different growing conditions**	4	57
		Decrease in agriculture production efficiency (High production costs and time)	5	71

Note*: Italic*: Negative effects**; Non Italic Bond:** Positive effects
Source: Key informants interviews

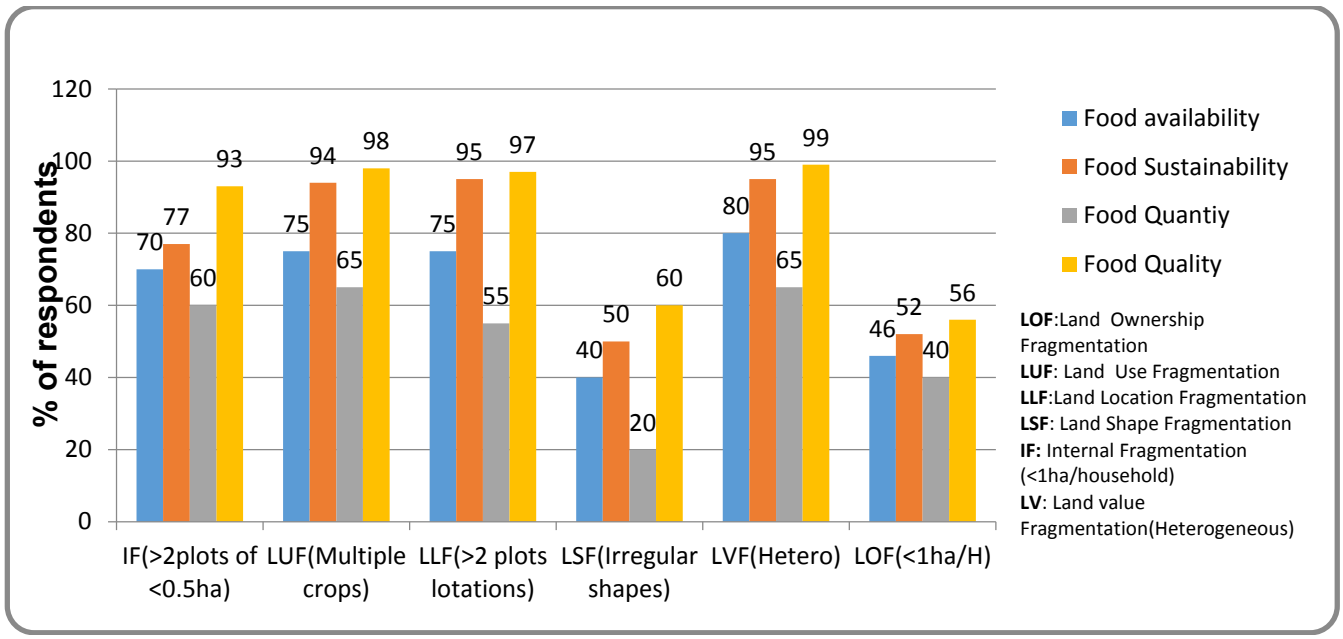

Figure 3A1. Impacts of land fragmentation on food security aspects

Source: Household survey

5. Results interpretation and discussion

The findings demonstrate that all the five forms of land fragmentation categorized in two main forms such as physical land fragmentation and land ownership fragmentation exist in the study area, but at different levels. Table 1, Figures. 2a, b & c show that the majority of households own/use more than 2 plots of land (90% of respondents) of less than 0.5 ha (63% of respondents) and located in more than 2 locations (70% of respondents). The majority of the surveyed parcels have irregular shapes (71%) and heterogeneous production potentials of land qualities (76% of respondents), while 62% of the parcels are cultivated under the monoculture system. Furthermore, the average household landholding size, the average number of plots per household, the average plot size, the average number of co-owners per household, the average plots size per co-owner, the average number of plots locations, and the average distance of plots from the homestead in the study area are 0.4ha; 4.4 plots; 0.1ha; 6 members; 0.07ha; 3 locations; and 0.8km respectively. These values indicate the presence of a very high level (extensive) of internal fragmentation and land location fragmentation, a high level of land shape and value fragmentation, with a low level of land use fragmentation in Gashora sector as indicators of high level of physical fragmentation, since the above values are far lower than the average indicators of land fragmentation shown in Table A1/Appendix A in appendices section. The findings indicate that the number of land owners/users under survey (98 owners) and the number of co-owners (610 co-owners) exceeds the size of total land block under survey (41.5 ha). This indicates the presence of excessive land ownership and hidden fragmentation in the area, referred to the standards of McPherson (1982, 5–6 cited in Hartvigsen, 2014).The presence of this very high level of land ownership, internal, and hidden fragmentation can be explained by the persistence of Egalitarian principles within the traditional

inheritance culture which leads to the subdivision of family land among all the descendants in equal shares in both quantity and quality, as confirmed by the majority of respondents during the household survey, key informants' interviews and the literature, which show this inheritance and the traditional succession as the main way of land acquisition and cause of land fragmentation in the study area. This will be discussed later in the causes of land fragmentation. This has been exacerbated by the informal land transactions like non-registered sales, donations and successions, while the article 30 of the law governing land in Rwanda prohibits the subdivision of agricultural and livestock land parcels which would result in small parcels of less than one hectare. Such small parcels cannot be individually registered. The same law encourages the common ownership of such parcels. Though this article 30 was established to prevent the continuous land ownership fragmentation, these informal subdivisions continue to be practiced in the Rwandan rural areas due to the historical culture of individual ownership for tenure security and high registration fees (Ntihinyurwa, 2015). The similar findings have been reported and supported by Kathiresan and MINAGRI (2012), Jayne et al.(2003 cited in GoR,2004; Bizoza and Havugimana, 2013; Musahara et al., 2014) when they showed that the majority of Rwandans (about 36 % of the households) own 6% of the farm lands with an average of 0.11 ha, and that almost a half of the farms are small with less than 0.3 ha (45.8%) with more than 83 percent of farms being smaller than 0.9 ha as the FAO economically viable farm's land size to sustain a family, since more than 50% of farm families have less than 0.70 ha, respectively. In this article, no distinction between land ownership and usership fragmentation has been drawn, since the focus was put on the number of land users/farmers in a given land block, regardless of the tenure status and type (leasehold, and freehold).

The high level of land location fragmentation could be explained by the preference of the majority of Rwandan farmers in the study area (90%) to have plots in different locations with different growing conditions (soil type, slope, microclimatic variations) as a risk management strategy, in case of long droughts, floods, and diseases. Since Gashora sector and Bugesera district in general is one of the driest areas with long droughts and sunny season, uncertain or even very few precipitations (NISR, 2015), farmers prefer to have land in lowlands around the wetlands, lakes and rivers for irrigation purposes along with the ones in uplands. They also prefer to grow the mixture of early maturing and late maturing, shallow and deep crops, diseases and sun resistant crops and water-resistant crops in different locations with different suitability. This is in accordance with the findings of Kathiresan and MINAGRI (2012), Mbonigaba and Dusengimana (2013) which advanced that the multiple holdings of over 4 –5 small plots often in multiple locations are valued by Rwandans since they can diversify their crop production across different locations, and thus provide protection against natural risks and unbalanced nutrition, even though it has been shown to lead to low agriculture productivity.

The findings about land use types in Figure. 2c have shown that the majority of households in the study area use their lands for agriculture purposes as confirmed by 80% of respondents and the 90% of the checked land titles along with the field observations without omitting other uses like forestry, mixed uses, residential and commercial respectively. The major part of this predominant agriculture land in the study area has been found to be cultivated through the monoculture(62% of the surveyed parcels in Table 1) under the Farm Land Use Consolidation program (LUC), where close farmers grow the same one

priority crop (maize, beans, wheat, Irish potatoes, cassava and soybeans) in a synchronized way based on the so called Agro Ecological Zones(AEZ) chosen for them by the government at the national level within the Crop Intensification Program (CIP) to boost the national agriculture productivity. Only 38% of the surveyed parcels in the study area are subject to the multiple crops, where farmers grow a mixture of different priority and non-priority crops with different production capacities in the same plots often located in different areas with various production potentials. This finding confirms the low level of land use fragmentation in Gashora sector, mainly due to this LUC program, though it has been recently found in different analytical studies by different researchers like Huggins (2012), Kathiresan and MINAGRI (2012), Konguka (2013), Musahara et al. (2014), and Ntihinyurwa and Masum (2017) to be inefficient and not participatory, since farmers do not participate in the choice of the priority crops suitable to their local agro-ecological conditions (soil, microclimate, etc). They have also found it to lead to the reduction of the area cultivated by the non-priority crops, thereby increasing the susceptibility to the risks from mono-cropping, and unbalanced nutrition as the main component of food insecurity at the household level. However, different other analytical studies like the ones conducted by Kathiresan and MINAGRI (2012), Mbonigaba and Dusengimana (2013), USAID (2014), at different times found this program to be a solution to the problem of land use fragmentation and food insecurity at the national level, through its contribution to the increase in agriculture production of the priority crops at the national level, which in turn increases the level of food quantity and food availability as components of food security as confirmed by the survey data above. With regard to the shape of parcels, the majority of the surveyed land parcels from the land titles (71%) have been found to have irregular shapes (with no well-defined geometric Figure like rectangular or square) as shown in the Table 1. This could be due to the absence of any organized land subdivision or redistribution program providing the standardized shapes and sizes to be used or followed during the land subdivision process. The high level of land value fragmentation in the study area can be linked with the heterogeneous topography and soils in Gashora sector.

The findings from the focus group discussions, key informants' interviews (driving forces of land fragmentation in Table 3) and household survey (ways of land acquisition in Table 2) along with the field visits and document review about the study area, have revealed different causes of land fragmentation grouped in the following 4 categories based on the forms of fragmentation:

a) Socio-cultural causes (Egalitarian inheritance laws, Egalitarian principles in customary practices, marriage, population growth and land related conflicts): Due to the high population growth on scarce and small land resources in the study area, the existence of inheritance culture and Egalitarian principles in land distribution through succession has led to the subdivision of family land among all the heirs in equal shares of all classes and grades, resulting into very small and non-contiguous parcels located in various places with different production potentials, as confirmed by the majority of respondents(38%) in household survey and all the key informants at 100%, along with the information from focus group discussion and the relevant reviewed literature. This has led in turn to the existing status of land ownership, hidden and internal fragmentation in the area. This tendency generalized to the whole Rwanda is complemented by the high national population density of 462 inhabitants /sqkm (NISR, 2015) as the highest in Sub-Saharan Africa. In the Rwandan culture, when women get married, they have to

join their husbands thereby leaving their plots in the home places often far away from their living places. This exacerbates the physical land location and internal fragmentation in the study area as mentioned by most of the respondents in key informants' interviews (100%) and focus group discussion, although no relevant literature has been found to confirm this finding. As mentioned above in the previous paragraphs, the article 30 forbidding the subdivision of parcels of less than 1 ha as a measure to cope with land fragmentation, has been accused by the majority of respondents (71% of key informants and the conclusions of focus group discussion) to lead to land ownership and use related conflicts among family members commonly owning the family land, since each family member wants to have his own portion for independent use or transaction. Despite the lack of enough supporting evidences of this finding in the Rwandan land sector literature, it has been pointed out to often lead to the hidden land use and ownership fragmentation in the study area. These findings and position are shared and quite similar to the findings of many different researchers in the literature like King and Burton (1982); McPherson (1982); Keeler and Skuras (1990); Bizimana et al. (2004), Niroula and Thapa (2005), Tan et al. (2006), Sklenicka and Salek (2008), Hristov (2009); Platonova et al.(2009); Sikor et al.(2009); Hartvigsen (2013,2014,2015a,b), Sklenicka et al. (2014); Ciaian et al.(2015); Hiironen et al. (2016) and Muchová (2017), at different times in different European, Asian and African countries who all emphasise on the Egalitarian principles in inheritance practices and land reforms, marriage and familial land related conflicts to be the main basis of both ownership (hidden and visible) and internal land fragmentation. The subsistence motive reasons have been also advanced by some authors like Ciaian et al. (2015) as factors of diversification when family members with different reasons prefer to have different heterogeneous lands with different crops suitability for their crops diversification to meet their various dietary preferences.

b) Economical causes (land market, formal and informal land transactions): Different land transactions through purchase of land parcels either formally or informally have been found to lead to high internal land fragmentation and ownership fragmentation, since farmers always tend to buy additional non-contiguous land parcels of different qualities and production potentials, often located in different places with different agro-ecological conditions far from the homestead, as advanced by 86% of the key informants, 23% of household survey respondents and focus group discussion conclusions. This can be explained by the fact that in the study area with heterogeneous topography (flat, hilly, and low lands, dry lands, wetlands), farmers believe that the soils are different in qualities, suitability and production potentials. For this, having different land parcels with different production potentials increases their risks management capacity and production diversification ability. In support to this from the literature, Ciaian et al. (2015) argued that it is somehow difficult to get additional parcels contiguous and close to the already farmed own land, thereby leading to the physical fragmentation (location and use). Additionally, the study of Grigg (1980) supports this finding by advancing that the growing land market through formal transactions like sales, purchases of land parcels contributes to land location fragmentation, since in many cases, farmers prefer or unwillingly purchase land which is not contiguous to their existing holdings or pieces of land as shares in other parcels. However, the later author argues that not all land market contributes to land fragmentation; rather, in some cases land purchase may reduce land fragmentation when farmers acquire neighbouring pieces of land to expand their holdings.

c) Physical causes (soil qualities, topography, location, shapes): From the belief of the majority of the respondents (100% of key informants, conclusions of focus group discussion) and 12% of household survey respondents, the presence of diverse soils with different soil fertility status and production potentials, diverse plots with different shapes, different locations with different microclimatic conditions, topography and biodiversity, gives the farmers the chances to diversify their output, and Figureht against the risks of loss of the entire production, in case of environmental risks prevalence like droughts, floods etc. For this, they prefer to have more plots with different physical properties located in different places, which leads to the physical land (use, location, internal, value and shapes) fragmentation. The small percentage of respondents who advanced the physical causes in the household survey resides in the fact that the majority of respondents were illiterate, and hence difficult to them to relate land fragmentation with more scientific and technical drivers. Furthermore, as mentioned above in the socio-cultural causes, these physical causes combined with the egalitarian principles in inheritance act as drivers of land ownership and hidden fragmentation in the study area, since all the family members receive the pieces of land of the same sizes, same qualities from all locations and all classes and grades (Keeler and Skuras, 1990; Tan et al., 2006; Ciaian et al., 2015). This position is supported by the studies of Johnson and Barlowe (1954); Buck (1964) and Netting (1972), which advanced a belief that land is not the same with respect to soil type, suitability, slope, altitude and agro-climatic location. They have found out that farmers decide to operate on many plots in different locations (land location fragmentation) to enable them reduce the risk of total loss of output due to perils such as floods, fires and droughts, since the scattering of plots also enables them to diversify their cropping mixtures across different growing conditions.

d) Operational/Normative/Institutional causes (land sharing program in Rwanda (1995–2012), land use consolidation program, Article 30 of the law governing lands in Rwanda, land redistribution programs before and after the 1994 Genocide and some rural infrastructures development):The findings from all data sources have revealed different land policies in the study area like the article 30 of land law forbidding the subdivision of land parcel less than 1 ha and encouraging the co-ownership of family land, LUC program, land sharing and redistribution programs after the 1994 genocide against Tutsis, to lead to hidden land use and ownership fragmentation as evidenced by 12% of respondents in household survey, 100% of key informants, and the key conclusions of focus group discussion, supported by some governmental reports and analytical literature about those policies and programmes. As an explanation to this, Rwandans like independency in ownership and use of their assets. In this regard, though the article restricts such subdivision, the customary practices and other social economic reasons like land use and ownership related conflicts push the persistence of these informal subdivisions all over the rural parts of the country without registering those resulting small plots. The Land Use Consolidation (LUC) program has also been stressed on to supplement this article 30 in stimulating these conflicts, when all the co-owners of the land parcels are obliged to grow one single priority crop which in some cases do not match the individual preferences Ntihinyurwa and Masum (2017). In this regard, the land conflicts can be confirmed as a cause of land subdivision for independent individual ownership and use, hence a cause of land ownership and use fragmentation. The study of Ciaian et al. (2015) supports this position by arguing that different family members may prefer to grow different crops to meet their various dietary preferences. The land sharing program which used the Egalitarian principles for the redistribution of land

among the 1959 returning refugees and the formal occupants of those lands at the time in equal shares also exacerbated the land ownership and physical land fragmentation problem in the study area as advanced by the majority of respondents. Different infrastructures development like roads construction disperses the contiguous land parcels in small pieces, leading in turn to physical internal fragmentation as supported by the reviewed global literature and some respondents during the key informants' interviews and focus group discussions.

In summary, the findings have revealed the causal interactions among the forms of land fragmentation as shown on the cross-cutting diagram in Figure 4 below.

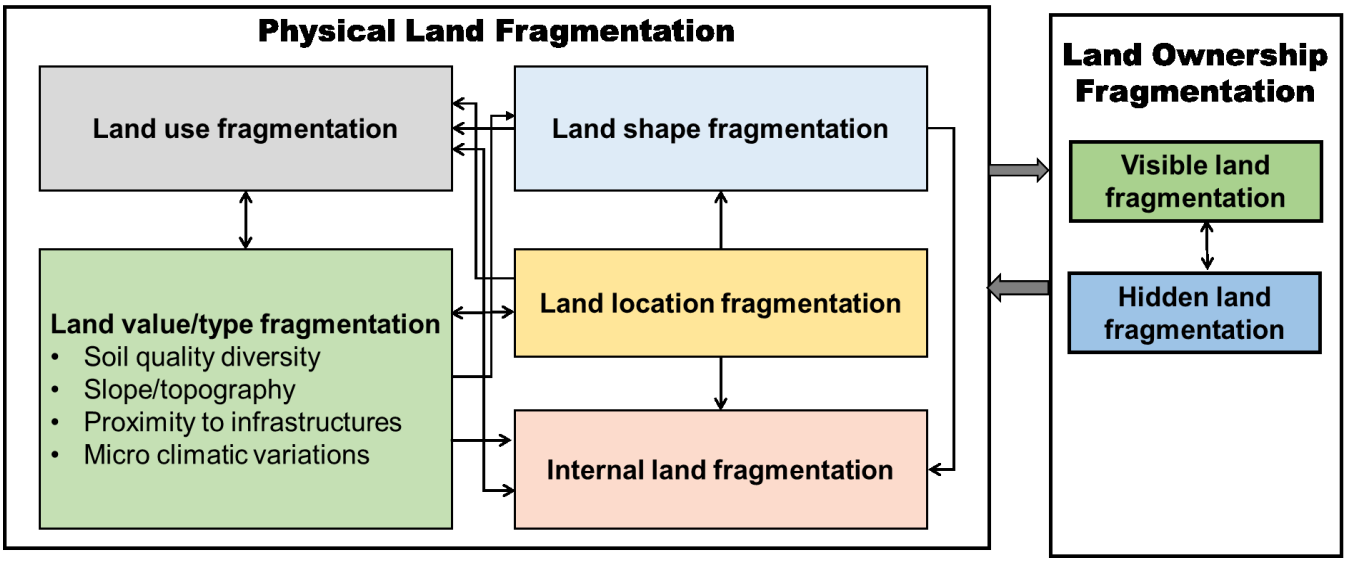

Figure 4A1. Causal interactions among land fragmentation forms

Source: Authors (2018)

The above diagram demonstrates that some forms of land fragmentation induce other forms and vice versa. The double arrow shows the mutual or bilateral interactions, while the single arrow shows the unilateral influence of one form to another. The diagram is a result of the combination of author's knowledge, primary data and the review of the existing literature about land fragmentation and its causes.

For the impacts of land fragmentation, the results in the Table 4 from the key informants' interviews and focus groups discussion reveal the increase in land tenure security, and reduction in ownership and use related conflicts as the key positive effects of land ownership and use fragmentation as advanced by 100% of respondents. With regard to the reduction in land ownership and use related conflicts, it has been argued that when each family member owns his parcel, there is an independency in use and management of that parcel. This in turn reduces the occurrence of intra familial land conflicts on the co-owned parcels, thereby increasing the tenure security, when the small individually owned parcels are legally registered. Furthermore, the majority of the key informants have reiterated the Environmental Risks Management Strategy (ERMS) through different growing conditions (Soil, slope, micro climate, etc.) and multiple crops, and the increase in nutritional balance through the variety of crops and different

growing conditions as an indicator of food quality to be the main effects of land location, use and shape fragmentation at 100% and 86% respectively. To support this version, the results from the household survey about the impacts of land fragmentation on food security at the household level have shown the increase in food quality and food sustainability as the key positive impacts of all the forms of land fragmentation with land value (99&95% of respondents), use (98&94% of respondents), location (97&95% of respondents) and internal (93&77% of respondents) fragmentation respectively at higher levels as shown in the above Figure 3.

These findings show that not all the land fragmentation forms are a problem, since there are some cases where *fragmented land is a risk management strategy especially in areas with high microclimatic variations* like Rwanda, as supported *by* different FAO land tenure studies (2003). The same findings are shared and supported by Konguka (2013) who indicates how fragmented land has some benefits associated with scattered pieces of landholdings at different locations with varying soils and ecological characteristics. He argues that varieties of soils enable a farmer with a number of small parcels to grow a wider variety of crops in comparatively small areas thereby reducing overreliance on a limited number of crops species that can be disastrous when disease strike or pests threaten to wipe out an entire harvest. Based on the explanations from the focus group discussion, this helps to withstand the effects of climate change in different risks prone areas in Rwanda especially in the study area, leading to the sustainable production of the diversity of crops throughout the whole year, thereby increasing the nutritional balance for food quality and food sustainability as components of food security. The findings of Sundqvist and Lisa (2006) about the impacts of land fragmentation on agriculture productivity in Northern Vietnam also confirm the same version of advantages of land use and location fragmentation. This positive position of land fragmentation is also similarly supported by the findings of Ciaian et al. (2015), since they have found that land fragmentation stimulates significantly more diversification for subsistence farm households than for market-oriented households in Albania. They have advanced that the consolidation policies that relocate and enlarge plots would have a significant impact on reducing agricultural production diversification and that land fragmentation contributes to the food security improvement by increasing the variety of foodstuffs produced by subsistence farm households. For them and similar to our findings, the more the differences, diversity or heterogeneity in land and soil qualities with various suitability classes and production potentials, the more the variety in growing conditions, the more the crops diversification and food stuffs diversity, the higher the nutritional balance, the higher the food quality and sustainability, the higher the food security.

This converge with the Sustainable Development Goals (SDGs 2, 13 and 15) of achieving Zero Hunger, adaptation to climate change, and the protection and sustainable use of land resources through the prevention and/or reduction of biodiversity loss in the Agenda 2030 respectively. The achievement of these goals stipulates the focus on the sustainable and climate smart agriculture which requires the growth of multiple crops with different adaptation capabilities on plots spread in different areas with different suitability and growing conditions, in order to promote the biodiversity of cultivated plants and livestock, increase the diversity of food stuffs to support the nutritional balance and sustainable food production throughout the whole year, rather than the widely known market-oriented agriculture on big

farms often promoting the monoculture and exposing the loss of the entire production in case of environmental risks outbreak as result of climate change. This climate resilient agriculture requires a sound recognition of the positive impacts of land use, location, value and in some cases of internal fragmentation discussed above. In support to our findings, King and Burton (1982); McPherson (1982); Bentley (1987); Keeler and Skuras (1990), Van Dijk (2003a,b), Tan et al. (2006), Van Hung et al. (2007), Sklenicka and Salek (2008); Hristov (2009); Platonova et al. (2009); Sikor et al. (2009); Demetriou et al. (2013), have all emphasized on the importance of land fragmentation in heterogeneous communities with varying land and soil conditions, when farmers find land fragmentation as desirable for social and environmental reasons. It acts as total harvest loss risks spreading management strategy (through disease, hail, droughts, floods and other natural disasters) and factor for diversification in various soils and growing conditions. This strengthens the idea of specifying land consolidation projects to different local conditions, rather than blindly following the ever growing panacea of transplanting modern land consolidation systems from more homogenous and market-oriented European agriculture contexts in different, heterogeneous local contexts which in many cases end up in failures. Similar to their findings, the group discussions and key informants' results have also mentioned the physical land fragmentation as a tool for equal distribution of resources through the Egalitarian principles, and driver of biodiversity conservation as sometimes opposed to the land consolidation practices in many countries with more market oriented and monoculture based agriculture.

On the other hand, besides the findings about the positive impacts of land fragmentation, Table 4 also indicates the main negative impacts of different forms of land fragmentation to be the decrease in agriculture production efficiency (high production costs due to time and transport) by 86%, 71%&57% of key respondents for land location and value, land shape, and internal fragmentation respectively; Decrease in yields of priority crops (agriculture production) by 71% of key respondents for both land ownership and use fragmentation respectively; Obstacle to mechanization, irrigation and drainage infrastructures by 100 % of key respondents for internal land fragmentation; Increase in land ownership, boundaries & use related conflicts by 100% & 86% of key respondents for land ownership and use fragmentation respectively; Loss/wastage of land through boundaries by 100% & 71% of key respondents for land ownership and internal fragmentation respectively. It has been argued during the key informant's interviews and focus group discussions that the fact of holding many different small parcels in different locations with irregular shapes and scattered uses makes the farming activities more difficult to supervise, increases the inputs and outputs transport costs and time consuming, thereby reducing the agriculture production efficiency. Furthermore, the small plots also reduce the national agriculture production of the priority crops per ha, since the evidences have shown the agriculture intensification of small plots in subsistence agriculture to be difficult. This multiple holding by many different owners has also been argued by the key informants to increase the number of boundaries leading to the occurrence of boundaries related conflicts and the loss of some land area through boundaries. It is considered as a major threat to efficient production system due to the fact that continuous subdivision of farms leads to small sized land holdings that may be hard to economically operate.

In addition to that, the results from the household survey have also revealed the negative linkages between different forms of land fragmentation (ownership, shape location) and some aspects of food security (food quantity, food availability and food sustainability). Only 20%, 40% &55% of the respondents have positively linked the high level of land shape, ownership and location fragmentation with the high level of food security in the study area respectively, while 40%&46% linked them with food availability. Generally, the data in Figure. 3 show land ownership and shape fragmentation to have the lowest levels of positive impacts on food security in the study area, as also confirmed by the percentages of respondents who linked them with food sustainability (50%&52% respectively), and food quality (60%&56% respectively), besides the above mentioned reverse linkages with food quantity and availability. This automatically highlights them as the main problematical land fragmentation situations in the study area, and targets for coping strategies like subdivision restrictions, and modern land consolidation instruments. In the support of this negative side of land fragmentation in Rwanda, the review of the existing literature has shown that GoR (2004), Musahara and Huggins (2005), Kathiresan and MINAGRI (2012), Ntirenganya (2012 cited in USAID, 2014), Mbonigaba and Dusengemungu (2013) find land fragmentation as a negative factor of food security through the reduction of the efficiency of agriculture production at the national level, since the yield per HA is small when agriculture is done on small plots far away from the residence due to the high production costs, and call for the emphasis on land consolidation practices to counter this internal and location fragmentation, regardless of their positive impacts. This slight difference from our finding resides in the fact that most of the previous studies did not consider all the forms of land fragmentation, the micro climatic variations, the climate change challenge and all the aspects of food security. Their studies were only focusing on land ownership and location fragmentation as a threat to the quantity of agriculture production and food quantity, thereby ignoring the nutritional balance and quality aspects. In this regard, the authors argue that the choice of strategies to cope with land fragmentation should be merely based on an in depth assessment of the available problematic forms, local agro-ecological conditions, social, economic and political contexts, along with the ever growing climate change global threat, since not all the land fragmentation forms are problematic.

According to Demetriou (2014), there exist different policies/strategies to tackle or control land fragmentation. These range from legislative strategies (restrictions regarding inheritance, minimum size of parcel division, absentee landowners, prevention of transfer to non-farmers, leasing, imposing a maximum limit on the size of a holding, etc) for land ownership and internal fragmentation control, land management strategies/approaches including the famous land consolidation, land funds and land banking, voluntary parcel exchange and cooperative farming for physical (internal, location, use and shape) and ownership land fragmentation control for market oriented/commercial agriculture purposes, and specific land protection policies/programmes to prevent agricultural land from being developed for housing or commercial use as a tool for land use fragmentation control. For this, it would be worth wealthy to wisely choose among the above strategies which ones would be specific to the problematic land fragmentation local situation, based on evidences based participatory feasibility and suitability studies, rather than always thinking of land consolidation as a panacea to all land fragmentation situations. The modern land consolidation instrument as it is applied in the European context to control the internal,

location and shape fragmentation problems to increase agriculture production efficiency through the increase in well-organised farm sizes in the context of commercial and mechanised agriculture can not necessarily solve all land fragmentation problems in the African rural context dominated by the subsistence agriculture as confirmed/proved by the above findings in the rural Rwandan case study. Therefore, it should be mainly applied with probable successful results in more homogenous areas with less variability in agro-ecological, physical (soil, slope, water, etc), socio-economic and climatic conditions in the developing countries with quite similar context to the European one. Otherwise, there is a need for the development of a more local context specific land consolidation approaches different from the modern one, in more heterogeneous areas.

Since this study has been conducted on a small quite homogeneous area, using only simple methods for measuring land fragmentation, the findings have been only limited to Gashora sector in Bugesera district due to high microclimatic variations in Rwanda, heterogeneity of the country´s social, economic and physical aspects. They cannot be generalized to the whole country, though previous studies in different regions have shown some similarities. However, the empirical findings are in line with the pre-established hypothesis, since they indicate that higher levels of physical land fragmentation (location, use, shape, value and internal), and hidden land ownership fragmentation act as risks management strategy, through crops and food stuffs diversification in the study area. Furthermore, the findings have also evidenced the positive correlation of some land fragmentation forms (use, location, value and internal) with the nutritional balance for food quality and food sustainability as components of food security at the household level in the study area, despite the negative relationship between land ownership and shape fragmentation, and food quantity and food availability. For this, the classical assumption of considering land fragmentation as always a bad phenomenon is not true, since the evidences in the study area have shown its positive side, when it comes to the heterogeneity of social, cultural, economic and physical conditions in areas like Gashora sector. Hence there is no uniform replication of the classical theory of land fragmentation, since it varies upon the type of fragmentation and the circumstances along with the social, economic, cultural, political, physical and environmental conditions of an area.

6. Conclusions

The discourse on land fragmentation has so far been rather idiosyncratic (i.e. focusing on single aspects only) and rather negative (being an obstacle to agriculture production and food security). The consistency of this narrative has contributed at times to inappropriate strategies which were not climate resilient. The resultant land consolidation practices may have increased agricultural production at the national level and significant derived benefits in the European context, but they have also exacerbated the problem of nutritional balance, food quality and food sustainability as components of food security at the national and household levels. In contrast, the findings of this study have indicated the positive impacts of some forms of land fragmentation (ownership, use, internal, value and location) in the study area at different levels. They have proved that a high level of fragmentation exists in the study area, both in terms of land ownership (visible and hidden) and physical landscape (internal, location, value and

shape), and a low level of land use fragmentation as a result of the ongoing Land Use Consolidation program (LUC) which is a national controversial strategy to broadly cope with land fragmentation problems in Rwanda. The dominant reasons of these high levels are that land users perceive land fragmentation as an effective risks management strategy which would positively affect food quality, food sustainability and food security as proved by the data from the household survey, key informants' interviews and focus groups discussion. Multiple land holdings with different shapes in different locations allow farmers to grow multiple crops with different adaptation capacities in different growing conditions (soil type, slope, microclimate variations, etc.). Furthermore, the findings from all the data sources in this article have shown that some forms of land fragmentation (use and ownership fragmentation) can contribute to the reduction of land ownership and use related conflicts through the increase of individual ownership and use independency, despite its negative impacts on agriculture production efficiency, loss of land through boundaries and boundaries related conflicts. The same findings also show the physical land fragmentation as a tool for biodiversity conservation. Therefore, the study confirms the positive impacts of land use, location, internal, value, ownership and shape fragmentation on food sustainability and food quality as components of food security at the household level as a new finding in this field, based on the evidences from the household survey (correlation of present high levels of land fragmentation forms in the study area, with the aspects of food security at the household level), key informants interviews and focus group discussions as pre-assumed in the study hypothesis. In this regard, the respondents have advanced that the multiple holding of small plots with different shapes in multiple different locations allow the farmers to grow different crops with different adaptation capacities (shallow versus deep rooted crops, droughts resistant versus floods resistant crops, early maturing versus late maturing crops, perennial versus cash crops, cereals versus vegetables and tubers, disease resistant and non-resistant crops) in different areas with different suitability and growing conditions(soil type, slope, microclimate variations etc.), as a risks management and climate change adaptation strategy through the prevention of the total loss of agriculture production in case of environmental disasters outbreak. This increases the level of the nutritional balance, food sustainability and food quality as components of food security at the household level as a result of crops and food stuffs diversification, as confirmed and supported by the literature on the positive side of land fragmentation.

Most of the chosen theories like the classical theory of land fragmentation as a negative phenomenon, FAO theory of land fragmentation as an environmental risk management strategy and food security driver, the food security theory as a multidimensional concept, and the methodology used in this research have been useful. The information about the indicators of land fragmentation, their causes, and implications (positive and negative) on food security could not have been obtained without using the household survey, field visits and literature review, key informant`s interviews and focus groups discussions respectively, along with the descriptive statistics, correlations and texts analysis methods. The correlation of the level and forms of land fragmentation and different aspects of food security has helped to draw the useful insights about the topic and confirm our hypothesis (land fragmentation as positive phenomenon), though there were some methodological limitations like small study area, no use of more sophisticated measurements of land fragmentation like different indexes as mentioned in the previous section.

Therefore, the study recommends an adaption to land fragmentation discourse. This adaption concerns the consideration of some forms of land fragmentation like physical land fragmentation (use, value, internal, location, shape) as a climate resilient solution to food insecurity, when preparing the coping and control strategies/policies to land fragmentation and food insecurity in climate change vulnerable and prone areas like Rwanda, in order to support the achievement of the Sustainable Development Goals (SDGs 2, 13 and 15) of meeting Zero Hunger, adaptation to climate change, and the protection and sustainable use of land resources through the prevention and/or reduction of biodiversity loss in the Agenda 2030 respectively. Since the research has been limited in scope and methodology, the authors recommend further detailed and generalized research on the level of land fragmentation covering a big heterogeneous area of Rwanda, using all the globally recognized methods for measuring land fragmentation, and the assessment of the suitability and necessity of land consolidation practices in the country. The choice of any strategy to control land fragmentation should be based on a feasibility study prior to its implementation in the local context for the benefits of local farmers. The modern land consolidation system would be mainly applied with probably successful results in more homogenous areas with less variability in agro-ecological, physical (soil, slope, water, etc), socio-economic and climatic conditions, and this should be the main focus in the Rwandan context as a climate change resilient and adaptation strategy to land fragmentation and food insecurity problems as stipulated by the SDGs.

Appendix A. Types and attributes of conceptualising land fragmentation

Table A1. Types and attributes of conceptualising land fragmentation

Emphasis on	Addressed in (article, literature)	Criteria to consider which result in fragmentation. There is fragmentation in parcels or in an area if:	Implications of each type of fragmentation
Absolute physical features or physical fragmentation(shapes or sizes of individual parcels, size of household land holding or farm, Number of parcels per household holding or farm, length of boundaries, distances from / to individual parcels)	King and Burton (1982); McPherson (1982); Keeler and Skuras (1990); Sabates-Wheeler (2002); Van Dijk (2003a, b); Sundqvist and Lisa (2006); Tan et al. (2006); Van Hung et al. (2007); Hristov (2009); Platonova et al. (2009); Sikor et al. (2009); Ciaian et al. (2015); de Vries (2016); Demetriou et al. (2013); Hiironen et al. (2016); Janus et al. (2018)	▪ There are Irregular shapes of parcels (not rectangular nor square) ▪ The size of the parcel or a farm is smaller than 1 ha. ▪ The number of parcels or plots per household land holding/farm is equal to 2 or more. ▪ Non-contiguous plots located in 2 or more different places ▪ Boundaries between parcels are long (indicating a meandering shape) ▪ Distance from house to parcel is longer than 500m.	▪ Difficult to harvest and reach parcels ▪ High production costs through transport of inputs like fertilizers and seeds. ▪ Low agriculture production efficiency (Small yields with high costs per small unit area ▪ Loss/wastage of land through boundaries ▪ Increase in boundaries related conflicts ▪ Risks management strategy through diversification of crops on plots with various production potentials ▪ Facilitates the Crop rotation flexibility/diversity and increases biodiversity ▪ Obstacle to market oriented agriculture
Relative or aggregate physical features (i.e. average size, average shapes, average distances, average number of plots/parcels)	King and Burton (1982); McPherson (1982); Keeler and Skuras (1990); Blarel et al. (1992); Van Dijk (2003a,b); Sundqvist and Lisa (2006); Tan et al. (2006); Platonova et al.(2009); Hristov (2009); Demetriou et al. (2013); Ciaian et al.(2015); Hiironen et al. (2016; Muchová (2017)	▪ In an area under consideration the majority (e.g. more than 50%) have irregular shapes ▪ In an area more than 50% of the parcels are smaller than 1ha. ▪ More than 50% of household land holdings/farms are divided in 2 or more parcels. ▪ More than 50% of the household landholding /farms have plots or parcels located in 2 or more places at the distances of more than 500m from the homestead.	▪ High transaction costs (given the waste of time to get to the parcels) ▪ High dependencies (on existing roads, and infrastructures) ▪ Obstacle to mechanization, irrigation and drainage infrastructures ▪ Risks management strategy (diseases and pests spreading control, droughts and floods control) ▪ Output or agricultural production variation ▪ Increase in food security through crops and food stuffs diversification ▪ Loss/wastage of land through boundaries and increase in boundaries related conflicts ▪ Abandonment of some potential agriculture lands distant from the homestead (difficult to access)

Socio-legal features (i.e. land ownership, land use) for ownership and use fragmentation	King and Burton (1982); Keeler and Skuras (1990); Sabates-Wheeler (2002); Van Dijk (2003a,b); Tan et al. (2006); Sklenicka and Salek (2008); Hristov (2009); Sikor et al.(2009); Demetriou et al. (2013); Sklenicka et al. (2014); Hartvigsen (2013, 2014, 2015a,b); Hiironen et al. (2016); Muchová (2017)	▪ Many land owners exist in a relatively small area ▪ Many land users exist in a relatively small area ▪ Many overlapping claims exist ▪ Many different crops exist in a single farm/household holding or within a small area ▪ More than 2 land use types exist in a household landholding (arable land, grassland, residential, forest land etc) ▪ Large number of household members (more than 4) co-owning a small land parcel (less than 1ha).	▪ Obstacle to mechanization, irrigation and drainage infrastructures ▪ Increase in land ownership related conflicts ▪ Increase in familial land use related conflicts in case of co-ownership ▪ Difficult land use planning ▪ Equal distribution of land (Equal and Equitable treatment) ▪ Inheritance flexibility ▪ Increase in tenure security through the use and ownership independency ▪ Household food self-sufficiency ▪ Abandonment of some potential agriculture lands distant from the homestead (difficult to access)
Bio-physical features (soil type, soil quality, biodiversity, environmental quality, ecological features, etc.) for value, use, ownership and location fragmentation	King and Burton (1982); McPherson (1982); Keeler and Sukras (1990); Blarel et al. (1992); Van Dijk (2003a, b); Sundqvist and Lisa (2006); Tan et al. (2006); Sklenicka and Salek (2008); Hristov(2009); Platonova et al., (2009); Sikor et al. (2009); Demetriou et al. (2013); Ciaian et al. (2015)	▪ Land parcels with diverse slopes (Steep slopes vs flat slopes) ; fertile and non-fertile soils ;wetlands versus mountainous ; rainfed versus dry lands ;agriculture suitable versus unsuitable lands ; heterogeneous soils, topography, flora and fauna, etc.	▪ Increase in food security through crops and food stuffs diversification ▪ Risks management strategy through diversification of crops on plots with various production potentials (diseases and pests spreading control, droughts and floods resistance) ▪ Output or agricultural production variation ▪ Strengthens subsistence agriculture ▪ Increases land use and ownership fragmentation ▪ Increase in land use and ownership related conflicts ▪ Increased biodiversity
Normative features (derived from policy, e.g. spatial justice, Land reforms, land market)	King and Burton (1982); Keeler and Sukras (1990); Tan et al. (2006); Sklenicka and Salek (2008); Hristov (2009); Platonova et al.(2009); Sikor et al. (2009); Sklenicka et al. (2014); Ciaian et al. (2015); Hartvigsen (2013, 2014, 2015a,b)	▪ Existence of the egalitarian inheritance principles in the area ▪ Existence of land sharing and distribution programs in the area ▪ Absence of land consolidation, sizes restrictions and land speculation control programs in the area ▪ Domination of subsistence agriculture in the area.	▪ Equal distribution of land (Equal and Equitable treatment) ▪ Inheritance flexibility ▪ Increases land use and ownership fragmentation ▪ Loss/wastage of land through boundaries and increase in boundaries and ownership related conflicts ▪ Reduction in agriculture production efficiency/obstacle to market oriented agriculture ▪ Increase in agriculture production diversification and food stuffs diversity

Source: Authors (2018), from the literature review

Appendix B. Overall Research Matrix

Table B1. Overall research matrix

Research variables	Indicators/Required information	Sources of data	Data collection methods	Data analysis methods
Forms and level of land fragmentation in Gashora sector/ Rwanda	**Physical Fragmentation** (Number of plots per household, Total number of plots in the study area or per land block, Size of farm or a land block in the study area (in ha), Average number of plots per owner, Average household land holding size (in ha), Average plot size in the study area, Average size of plot per co-owner (in ha), Land use types, land shapes, land types)	Land owners (Farmers), land titles, Literature and field visits.	Household survey through semi-structured interviews, and field observations (primary data), Literature/document review (secondary data).	Descriptive statistics (percentages, means or averages and frequencies), images analysis
	Ownership Fragmentation (Number of land owners, Total number of co-owners (Household members) per land block in the study area, Average number of co-owners (Household members) per land holding, Size of farm or a land block in the study area (in ha), Average number of plots per owner, Average household land holding size (in ha))	Land owners (Farmers), land titles, Literature and field visits.	Household survey through semi-structured interviews, and field observations (primary data), Literature/document review (secondary data).	Descriptive statistics (percentages, means or averages and frequencies), images analysis
Causes/driving forces of land fragmentation in Gashora sector/ Rwanda	**Social-cultural and economic causes**(Land market, inheritance, land transactions, marriage, Egalitarian principles, customary practices etc)	Government officials (Land managers, agronomists, Agriculture Land Policy makers), Land owners (Farmers) local leaders, Literature.	Household survey through semi-structured interviews, Key informants unstructured interviews , focus group discussions and field observations (primary data), Literature/document review (secondary data)	Descriptive statistics (percentages, means or averages and frequencies),Texts(Reduction, Display, and conclusions drawing)
	Biophysical causes (Land and soil qualities, climatic conditions, topography, etc)	Government officials (Land managers, agronomists, Agriculture Land Policy makers), Land owners (Farmers), Literature and field visits	Household survey through semi-structured interviews, Key informants unstructured interviews , focus group discussions and field observations (primary data), Literature/document review (secondary data)	Descriptive statistics (percentages, means or averages and frequencies),Texts (Reduction, Display, and conclusions drawing)
	Normative causes(land reforms, land policies, etc)	Government officials (Land managers, agronomists, Agriculture Land Policy makers), Land owners (Farmers) local leaders, Literature	Household survey through semi-structured interviews, Key informants unstructured interviews , focus group discussions and field observations (primary data), Literature/document review (secondary data)	Descriptive statistics (percentages, means or averages and frequencies),Texts (Reduction, Display, and conclusions drawing)
Effects/implications of land fragmentation in Gashora sector/Rwanda	**Positive implications and food security**	Government officials (Land managers, agronomists, Agriculture Land Policy makers), Land owners (Farmers), Literature and field visits, local leaders	Household survey through semi-structured interviews, Key informants unstructured interviews , focus group discussions and field observations (primary data), Literature/document review (secondary data)	Descriptive statistics (percentages, means or averages and frequencies),Texts (Reduction, Display, and conclusions drawing), correlations
	Negative implications	Government officials (Land managers, agronomists, Agriculture Land Policy makers), Land owners (Farmers), Literature and field visits, local leaders	Household survey through semi-structured interviews, Key informants unstructured interviews , focus group discussions and field observations (primary data), Literature/document review (secondary data)	Descriptive statistics (percentages, means or averages and frequencies),Texts (Reduction, Display, and conclusions drawing),correlations

***Source*:** Authors (2018)

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Appendix 2 (A2). Farmland fragmentation concourse: Analysis of scenarios and research gaps

Abstract

The conceptualization of farmland fragmentation varies across different scientific disciplines and units of analysis. Although a large body of literature on this phenomenon exist, yet there is no comprehensive understanding about the underlying reasons behind this conceptual variety and how it affects the management of different fragmentation scenarios. Consequently, policy makers and research scholars are unable to devise suitable fragmentation management strategies, which leads to contradictory, irrelevant and inappropriate interventions. This study explicitly and comprehensively displays how and why the farmland fragmentation conceptualizations differ, and which derived scenarios exist. The goal is to develop the typology of fragmentation which can guide farmland fragmentation management decisions for food security. This guide connects to the framework of the Sustainable Development Goals, notably SDGs 1,2,12,13 & 15. The study draws on rationalist theory and adopts an integrative concept-centric qualitative approach which builds on the analysis of the existing body of multi-disciplinary literature on farmland fragmentation and on deductive logical reasoning to create new comprehensive scientific knowledge, as an informative guidance for future research and policies. The analysis revealed an ontological and epistemic variety of both the spatial units (such as plot, parcel, farm, and farmland or land block) and the social and physical characteristics which underlie the description of land fragmentation. Moreover, the study identified a diversity of land fragmentation forms falling into two categories of Physical and Tenure fragmentation, whose extent and measurements are determined by specific local conditions and vary from case to case. These can separately apply in practice in different land areas or coexist in the same area under a typology of 40 different fragmentation scenarios based on various mathematical combinations of its spatial and non-spatial descriptors at different levels (parcel, farm, land block). As land managers need to be aware of all farmland fragmentation scenarios, we posit that any farmland fragmentation management intervention is a combination of various spatial and non-spatial effectors in order to be responsible and sustainable. Therefore, since the management of farmland fragmentation varies from scenario to scenario, any attempt to control it should consider the understanding of all the possible scenarios in a given area (as have been identified in this study) as a precondition for action. This is relevant because it would allow to grasp the causes, impacts (positive and negative), the conditions determining the problematic and rational scenarios of farmland fragmentation, and their functional distinctiveness at different spatial levels.

Keywords: Farm; Farmland fragmentation; Farmland fragmentation scenarios; Food security; Responsible land management; Integrative review.

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1. Introduction

The concept of farmland fragmentation appears to be very complex, fluid, multidisciplinary and refers to a widespread multidimensional phenomenon (Bentley, 1987;Sabates-Wheeler, 2002). A group of many authors define it as the situation in which a single farm consists of numerous spatially

separated (non-contiguous) small parcels often scattered over a wide area (Binns, 1950;McPherson, 1983;Simons, 1985;Bentley, 1987;FAO, 2003;Ciaian *et al.*, 2018a). However, this definition only considers the physical aspect of land at the farm level, thereby ignoring its social/tenure aspect and other spatial levels like parcel (land unit with determined boundaries and unique legally recognised homogeneous rights and interests) (Brown and Moyer, 1994;Henssen, 2010) and land block, where a relatively small area of land may be owned/leased by a big number of users/farmers resulting in the increase of the number of small farms or plots in that area (Van Dijk, 2003;Vranken *et al.*, 2004;Hartvigsen, 2014;Sklenicka *et al.*, 2014;Muchová, 2019;Ntihinyurwa *et al.*, 2019). Also known as – pulverization (Bentley, 1987;Kadigi *et al.*, 2017),subdivision (Farmer, 1960;King and Burton, 1982), parcellisation (Roche, 1956), scattering and dispersion (Sorbi, 1952;Farmer, 1960;Sanderatne, 1972;Galt, 1979;King and Burton, 1982;Bentley, 1987;Kadigi *et al.*, 2017), this land fragmentation concept - is epistemically referred to as farm fragmentation (Blarel *et al.*, 1992), agricultural land fragmentation (Brabec and Smith, 2002;Kalantari and Abdollahzadeh, 2008;Sklenicka and Salek, 2008;Vijulie *et al.*, 2012), landscape fragmentation (Lisec and Pintar, 2005;Muchová and Petrovič, 2010;Farley *et al.*, 2012), field fragmentation (Galt, 1979), and ownership fragmentation (Sklenicka *et al.*, 2014;Muchová, 2019;Muchová and Raškovič, 2020) in various documents.

Despite this epistemic variety, most studies treat it as common and universal feature of historical development of agricultural land and societies (Bentley, 1987;Van Hung *et al.*, 2007). The common notion is that fragmentation is defective and ineffective for agricultural production, and leads to lower quantities of food through farm inefficiency (Binns, 1950;Sabates- Wheeler, 2002;Bizimana *et al.*, 2004;Tan *et al.*, 2008;Kawasaki, 2010;Latruffe and Piet, 2014;Abubakari *et al.*, 2016;Hiironen and Riekkinen, 2016;Alemu *et al.*, 2017;Asiama *et al.*, 2019). However, yet, there also exist alternative views which posit that not all fragmentation forms are problematic. In fact, there is documented evidence that farmers deliberately use fragmentation for the purposes of crops diversification and as an adaptive and risks management strategy for food security (Igbozurike, 1970;Bentley, 1987;Blarel *et al.*, 1992;FAO, 2003;Niroula and Thapa, 2007;Di Falco *et al.*, 2010;Isaacs *et al.*, 2016;Ciaian *et al.*, 2018a;Cholo *et al.*, 2019;Ntihinyurwa *et al.*, 2019). This polarized nature and epistemic controversy about farmland fragmentation make it necessary to derive a comprehensive classification of the varieties of fragmentation which can better devise different specific alternative strategies that could simultaneously minimise its defective effects, thereby optimising or without compromising its potential benefits for its optimal management. This requires a sound comprehensive informative knowledge and common understanding and description of how to detect and measure different fragmentation scenarios, which would incorporate fragmentation forms and their characteristics, fragmentation descriptors, and fragmentation actors and their interactions.

Nevertheless, the current epistemic positions on fragmentation suffer from biases in subjectivity, inconsistency, fluid and complex conceptualizations, which make it difficult for policy makers and research scholars to devise the suitable farmland fragmentation management interventions, despite the existence of a large body of literature on this concept. This lack of consistency and variety in epistemic definitions has often led to the formulation of broad irrelevant and non-appropriate fragmentation control strategies as can be witnessed in countries such as Kenya, Malawi, Tanzania, Rwanda, India, and Central and Eastern Europe, thereby contributing to their general failure (King

and Burton, 1982;Bentley, 1987;Blarel *et al.*, 1992;Sabates- Wheeler, 2002;Huggins, 2013;Pritchard, 2013;Kadigi *et al.*, 2017;Chigbu *et al.*, 2019;Ntihinyurwa *et al.*, 2019). These examples call for a more comprehensive research about the typology which better captures the variety and dynamics of farmland fragmentation scenarios and would be able to better detect the underlying reasons for this variety, and the possible land management interventions to deal with it.

In light of that, this study critically and objectively reviews and synthesizes the existing literature on land fragmentation, its different forms, characteristics, indicators, measurements, extent, and actors embedded in different scenarios. The aim is to clarify the existing ontological and epistemic differences, and explain the underlying reasons; identification of the knowledge gaps and openings for further research; and the reconceptualization of this fragmentation phenomenon. This results in explicit typology of different farmland fragmentation scenarios, which can guide policy makers and inform future studies about suitable farmland fragmentation management strategies.

Being an integrative review, the article builds on the analysis of the existing body of literature through a process of logical reasoning following the rationalist theory, and a concept-centric approach literature query, selection, analysis and synthesis to create new comprehensive knowledge about the topic. Moreover, the review extends the existing debate about the position and integration (how and where) of farmland fragmentation in the Sustainable Development Goals 1,2,12,13 &15, and the market -oriented agriculture nexus. Since the farmland fragmentation term is variously conceptualized in different contexts, disciplines and levels of analysis, only its meaning in the context of agriculture production at all levels is followed in this article. Only the literature in English language about the topic is considered. Hence, this article is structured as follows: First, the concept of land fragmentation is introduced. Second, the methodology of the literature identification, review, analysis, synthesis and reconceptualization is described. Third, the existing conceptualizations and their underlying reasons for their variations, forms, indicators, measurements, extent and scenarios of land fragmentation are discussed. Fourth, the new possible fragmentation scenarios are developed, the various complex and subjective fragmentation meanings reconceptualised and harmonized, and the new relationships discussed and motivated. Finally, the conclusions and implications for further research are drawn.

2. Materials and methods

2. 1. Research approach and boundaries

Being a review article, this study relies only on secondary data to create new scientific knowledge and inform future research and policies. It adopts an integrative concept-centric qualitative approach which follows the rationalist theory as suitable epistemology and research method for this kind of studies to deduct the scientific knowledge from the existing literature through the exploratory research design (Webster and Watson, 2002;Torraco, 2005, 2016). According to Webster and Watson (2002) and Torraco (2016), a concept centric approach facilitates the critical review, analysis and synthesis of existing knowledge about a topic, and may derive the key definitions and the variations thereof. In addition, the historical developments of the key concepts and the key proponents of seminal articles may be derived. It deductively uses own reasoning (abstract way of reasoning) without sensory experiences or empirical data to reconceptualise the topic for a better understanding and guide future perspectives. This helps to draw the possible relationships/linkages among different variables, identify the gaps, deficiencies, contradictions and opportunities for future research, and

reconceptualise it for a better understanding to guide future perspectives. The approach further relies on initial acquaintance and knowledge about a topic which may enable a critical analysis of how relevant previously defined concepts are still in current contexts, and for addressing contemporary problems (Webster and Watson, 2002;Torraco, 2016). Given the aim of deriving various conceptualizations of farmland fragmentation and exploring how this can be best managed, the literature review focused on the concourse about agricultural land fragmentation across contexts and disciplines at all levels as a contextual boundary. The use of multi-levels of analysis is explained by the fact that land fragmentation itself is a multi-level phenomenon, whose impacts as well as control strategies can be identified from the local (individual, household, family, village) to regional and national levels. For internal data validity purposes, spatial and temporal limitations were not considered, which led to the geographically unlimited review of both old and new available literature, as a suitable method for this case of research approach. It adopts a synthetic strategy of sense making which suggests the use of multiple cases and broad selection criteria to create a more comprehensive knowledge (Langley, 1999;Webster and Watson, 2002). However, in order to prevent the divergences, misuse, and linguistic bias about different concepts, both empirical and review literature only in English language in which the large body of extensive literature exist on this topic was considered for review. The next section explains the processes and methods for literature identification (search, selection criteria and its sources or databases), review, analysis and synthesis techniques, and the reconceptualization or modelling methods and procedures for new scientific knowledge creation on the topic as summarized in the research design (see Figure.1).

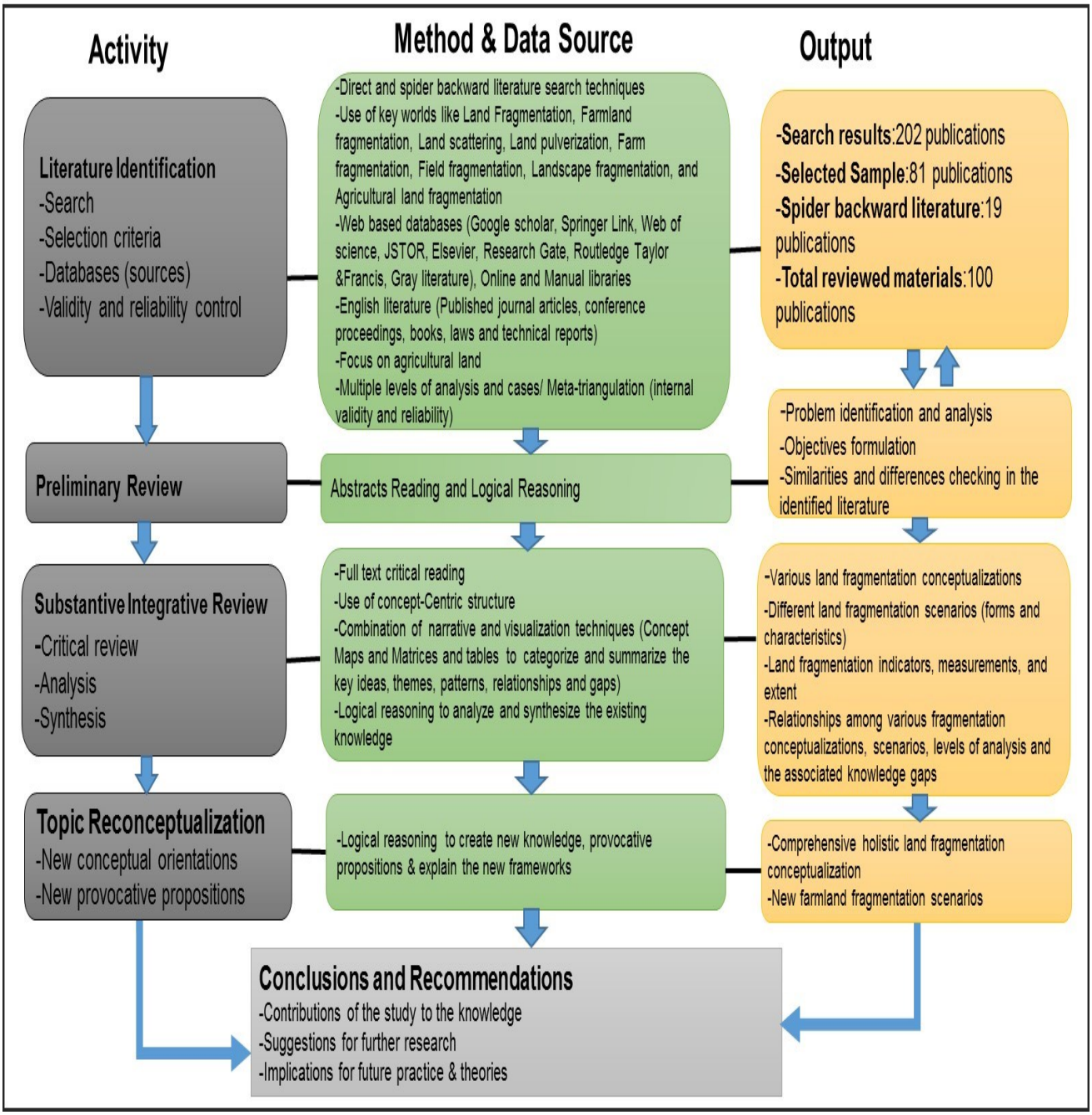

Figure 1A2. Overview of the research process and design

2. 2. Data sources and research methods

The systematic literature search started by choosing the key words such as land fragmentation, farmland fragmentation, farm fragmentation, field fragmentation, landscape fragmentation, land scattering, land pulverization, and agricultural land fragmentation. Individual instances and their various combinations were used to search across different web based scientific repositories including Google scholar, Springer Link, Web of science, JSTOR, Research Gate, Routledge Taylor & Francis), Journals, and the electronic Grey literature (Published and unpublished non-commercial documents from different governmental and non-governmental institutions like FAO, IFPRI, World Bank, GLTN and UN-Habitat), coupled with the online and manual library check-ups for hard documents. This use of multiple synonymous and different key words across many different data sources in literature

identification provides an advantage of offering a large body of various documents about the topic, for validity and authenticity purposes. The search was nearly complete when no new concepts were found in the articles set (Webster and Watson, 2002;Torraco, 2016). The literature identification process has resulted in the retrieval of 202 documents including 189 electronic/digital documents ranging from published peer reviewed journal articles, conference proceedings, books, laws and acts, technical reports, theses and press releases, and 13 hard documents from visited libraries. A preliminary review of the search results was performed by critically reading all titles and abstracts of the articles taking into consideration the research boundaries mentioned above in the previous sections. This has resulted in the selection of 81 relevant materials to undergo the substantive full text review, and the formulation of the research problem and objectives, after a careful identification of similarities and differences, contradictions, deficiencies and research gaps in the preliminary reviewed documents.

Following the concept-centric approach, all the articles with similar point of views or concepts were grouped together and split into different categories using the combination of narrative (text) and visual representations as suitable organization strategy for integrative literature analysis and synthesis (Webster and Watson, 2002;Torraco, 2016).Throughout the review process, new relevant citations and references were identified and traced backward from their original articles which were also further considered in the review using a spider backward literature search technique. This resulted in the selection of 19 additional soft documents thereby making the total of 100 reviewed publications. During the reading session, a concept matrix (Salipante *et al.*, 1982;Klopper *et al.*, 2007) was developed to categorise different ideas and themes across different concepts of farmland fragmentation in a more understandable and subtle way. These concepts were thoroughly reviewed to identify the convergences and divergences or contradictions in their conceptualizations by different authors across different disciplines (social, economic, philosophical, agricultural and environmental), and the reasons behind the identified relationships were discussed using the authors existing knowledge about the topic. Various land fragmentation concepts and scenarios were critically analysed for their relevant use at different levels to inform the formulation of a new comprehensive conceptual thinking about land fragmentation, and the development of possible fragmentation scenarios one can find in agricultural land, for the purpose of its proper management within the existing climate change realities. In this respect, different fragmentation forms and extent under different conditions and their highlighted relationships were critically analysed using the logical reasoning which follows the rationalist epistemology (Webster and Watson, 2002;Torraco, 2016), in order to identify the strengths, weaknesses, deficiencies, contradictions and problematical situations or gaps that need to be closed by the new knowledge. This approach of conceptual reasoning is suitable for integrative theoretical researches like this one, seeking to analyse the past in order to prepare the future perspectives, and has been previously used by many researchers in the similar context including McPherson (1982), Bentley (1987), and Asiama *et al.* (2017b).

The identified relationships and gaps from the critical analysis were exhaustively summarized in tables, matrices, Figures, maps and different alternative models, or weaved together in a unique synthesis for a better presentation of the situation, and basis for a more comprehensive and harmonized reconceptualization of farmland fragmentation phenomenon. The ArcMap drawing tools in ArcGIS were used to map different farmland fragmentation scenarios developed by the authors

from the mathematical and logical combinations of different land fragmentation indicators (variables) and actors in the reviewed literature and their own knowledge about the topic, using the logic conceptual reasoning approach (Webster and Watson, 2002;Robinson *et al.*, 2015) coupled with the reviewed theoretical foundations and empirical results. This rationalist approach was also used to justify and explain different combinations and propositions of the new conceptualization of farmland fragmentation and the developed scenarios. Finally, the implications of the new logic to the existing knowledge and decision makers were explained, and the suggestions for future research to fill the newly revealed gaps and empirically test the new relationships and scenarios were derived.

3. Farmland fragmentation concept, forms, and characteristics

The concept of land fragmentation appears to be very complex and fluid in multiple disciplines. The earliest mention of fragmentation dates back to the 17th century (Tan, 2005), and its worldwide concern much later in 1911, when a conference on the "consolidation of scattered holdings" was held to deal with the "evils of fragmentation (Lusho and Papa, 1998). A more comprehensive discussion about the term itself emerges in agricultural literature of the 1950s, such as in Binns (1950), Pihkala and Suomela (1952), Sargent (1952), Sorbi (1952), Schultz (1956), Fals Borda (1956), Hyodo (1956), Papageorgiou (1956), Lynn-Smith (1959), and Farmer (1960). Since then, the term has been broadly used in agriculture economics, anthropology, geography, ecology and other agriculture related fields. Yet, it has been used as a loose term in each of these disciplines, with no standardized objective definition for it (Ntihinyurwa *et al.*, 2019). Although the reviewed literature reveals that the nature of the concept of land fragmentation is ambiguous (King and Burton, 1982), the majority of authors regard farm fragmentation from farm or household perspective characterised by the size of the farm (household landholding),the number of parcels and plots per farm, their respective sizes, shapes, uses, and spatial distribution or location (the distances among them and from the farm homestead) (Bentley, 1987;Blarel *et al.*, 1992;Sundqvist and Andersson, 2006;Janus, 2018). Alternatively, farmland fragmentation is characterised by spatial or regional perspective features of entire area, such as the description of the number of farms, their respective sizes, the total or variation of owners and users in a given agricultural land area, zone or land block at the village, regional and national levels (Van Dijk, 2003;Sklenicka and Salek, 2008;Hartvigsen, 2014;Sklenicka *et al.*, 2014;Muchová, 2019). Farmland fragmentation in this perspective reflects situations in which a single farm consists of numerous spatially separated (non-contiguous) small parcels often scattered over a wide area (Sorbi, 1952;Downing, 1977;Burton and King, 1982;McPherson, 1983;Simons, 1985;Bentley, 1987;Blarel *et al.*, 1992;FAO, 2003;Sklenicka and Salek, 2008;Ciaian *et al.*, 2018a). For King and Burton (1982), fragmentation is considered as a basic rural spatial problem where farms are subdivided into undersized units which are too small for rational exploitation on one hand, and poorly organized individual holdings split into many non-contiguous parcels at different locations across an area on the other hand. Farmer (1960) refers to the first form as subdivision or pulverization (Bentley, 1987) and the second as scattering, whilst Roche (1956) and Sanderatne (1972) call them fragmentation and parcellisation respectively. These two quite distinct forms which frequently coexist together have been reconciled and commonly referred to as *Internal (Within farm) land fragmentation*, *Farm fragmentation*, or *Physical fragmentation* with the focus on household landholding or the farm level (Van Dijk, 2003;Van der Molen *et al.*, 2004;Tan, 2005;Demetriou *et al.*, 2012;Demetriou, 2014).

In contrast to the spatial perspectives, it is possible to view fragmentation from the tenure perspective (i.e. owning, leasing and/or renting). For Tan (2005), internal fragmentation exists when a household operates a number of owned or rented non-contiguous plots at the same time. Besides that, Schultz (1953), Van Dijk (2003), Hartvigsen (2014), Sklenicka *et al.* (2014), Muchová (2019), and Van der Molen *et al.* (2004) have documented other aspects of land fragmentation in the central and eastern European context such as land ownership fragmentation, land use fragmentation, and the discrepancy between ownership and use. In this perspective, ownership fragmentation refers to the situation when many land owners or farms exist in a relatively small land block or area, while land use fragmentation denotes many land users as tenants on a relatively small area or land block, with the discrepancy between the two forms as the small share of their overlap (small number of land owners who are using their own lands). These have been categorized in a new particular form of *Land tenure fragmentation* (Van Dijk, 2003;Jürgenson, 2016;Asiama *et al.*, 2017b, 2019;Ntihinyurwa *et al.*, 2019), although the term was previously used by the first two references to mean the above mentioned discrepancy between the use and ownership fragmentation contrary to the last one. In some instances, the terms of land tenure fragmentation and land ownership fragmentation are used interchangeably to mean the same thing (Asiama *et al.*, 2017b, 2019). Irrespective of different forms, Igbozurike (1970) proposes a more objective and holistic conceptualization of agricultural land fragmentation by defining it as the process by which a contiguous block of land is split into two or more parts. However, Ntihinyurwa *et al.* (2019) argue that land use fragmentation refers to the actual use of land (whenever there are more than one land use on a single farm, parcel or land block). For them, it does not have anything to do with the number of users, since one user or owner can have multiple uses on his farmland. For this, they introduce a new different type of fragmentation which is *Usership fragmentation* referring to the big number of farmers using a rented land (tenants) in a given relatively small area, merely associated with *Ownership fragmentation* in tenure fragmentation depending upon whether the users are using their own lands. The term land use fragmentation in this sense refers to the actual utilization of the land as *Land utilization fragmentation*. Furthermore, following the studies of King (1977) and Bentley (1987), Demetriou *et al.* (2013b), Hartvigsen (2014), and Muchová (2019) extended the discussion by emphasizing the new notions of external (outer) and internal (inner) land ownership fragmentation, referring to the *Visible or documented* (many recorded land owners) and *Hidden or undocumented* (many unrecorded land co-owners) land ownership fragmentation in a relatively small land unit respectively. This phenomenon of hidden ownership fragmentation also known as *Co-ownership fragmentation* in some cases exists in many customary communities with shared ownership of land by all the family members (Ghana, Kenya, Nigeria, etc), where the individuals are only assigned with the use rights over land (Abubakari *et al.*, 2016;Asiama *et al.*, 2017b, 2019), and in countries like Rwanda, Albania, Slovakia and Bulgaria, where the subdivision of farmland is restricted, and the cooperative farming encouraged (Vranken *et al.*, 2004;Muchová, 2019;Ntihinyurwa *et al.*, 2019). In this case, each household member tends to ask for his own share for individual use, based on his use and food preferences.

Binns (1950), Dovring (1960), McPherson (1982), and Hartvigsen (2014) define *Excessive fragmentation as* a situation whereby the number of parcels in a farm exceeds their size in ha (as an example, a 20 ha farm would be excessively fragmented if it consisted of more than 20 parcels). Bentley (1987) calls fragmentation *Extensive* when parcels become so small that they are not economically viable enough, which would lead to land abandonment. In general, different land

fragmentation forms and categories exist. However, many of these conceptualizations seem to be either very subjective or overlapping with each other as a common critic.

Sabates-Wheeler (2002) points out four dimensions of land fragmentation: (1) *Physical fragmentation*, (2) *Social fragmentation*, (3) *Activity fragmentation*, and (4) *Ownership fragmentation*. He/she characterises *Physical fragmentation* as a combination of the following situations: (i) non-contiguous land parcels which are owned and used as a single enterprise, (ii) dispersed parcels which are distant from the owner's homes or from each other, or (iii) a single ownership of many small parcels. In contrast, *Ownership fragmentation* refers to situations where large collectives have been privatized and individuals receive legal titles which specify the land size, with no exact location or boundaries of the parcel. *Social fragmentation* reflects a situation in which different types of land reforms have occurred. For example, in Central and Eastern European countries, subsequent processes of restitution, redistribution and privatisation of former collective farms resulted in the assignment of ownership rights over land to people who were not farmers. The farmers did not benefit from these processes, resulting in different social conflicts. Finally, *Activity fragmentation* is the situation whereby complementary means of production around land usage become disconnected from each other. Considering the characteristics of land as a spatial property with different spatial units, the two latter forms can be rather considered as the socio-economic effects of fragmentation than instances or classes of fragmentation forms. In addition, Farley *et al.* (2012) refer to both forms of tenure (ownership) and physical fragmentation by combining them into one concept of *Landscape fragmentation*.

Ntihinyurwa *et al.* (2019) argue that the forms of land fragmentation should be linked with the characteristics of land, such as its ownership, use, size, shape, location and value, and thereof limit them to land ownership (hidden and visible) and usership as tenure fragmentation, and internal (within farm), location, use, shape and value as physical fragmentation. In order to strengthen their argument, they posit that the causes and effects of land fragmentation also vary from form to form, and the decisions about its management should vary accordingly. Previous studies of Van Dijk (2003), Miranda and Crecente (2004), and Hiironen and Riekkinen (2016) support this view by positing that different forms of land tenure and physical fragmentation should be reconciled, since they may coexist in the same land block and could be detected through a holistic set of indicators such as the number of plots per HA (plots density), number of land owners/farms in a given land zone, size of the farm, number of plots per owner and their respective sizes, shapes and spatial distribution in that zone, when identifying land fragmentation forms.

The above overview of ontological and epistemic differences proves that there is a generic lack of harmonization and agreement on what fragmentation actually entails. On the one hand, there is no cohesion on spatial unit definitions since fragmentation at the parcel level as the smallest unit of land records does not equal fragmentation definitions at the farm, land block, or land zone levels. As a consequence, there is a granularity problem: indicators do not match the level at which land management decisions are taken. In other words, the land management interventions to deal with fragmentation mismatch the indicators to measure it. In the context of agricultural land management, whilst a wide number of studies considers a farm as the total area of land under a single ownership often confused with a parcel (land unit with homogeneous rights and interests), or a household landholding with homogeneous use rights, or simply as any continuous land block used for agricultural

purposes (Asiama *et al.*, 2017b), in this paper, this concept (farm) refers to the total area of land (sum of all parcels) operated or tilled as a single agricultural enterprise (unit) (Sanderatne, 1972;King and Burton, 1982;McPherson, 1982;Sabates-Wheeler, 2002), regardless of its tenure (ownership and usership) and its physical characteristics (size, shape, use, value and location). Since a land parcel refers to an area of land unit with determined boundaries and unique legally recognised homogenous interests, and the smallest recorded land unit (Brown and Moyer, 1994;Henssen, 2010) in land administration, interchangeably used as a field (Veldkamp *et al.*, 2011), its subdivision into small non-documented spatial portions for different agro-ecological use purposes results into land plots as the smallest land units in agricultural use (Dalgaard *et al.*, 2003). A plot in this case can be defined as a continuous portion of land parcel used for specific agricultural purpose (ibid). This implies the existence of fragmentation at different spatial scales and levels of analysis or different land units. However, the fragmentation at the parcel level is generally overlooked by the existing literature on farmland fragmentation. Furthermore, the two terms of parcel and plot are often interchangeably used to mean the same thing as a common identified gap in the literature (see the studies of Bentley (1987), Sabates- Wheeler (2002),and Jürgenson (2016)). Therefore, we postulate that the *Parcel fragmentation* refers to any type of physical or socio-economic subdivision of the parcel into many smaller land units (plots in agriculture) in terms of use, shape, location and hidden tenure, which can also be considered as internal fragmentation at the parcel level. The *Farm fragmentation* (internal fragmentation, within farm fragmentation) denotes the situation when a single farm is physically split into many relatively small plots/parcels either spatially dispersed/non-contiguous or contiguous (physical fragmentation), or shared by many undocumented co-owners or co-users (hidden tenure fragmentation).

Galt (1979) refers to these first two forms as *Field fragmentation and Scattering* (in case of the spatial dispersion of the fields of a single household in different locations). The *Farmland fragmentation* on the other hand refers to the split of the farming (agrarian) structure in a relatively small land block or region into many small farms (visible and hidden tenure fragmentation), or into many small plots or parcels (physical fragmentation or landscape fragmentation). In the light of this position, the extent of the farm (internal) fragmentation indicated by the number or percentage of internally fragmented farms in a given area (land block, village, region, nation) can inform about the status of farmland fragmentation in both physical and tenure (social) but not vice versa. This entails that farm fragmentation can exist at both the farm (except the visible tenure fragmentation) and higher levels (land block, regional, national, global), while the farmland fragmentation occurs at both the parcel, farm and land block (village, watershed, regional, national, global) levels only in forms of physical or landscape fragmentation and hidden tenure fragmentation, and separately at the land block or regional level in form of visible tenure fragmentation regardless of the internal details about the individual farms apart from their number. Thus, both terms of farmland fragmentation and farm fragmentation can be used interchangeably in some instances to refer to the fragmentation of agricultural land at the farm and farmland block or higher levels, or reconciled by the common term of *Internal farmland fragmentation* which can also be extended to the parcel level, in both social (tenure) and spatial (physical) aspects.

Despite the ontological and epistemic variations of land fragmentation concept, King and Burton (1982) posit that the above mentioned land fragmentation forms can coexist in the same area at

different spatial levels (parcel, farm or household, village, regional, national and global). This explains the co-existence of different fragmentation scenarios based on various mathematical and qualitative combinations of its indicators elucidated later in the first paragraph of section 5. Irrespective of various conceptualizations of this phenomenon from the socio-economic and physical perspectives, all the analysed literature materials share the common feature of referring to agriculture land fragmentation regardless of different subjective levels of analysis. The above discussed fragmentation forms and their characteristics at different spatial levels are summarized in the following matrix in Table 1.

Table 1A2. Summary of the possible fragmentation forms at different spatial levels of analysis

Level of Analysis	*Fragmentation Forms*		*Characteristics*	*References*
Farmland Parcel	***Category***	***Form***		
	Physical (field) Fragmentation	**Internal**	Many small plots per parcel (small plot sizes)	(Binns, 1950; Galt, 1979)
		Location (Scattering)	Small spatially dispersed plots within a parcel	-
		Use	Multiple crops (agricultural uses) on a single parcel (Multiculture)	(Bentley, 1987; Isaacs *et al.*, 2016; Ciaian *et al.*, 2018a; Ntihinyurwa *et al.*, 2019)
		Shape	Many small irregularly shaped plots per parcel	-
		Extensive	Very small non-economically viable parcels	(Bentley, 1987; Hartvigsen, 2014; Ntihinyurwa *et al.*, 2019)
	Tenure Fragmentation (hidden)	**Co-ownership**	Many hidden owners (co-owners) per parcel	(King, 1977; Bentley, 1987; Vranken *et al.*, 2004; Hartvigsen, 2014; Sklenicka *et al.*, 2014; Muchová, 2019)
		Co-usership	Many hidden users or tenants (co-users) per parcel	-
Farm	**Physical Fragmentation**	**Internal (Within farm)**	Many small contiguous or scattered parcels and/or plots per farm	(Binns, 1950; Farmer, 1960; Thompson, 1963; Simmons, 1964; Igbozurike, 1970; Edwards, 1978; King and Burton, 1982; McPherson, 1982; Bentley, 1987; Blarel *et al.*, 1992; Crecente *et al.*, 2002; Bizimana *et al.*, 2004; Di Falco *et al.*, 2010; Latruffe and Piet, 2014; Isaacs *et al.*, 2016; Saint-Cyr *et al.*, 2016; Ciaian *et al.*, 2018a; Janus *et al.*, 2018; Cholo *et al.*, 2019; Ntihinyurwa *et al.*, 2019)
		Location (Scattering)	-Many small spatially scattered (non-contiguous) parcels and/or plots at different locations per farm - Above average distance of the parcels to the farm homestead and between them	(Sorbi, 1952; Igbozurike, 1970; Schmook, 1976; Galt, 1979; Burton and King, 1982; Bentley, 1987; Blarel *et al.*, 1992; Crecente *et al.*, 2002; Cholo *et al.*, 2019)
		Use	Multiple crops (agricultural uses) in a single farm (Multiculture)	(Netting, 1972; Bentley, 1987, 1990; Blarel *et al.*, 1992; Crecente *et al.*, 2002; Di Falco *et al.*, 2010; Isaacs *et al.*, 2016; Ciaian *et al.*, 2018a; Chigbu *et al.*, 2019; Cholo *et al.*, 2019; Ntihinyurwa *et al.*, 2019)
		Shape	Many small irregularly shaped parcels and/or plots per farm	(Schmook, 1976; McGarigal and Marks, 1995; Rutledge, 2003; Demetriou *et al.*, 2013a; Demetriou *et al.*, 2013b; Gąsiorowski and Bielecka, 2014; Latruffe and Piet, 2014; Janus, 2018; Ntihinyurwa *et al.*, 2019)
		Excessive	The number of parcels and/or plots per farm exceeds its size	(Binns, 1950; Dovring, 1960; McPherson, 1982; Hartvigsen, 2014; Ntihinyurwa *et al.*, 2019)
	Tenure Fragmentation (hidden)	**Ownership**	Many hidden owners (co-owners) per farm	(King, 1977; Bentley, 1987; Vranken *et al.*, 2004; Hartvigsen, 2014; Sklenicka *et al.*, 2014; Muchová, 2019; Ntihinyurwa *et al.*, 2019; Muchová and Raškovič, 2020)
Farmland Block	**Physical (landscape) Fragmentation**	**Internal**	-Above average percentage or number of internally fragmented farms and/or parcels per farmland block -High average number of plots per farm in the area	(Pihkala and Suomela, 1952; Fals Borda, 1956; Papageorgiou, 1956; Roche, 1956; Sanderatne, 1972; McCloskey, 1975; Downing, 1977; Simons, 1985; Bentley, 1987; Blarel *et al.*, 1992; Crecente *et al.*, 2002; FAO, 2003; Van Dijk, 2003; Van der Molen *et al.*, 2004; Sundqvist and Andersson, 2006; Van Hung *et al.*, 2007; Sklenicka and Salek, 2008; Vijulie *et al.*, 2012; Abubakari *et al.*, 2016; de Vries, 2016; Kadigi *et al.*, 2017; Ciaian *et al.*, 2018a; Janus *et al.*, 2018; Asiama *et al.*, 2019; Cholo *et al.*, 2019; Ntihinyurwa *et al.*, 2019)

	Location (Scattering)	-Above average percentage or number of the farms' plot or parcel locations in a farmland block -High average number of plot locations in a farmland block -Above average number of farms with non-contiguous plots (parcels) located in more than one location -Above average distance of the parcels to the homesteads or between them in a given farmland block	(Sorbi, 1952; Dovring, 1965; Igbozurike, 1970; Igbozurike, 1974; Schmook, 1976; Galt, 1979; Burton and King, 1982; Bentley, 1987; Blarel *et al.*, 1992; Crecente *et al.*, 2002; Tan *et al.*, 2006; Demetriou *et al.*, 2013b; Ciaian *et al.*, 2018b; Cholo *et al.*, 2019; Ntihinyurwa *et al.*, 2019)
	Use	Multiple crops (agricultural uses) in a farmland block (Multiculture)	(Netting, 1972; Bentley, 1987, 1990; Blarel *et al.*, 1992; Crecente *et al.*, 2002; Bizimana *et al.*, 2004; Di Falco *et al.*, 2010; Isaacs *et al.*, 2016; Ciaian *et al.*, 2018a; Chigbu *et al.*, 2019; Cholo *et al.*, 2019; Ntihinyurwa *et al.*, 2019)
	Shape	Above average number of irregularly shaped parcels and/or plots in a farmland block	(Schmook, 1976; McGarigal and Marks, 1995; Rutledge, 2003; Gonzalez *et al.*, 2004; Akkaya *et al.*, 2007; Demetriou *et al.*, 2013a, b; Gąsiorowski and Bielecka, 2014; Latruffe and Piet, 2014; Janus, 2018; Ntihinyurwa *et al.*, 2019)
	Excessive	-Above average number or percentage of excessively fragmented farms in the farmland block -Higher average number of plots/parcels than the average farm size	(Binns, 1950; Dovring, 1960; McPherson, 1982; Hartvigsen, 2014; Ntihinyurwa *et al.*, 2019)
	Extensive	Above average or high average number or percentage of non-economically viable parcels in the farmland block	(Bentley, 1987; FAO, 2003; Hartvigsen, 2014; Ntihinyurwa *et al.*, 2019)
Physical (landscape) and Tenure (visible and hidden) Fragmentation	**Internal, Ownership and Usership**	-Above average percentage or number of small internally fragmented farms and/or parcels per farmland block -Big number of land owners/users/co-owners/co-users in a relatively small farmland block -High average number of plots (parcels) per farm -Low average parcel or plot size -Low average farm size	(Igbozurike, 1974; Bentley, 1987; Brabec and Smith, 2002; Sabates-Wheeler, 2002; Van Dijk, 2003; Van der Molen *et al.*, 2004; Vranken *et al.*, 2004; Lisec and Pintar, 2005; Sklenicka and Salek, 2008; Muchová and Petrovič, 2010; Farley *et al.*, 2012; Vijulie *et al.*, 2012; Demetriou *et al.*, 2013b; Hartvigsen, 2014; Abubakari *et al.*, 2016; Asiama *et al.*, 2017a, b, 2019; Ntihinyurwa *et al.*, 2019)
Tenure Fragmentation (visible and hidden)	**Ownership**	-Above average number of land owners in a relatively small farmland block -Big number of farms per farmland block -Low average farm size	(Igbozurike, 1974; King, 1977; Bentley, 1987; Lusho and Papa, 1998; Van Dijk, 2003; Damen, 2004; Vranken *et al.*, 2004; Hartvigsen, 2014; Sklenicka *et al.*, 2014; Abubakari *et al.*, 2016; Asiama *et al.*, 2017b, 2019; Muchová, 2019; Ntihinyurwa *et al.*, 2019; Muchová and Raškovič, 2020)
	Usership	-Above average number of land users (tenants) in a relatively small farmland block -Big number of farms per farmland block -Low average farm size	(Van Dijk, 2003; Hartvigsen, 2014; Sklenicka *et al.*, 2014; Asiama *et al.*, 2017b; Ntihinyurwa *et al*., 2019)

***Source*:** Authors constructs from the literature and the deductive logic

The analysis of the concepts presented in Table 1 has led to the following claims:

1) A pragmatic way of overcoming the *ontological* differences in fragmentation is to make a distinction among parcel, farm, and farmland block-based fragmentation forms. This distinction will guide the determination of the degree and extent of various fragmentation scenarios in a given area, which will facilitate the design of suitable interventions for specific scenarios at each spatial level. Therefore, we can distinguish land fragmentation forms at the parcel (internal in the form of both physical and hidden tenure), farm (internal, or within farm, both physical and tenure), and farmland block, regional and national levels (fragmentation of the farming structure in a given area or region either in the form of physical or tenure or both, often referred to as farmland fragmentation).

2) A pragmatic way of overcoming *epistemological* differences in fragmentation is to rely on spatial and socio-economic units to measure and control fragmentation. This will improve the design of spatial and non-spatial interventions, because farmland fragmentation as simultaneously a natural and social phenomenon needs to be managed from its epistemological roots in the relationship between land parcel (object) and people (subject) in land management paradigms. In this regard, the fragmentation in the physical characteristics of a land parcel as an object (size, use, shape, value, location) implies the existence of different physical fragmentation forms, whilst the one in its social relationships (rights, restrictions and responsibilities) with people as a subject implies the occurrence of different social or tenure fragmentation forms (both visible and hidden ownership and usership) at different spatial levels.

3) A pragmatic way to handle the *granularity* problem of fragmentation is to distinguish the governance levels of fragmentation management strategies. This distinction is better than relying on the current ambiguity in spatial and governance units, because farmland fragmentation management interventions are mostly drawn at higher levels (community, regional, national and global), while the results are always depicted at lower spatial levels (plot, parcel, farm). This often leads to the mismatch between farmland fragmentation control strategies and their results at different spatial units. Hence the distinction of governance levels of fragmentation control strategies would solve this problem.

In the light of these claims, we posit that physical farmland fragmentation denotes any type of fragmentation in physical characteristics of land either internal or external at all levels, while farmland tenure fragmentation refers to any derived form from the split in the social characteristics of land in terms of its relationships with people at all levels, regardless of the exclusive internality and externality criteria. The next section discusses various fragmentation indicators, their measurement methods and extent.

4. Farmland fragmentation measurements and indicators

Due to the multidimensional and complex nature of land fragmentation, there is currently not an internationally accepted standard proxy or indicator for farmland fragmentation. There is indeed a variety of measures and methods applied for measuring its degrees or indicating its qualities. These range from

simple to more complex indices at different levels and for specific land fragmentation forms (Janus, 2018). However, it is still difficult to use these indicators effectively for the design and evaluation of effective land fragmentation management interventions. Despite this lack of standard comprehensive measurable and tailored indicators for all the above discussed fragmentation forms besides the subjective and somehow incomplete indices, the number of owners and/or users in a given farmland block and the number of household members or co-owners for tenure fragmentation (Hartvigsen, 2014;Sklenicka *et al.*, 2014;Muchová, 2019;Ntihinyurwa *et al.*, 2019;Muchová and Raškovič, 2020), the size of household land holding, the number of plots per household, the sizes of respective small plots and their averages, the shapes of those plots, their uses and spatial distributions for physical fragmentation (Igbozurike, 1974;Edwards, 1978;Bentley, 1987;Gonzalez *et al.*, 2004;Miranda and Crecente, 2004;Platonova *et al.*, 2011;Demetriou *et al.*, 2013b;Janus, 2018;Ntihinyurwa *et al.*, 2019) along with different ratios and percentages have been identified to be commonly used in measuring farmland fragmentation in different ways. Most of the attempts to measure land fragmentation in the past have used simple methods considering only the number of farms/owners, the number of plots per farm/owner, their respective sizes, averages and percentages in a given area (Binns, 1950;Van Dijk, 2003;Tan, 2005;Sklenicka *et al.*, 2014;Janus *et al.*, 2017;Muchová, 2019). In this vein, by considering the bimodality of the farm structure (small scale and large scale farms), Bentley (1987) and Van Dijk (2003) respectively mention the use of the percentage of small scale farms (<5ha) in a given area and the percentage of regional farms that comprise over 10 plots as the suitable measurements of land ownership and internal fragmentation at the regional level. Some other authors developed more complicated descriptors (indices and coefficients) involving more sophisticated mathematical calculations that integrate more than one variable among the above mentioned indicators (Bentley, 1987;Tan, 2005;Vijulie *et al.*, 2012;Demetriou *et al.*, 2013b;Janus *et al.*, 2017;Janus, 2018;Muchová, 2019;Ntihinyurwa *et al.*, 2019). These include among others the most popular and commonly used ones like the *Simmons index* given by the sum of the squares of the plot sizes divided by the square of the farm size, with the values varying from 0 (total fragmentation) to 1 (complete consolidation) (Simmons, 1964), the *Simpson index (Simpsi)* given by the subtraction of the Simmons index from one, with the values ranging between 0 (no fragmentation and 1 (high fragmentation) (Tan, 2005;Demetriou *et al.*, 2013b)*, and* the *Januszewski index (janusi)* as the ratio of the square root of the total farm area to the sum of the square roots of the plot sizes (Januszewski, 1968). The particularity of the later is that fragmentation decreases when the area/share of big plots increases and that of small plots decreases proportionally with the total number of plots, contrary to other measures which hypothesize that small farms are less fragmented than big ones (Bentley, 1987;Demetriou *et al.*, 2013b). Contrary to the *Janusi* and *Simmons index,* a higher *Simpsi* value indicates a higher degree of land fragmentation and vice versa (Tan, 2005).

However, these indices suffer from the phenomenon of neighbouring plots due to the exclusive consideration of the number of plots per farm/owner and their respective sizes in a given land block regardless of the adjacency of plots belonging to the same owner (McCloskey, 1975;Janus *et al.*, 2017), and are somehow contradictory in their interpretations. The methods focus on plot as a substitute to the parcel, while the two spatial units are substantially different as previously explained in section 3. As remedy to this, Edwards (1978) developed a coefficient which is expressed as the percentage of the

farm's land that is not contiguous to the farmstead. This indicator has also been criticised as it ignores aspects of distance and size. The common drawback of these indicators is the ignorance of the distance and shape aspects. As a solution to this, Dovring (1965) proposed a theoretical distance factor which takes distance into account in fragmentation calculation. It computes fragmentation as the distance a farmer would travel to reach each of his/her parcels and returning back to the farmstead after each visit. This factor however disregards the size of each parcel, as well as the number of actual visits per year and the potential that any parcel could be visited without returning back to the farmstead (Bentley, 1987;Demetriou *et al.*, 2013b). Igbozurike (1974) suggests a relative index of land parcellisation as the average size of the parcels multiplied by the distance travelled by a farmer to visit all his parcels sequentially (in one round trip) per 100. King and Burton (1982) and Bentley (1987) criticise this method for lacking a uniform definition and a consistent use of distance (from plot to plot in a single round, versus the sum of distances covered from the farmstead to each plot) in his/her calculations. Schmook (1976) suggests two mathematical coefficients of land fragmentation, calculated as the ratio of the area of an irregular polygon circumscribing all the plots of a farm to the farm size, and the ratio of the mean distance to plots per mean plot size. The values which are far higher than 1 indicate an intense fragmentation. This method ignores the number of plots and the sizes of the farm and plots respectively, and the isolation of the most distant plots from the calculations, which makes it more complicated in use. With regard to the shape as an important feature of mechanized agriculture, various shape based indices which use different shape metrics like the shape and edge length of a parcel, and few other more sophisticated indexes integrating both shapes, distances and other variables have been developed. These include the shape indices (SI) of McGarigal and Marks (1995), Rutledge (2003), and Akkaya *et al.* (2007), the size and shape fragmentation index (Gonzalez *et al.*, 2004), the morphometric parameters for size, shape and dispersion (Gąsiorowski and Bielecka, 2014), the Parcel Shape Index (PSI) given by the ratio of the sum of the weighted shape parameters to the number of involved parameters, with the values ranging from 0 (worst or irregular complex parcel shapes) to 1 (best or regular rectangular parcel shapes) (Demetriou *et al.*, 2013a) and Global Land Fragmentation Index (GLFI) given by the mean/median weighted score of fragmentation factors by the size of all the holdings in a given area, with the values ranging from 0 (full fragmentation to 1 (no fragmentation) (Demetriou *et al.*, 2013b), the Grouping index and Structural index (Latruffe and Piet, 2014),and the Parcel Aggregation Indexes (Janus, 2018;Janus *et al.*, 2018).

More recently, with respect to the incomprehensiveness and incompleteness of the above indices as their major drawbacks since none of them integrates all the indicators at the same time in their measurements, Vijulie *et al.* (2012), Demetriou *et al*. (2013a,b), Muchová (2019), Janus (2018), and Janus *et al.*(2018) suggested the use of multiple methods in measuring specific forms of land fragmentation phenomenon. In this regard, Vijulie *et al.* (2012) combined both simple and complex indices to measure the level of land fragmentation in Albania, whilst Demetriou *et al*. (2013a, b) used the parcel shape and global land fragmentation indexes as a complementary integrated technique capturing as many variables as possible to measure both physical and tenure fragmentation through a digitalized GIS based model (LandFragmentS) to support land consolidation program in Cyprus. Janus *et al.* (2018) developed different parcel aggregation indexes which only consider the number of plots belonging to the same owner before and after aggregation of contiguous plots (after elimination of the boundaries) when

calculating physical land fragmentation (internal) to overcome the so called phenomenon of neighbourhood of plots as a critic to other indices. This method is coupled with the existing Reduction Index or Land Consolidation (LC) coefficient expressed as the ratio of the number of parcels before and after the consolidation project with relation to the number of LC owners (Crecente *et al.*, 2002). However, this method does also not clearly show land fragmentation indicators to be considered and their calculation, neither gives any attention to land ownership fragmentation. On the other hand, Muchová (2019) proposed more detailed ratios to determine the level of land ownership fragmentation by considering multiple criteria like the number of owners and plots per land unit, the number of co-owners per parcel, the size of land, the size of plots, the average number of plots, average size of plots, average number of co-owners, and different ratios, although his/her approach does also not consider some physical fragmentation features (uses and shapes of parcels, and the number of parcels per owner). It however brings in the debate, a new argument of considering the external ownership fragmentation and internal ownership fragmentation (co-ownership) when preparing or evaluating land consolidation projects. The common weakness of these recent attempts is that they are all oriented towards the support of land consolidation projects rather than being objectively land fragmentation problem-oriented, since not all land fragmentation forms need land consolidation as a management strategy. Moreover, they are mostly represented by complicated standard mathematical formulae, which hinders their flexible use in particular cases that need specific simple measurements under certain conditions.

Generally, the extent and/ or the level of analysis indicating if land is too fragmented or not depends upon its measurement methods which also have their own advantages and disadvantages. Furthermore, the nature of fragmentation also depends on the type of farming system (subsistence vs market-oriented), the farm structure (small vs big farms), socio-economic, environmental (natural or ecological) and political conditions in a given area, and vary from case to case. According to Bentley (1987) and Blarel *et al.* (1992), small subsistence farms tend to be more internally fragmented than big mechanized farms. This explains how much the choice of spatial units may influence the analysis of land fragmentation forms and scenarios. This implies that the indicators and degree of fragmentation at the parcel and farm levels are different from those at the village, regional, national and global levels, which hinders the cross cultural and geographical comparisons of land fragmentation levels.

Despite this methodological challenge, Bentley (1987) considers fragmentation as a universal trait of all agricultural systems, and no society without land fragmentation has been documented before, except some individual farms. According to Van Hung *et al. (*2006), it is a common feature of agriculture especially in developing countries. It can be seen under scarce land conditions with small farms as well as in abundant land with big farms, in heterogeneous as well as in homogenous conditions, and in simple economies (subsistence) as well as in complex ones (modern or market-oriented). Its prevalence and problematical situations depend upon its causes and different local circumstances (conditions). Since the level of fragmentation is a key determinant in the decisions about its management, the authors suggest the use of simple descriptive statistical methods like the percentages or proportions and average numbers and sizes to inform the level of fragmentation at higher levels (village, regional, national and global) under different scenarios, besides the commonly used indices discussed above. For example, 80 % of leased

farms (tenants) in a given area would indicate a high level of land usership fragmentation, while 90 % of farms split into more than 4 parcels would indicate a high level of internal land fragmentation. Similarly, 80 % of parcels having irregular shapes can be a simple indicator of land shape fragmentation, whereas a 10 ha farm or land block split among 25 owners would indicate an excessive ownership or internal fragmentation in a given area (Dovring, 1960;McPherson, 1982;Ntihinyurwa *et al.*, 2019). The FAO indicator of viable farm (>0.9ha) can also be used as a reference point for measuring farm fragmentation in a given area, based on the number or percentage of farms under that standard (Blarel *et al.*, 1992;FAO, 2003;Abubakari *et al.*, 2016). We therefore recommend the combination of multiple methods capturing both the spatial (physical) and non-spatial (tenure) parameters of land fragmentation described above in this section and in the first paragraph of the following section 5 to grasp the complete information about the extent of all the coexisting forms of land fragmentation at different levels in a given area, to guide the decisions about its management. The next section discusses various complex land fragmentation scenarios resulting from different combinations of fragmentation indicators and the involved actors (land owners, land owner-users, and land users/lessees/leasers or tenants).

5. Farmland fragmentation scenarios

In the light of the variety of existing indicators and forms of land fragmentation, this study identifies 40 different hypothetical fragmentation scenarios which were generated to evaluate how to better quantify and qualify fragmentation. The limitation to 40 out of the 64 possible fragmentation scenarios resulted from the logical abstraction of mathematical combinations of 6 variables of two general categories of fragmentation (**$64=2^6$**) at various spatial levels (farm, village, regional, national, global) in practice. They are grouped into 10 different categories covering the major forms of physical and tenure fargmentation resulting from the combinations of the above mentined 6 common indicators of farmland fragmentation such as: parcel ownership and usership as visible and hidden social or tenure characteristics; the number of parcels and/ or plots per farm, their shapes (regular vs irregular), uses or utilization (monoculture vs multiculture) and locations as physical characteristics. The following formula was used to calculate the number of scenarios: ***Fragementation Scenarios (FSC)*** $=2^n$; where ***n*** means the number of indicators (variables) into consideration,and ***2*** stands for the two general categories of fragmentation forms (physical and tenure). The aspects of size, distance and dispersion are indirectly reflected in descriptors like parcel ownership/usership, the number of plots/parcels, and their location respectively. The study ignored the scenarios at the parcel level, since they somehow overlap with and are represented by the ones at the farm level. Furthermore, some similar and practically impossible scenarios in reality that present general overlaping features were combined or ignored, which led to the reduced number of **40** possible scenarios. Figures. 2 to11 represent the 10 hypothetical maps with 40 variations of scenarios. All the maps are a result of the authors own drawing in ArcMap, from the combination of the literature and the logical reasoning. All the scenarios in the maps are self-explanatory with the corresponding texts.

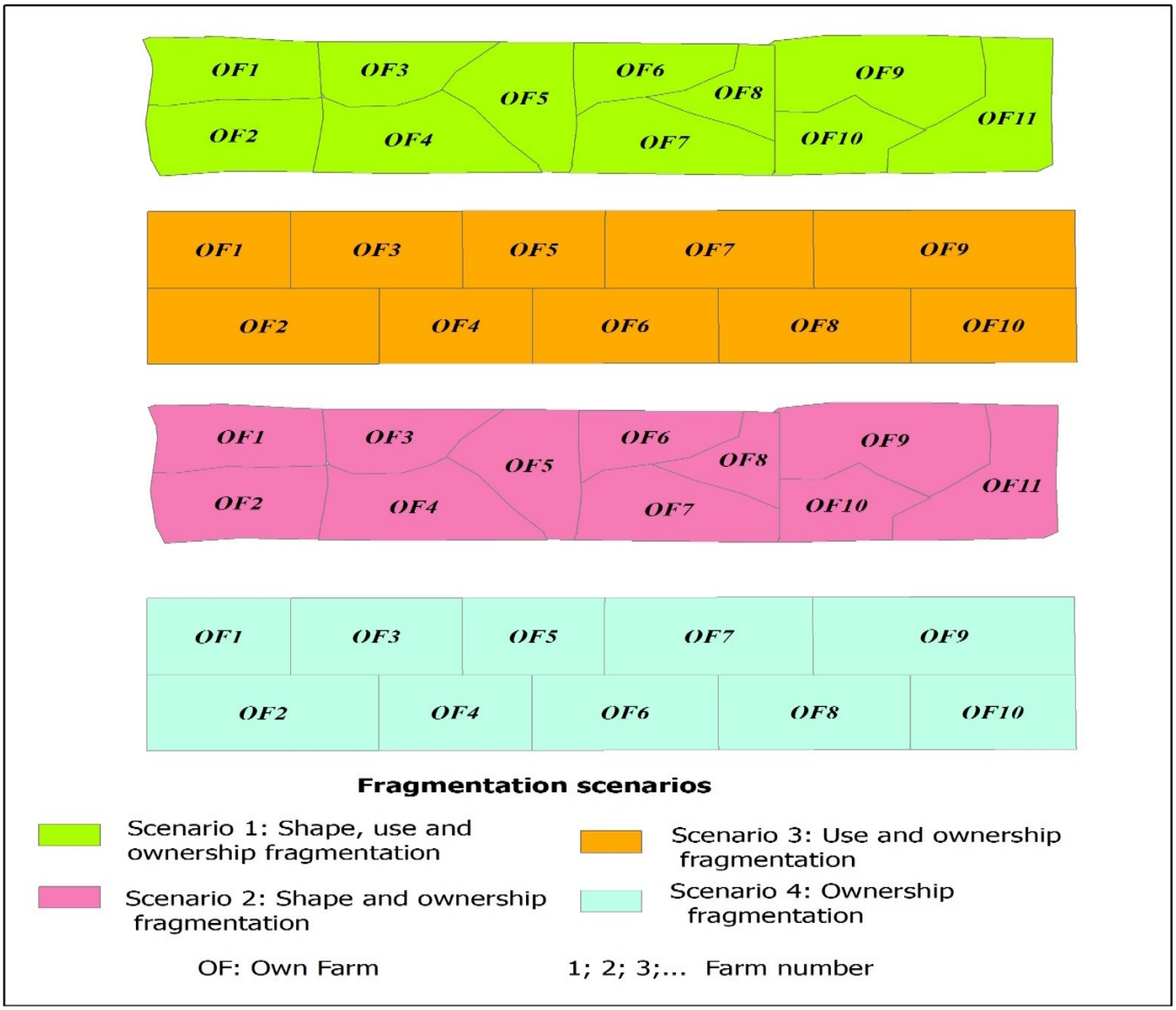

Figure 2A2. Visible and hidden ownership fragmentation

***-Scenario 1*:** *Visible and hidden ownership, shape and use fragmentation*: Many land owner (co-owner)-users (farmers operating their own lands) with irregular shapes and uses (multiculture) in a relatively small land block/area: Many small farms with different parcel shapes and multiple agricultural uses.

***-Scenario 2*:** *Visible and hidden ownership and use fragmentation*: Many land owner (co-owner)-users (farmers operating their own lands) with regular shapes and multiple uses (multiculture) in a relatively small land block/area: Many small farms with regular shapes but multiple agricultural uses.

***-Scenario 3*:** *Visible and hidden ownership and shape fragmentation:* Many land owner (co-owner)-users (farmers operating their own lands) with irregular shapes and regular use (monoculture) in a relatively small land block/area: Many small farms with different shapes but consolidated agricultural use.

-Scenario 4: *Visible and hidden ownership fragmentation*: Many land owner (co-owner)-users (farmers operating their own lands) with regular shapes and use (monoculture) in a relatively small land block/area: Many small farms with regular shapes and consolidated agricultural use.

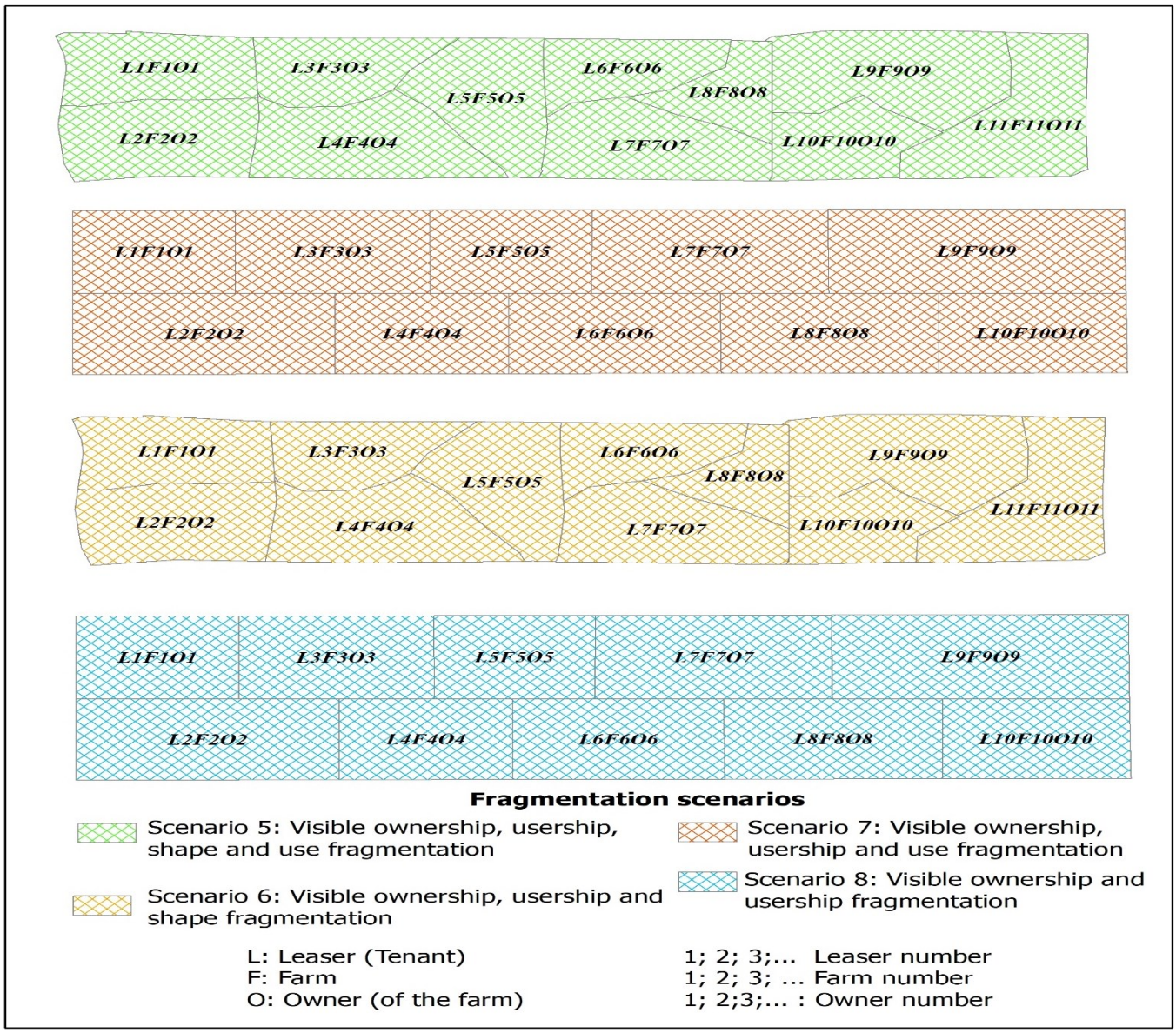

Figure 3A2. Visible ownership and usership fragmentation

-Scenario 5: *Visible ownership, usership, shape and use fragmentation:* Many land owners leasing out their farms with irregular shapes and uses (multiculture) to many users in a relatively small land block/area: Many small leased farms with different parcel shapes and multiple agricultural uses.

-Scenario 6: *Visible ownership, usership and use fragmentation***:** Many land owners leasing out their farms with regular shapes and multiple uses (multiculture) to many users in a relatively small land block/area: Many small leased farms with regular shapes but multiple agricultural uses.

-Scenario 7**:** *Visible ownership, usership and shape fragmentation***.** Many land owners leasing out their farms with irregular shapes and regular use (monoculture) to many users in a relatively small land block/area: Many small leased farms with different parcel shapes but consolidated agricultural use.

-Scenario 8: *Visible ownership and usership fragmentation***:** Many land owners leasing out their farms with regular shapes and use (monoculture) to many users in a relatively small land block/area: Many small leased farms with regular shapes and consolidated use.

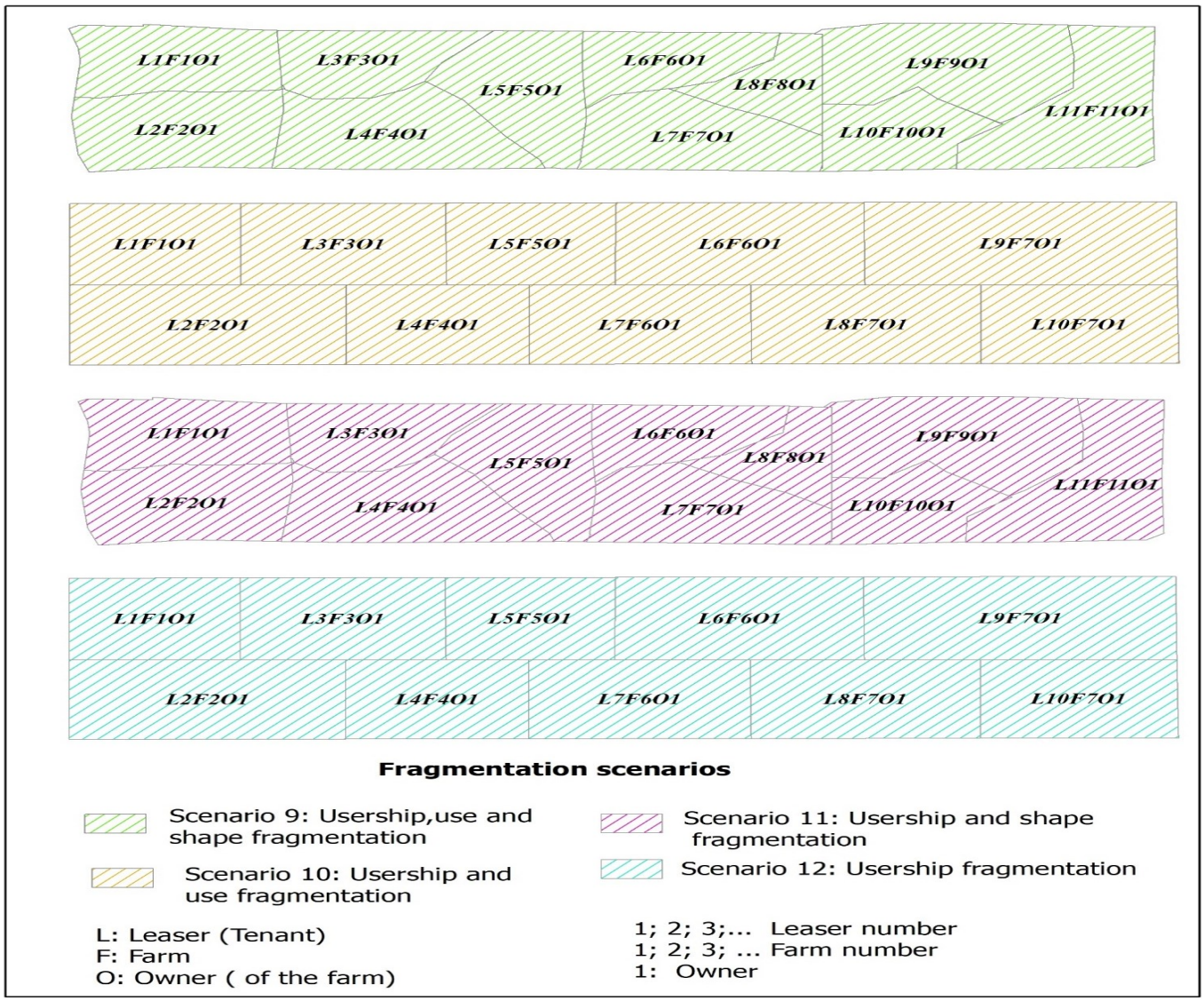

Figure 4A2. Usership fragmentation

-Scenario 9: *Usership, use and shape fragmentation*: Many land users leasing their farms with irregular shapes and uses (multiculture) from one or few owners in a relatively small land block/area: Many small visible leased farms with multiple parcel shapes and agricultural uses.

-Scenario 10: *Usership and use fragmentation*: Many land users leasing their farms with regular shapes and multiple uses (multiculture) from one or few owners in a relatively small land block/area: Many small visible leased farms with regular shapes but multiple agricultural uses.

-Scenario 11: *Usership and shape fragmentation*: Many land users leasing their farms with irregular shapes and regular use (monoculture) from one or few owners in a relatively small land block/area: Many small visible leased farms with multiple shapes and consolidated agricultural use.

-Scenario 12: *Usership fragmentation*: Many land users leasing their farms with regular shapes and use (monoculture) from one or few owners in a relatively small land block/area: Many small visible leased farms with regular parcel shapes and agricultural use.

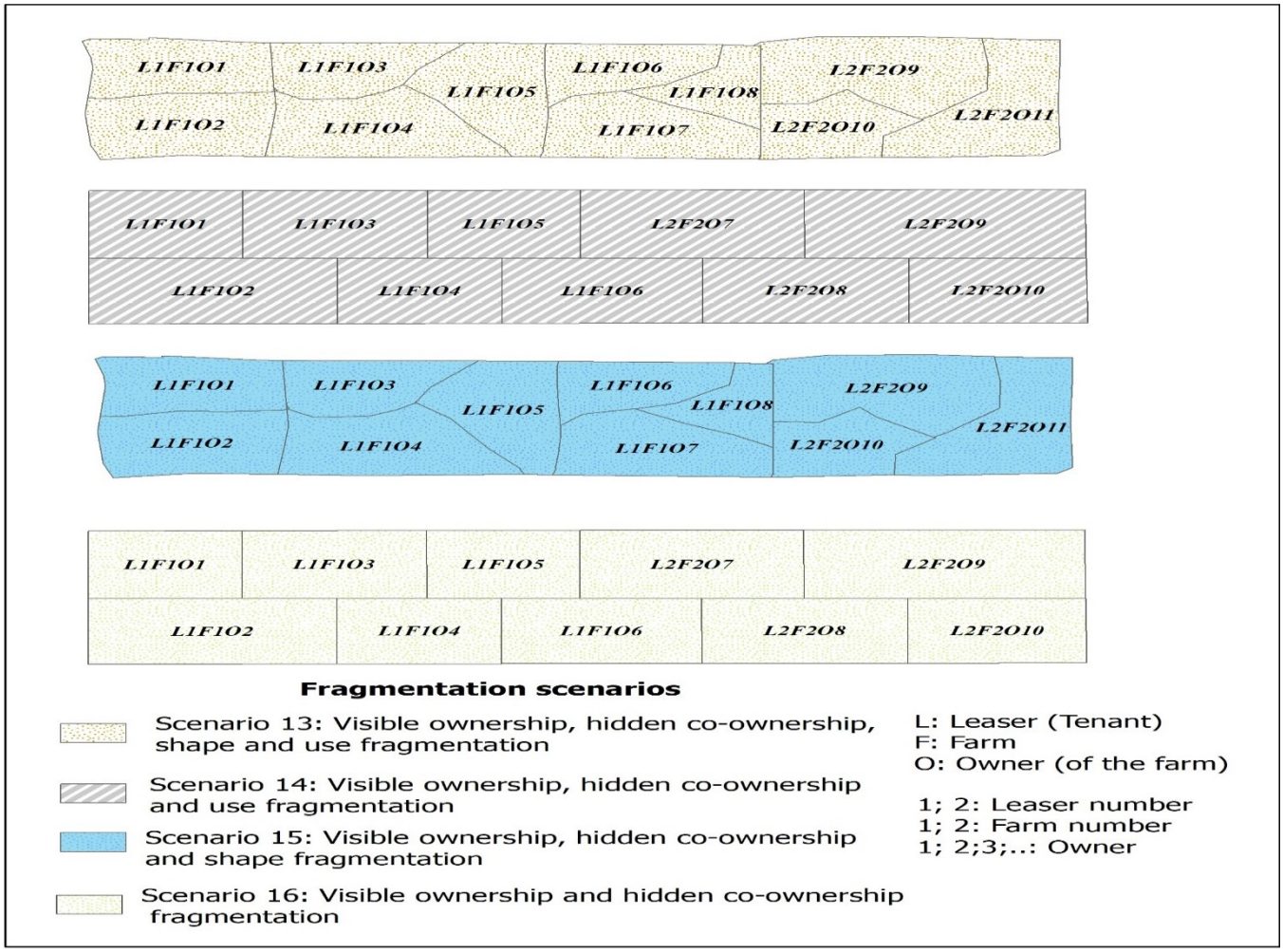

Figure 5A2. Visible ownership and hidden co-ownership fragmentation

-Scenario 13: *Visible ownership, hidden co-ownership, shape and use fragmentation:* Many documented land owners and/ or undocumented co-owners in a relatively small land block/area leasing out their farms with irregular shapes and uses (multiculture) to one or few users (tenants): Many small hidden farms used under one or few big farms with multiple parcel shapes and agricultural uses.

-Scenario 14: *Visible ownership, hidden co-ownership and use fragment*ation**:** Many documented land owners and/ or undocumented co-owners in a relatively small land block/area leasing out their farms with regular shapes and multiple uses (multiculture) to one or few users (tenants): Many small hidden farms used under one or few big farms with regular shapes but multiple agricultural uses.

-Scenario 15: *Visible ownership, hidden co-ownership and shape fragmentation***:** Many documented land owners and/or undocumented co-owners in a relatively small land block/area leasing out their farms with irregular shapes and regular use (monoculture) to one or few users (tenants): Many small hidden farms used under one or few big farms with multiple shapes and consolidated agricultural use.

-Scenario 16: *Visible ownership and hidden co-ownership fragmentation***:** Many documented land owners and/ or undocumented co-owners in a relatively small land block/area leasing out their farms with regular shapes and use (monoculture) to one or few users (tenants): Many small hidden farms used under one or few big farms with regular parcel shapes and consolidated agricultural use.

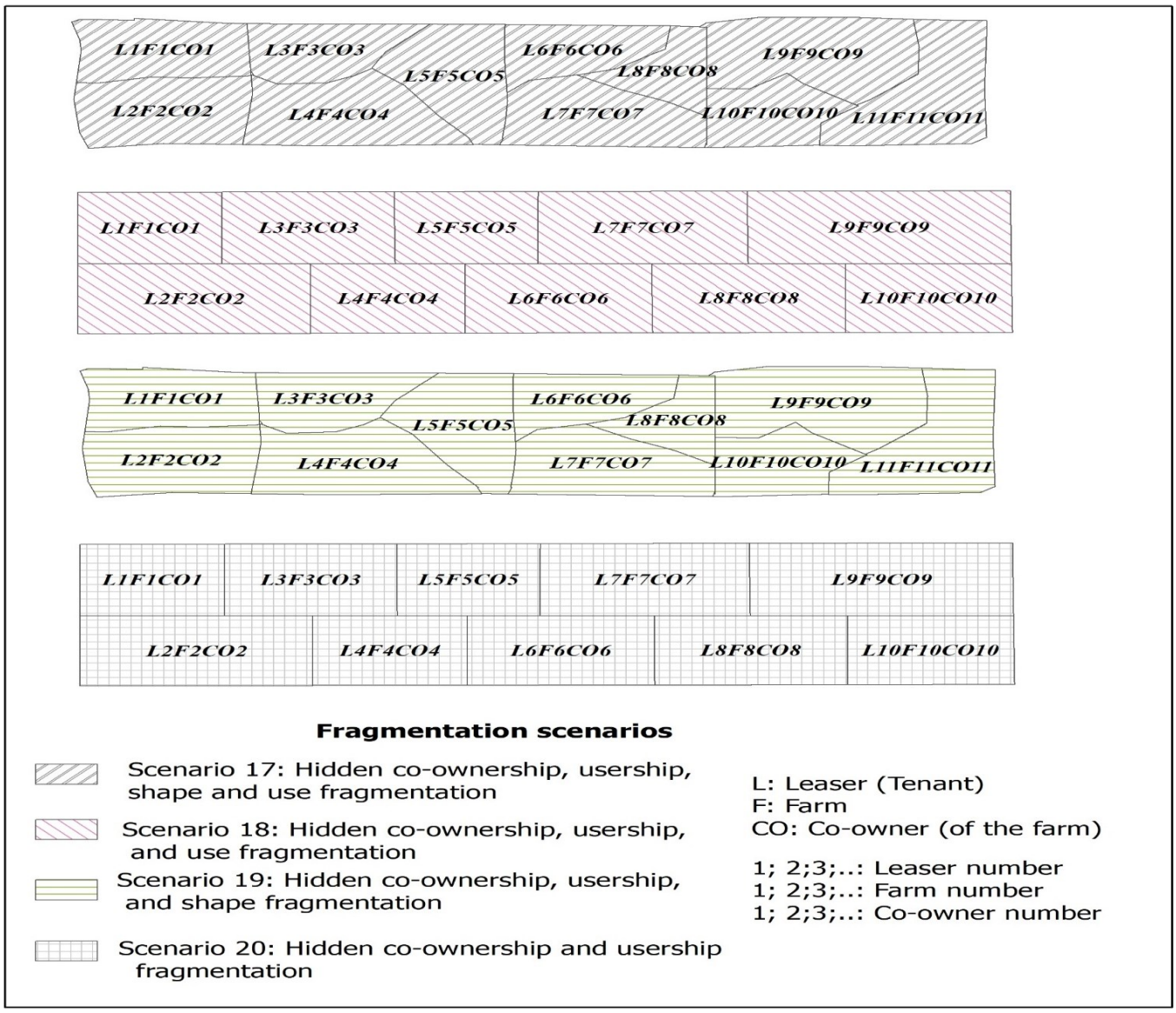

Figure 6A2. Hidden co-ownership and usership fragmentation

-Scenario 17: *Hidden co-ownership, usership, shape and use fragmentation*: Many land co-owners leasing out their farms with irregular shapes and uses (multiculture) to many users in a relatively small land block/area: Many small hidden leased farms with multiple parcel shapes and agricultural uses.

-Scenario 18: *Hidden co-ownership, usership, use fragmentation*: Many land co-owners leasing out their farms with regular shapes and multiple uses (multiculture) to many users in a relatively small land block/area: Many small hidden leased farms with regular shapes but multiple agricultural uses.

-Scenario 19: *Hidden co-ownership, usership and shape fragmentation*: Many land co-owners leasing out their farms with irregular shapes and regular use (monoculture) to many users in a relatively small land block/area: Many small hidden leased farms with multiple shapes and consolidated agricultural use.

-Scenario 20: *Hidden co-ownership and usership fragmentation*: Many land co-owners leasing out their farms with regular shapes and uses (monoculture) to many users in a relatively small land block/area: Many small hidden leased farms with regular parcel shapes and consolidated agricultural use.

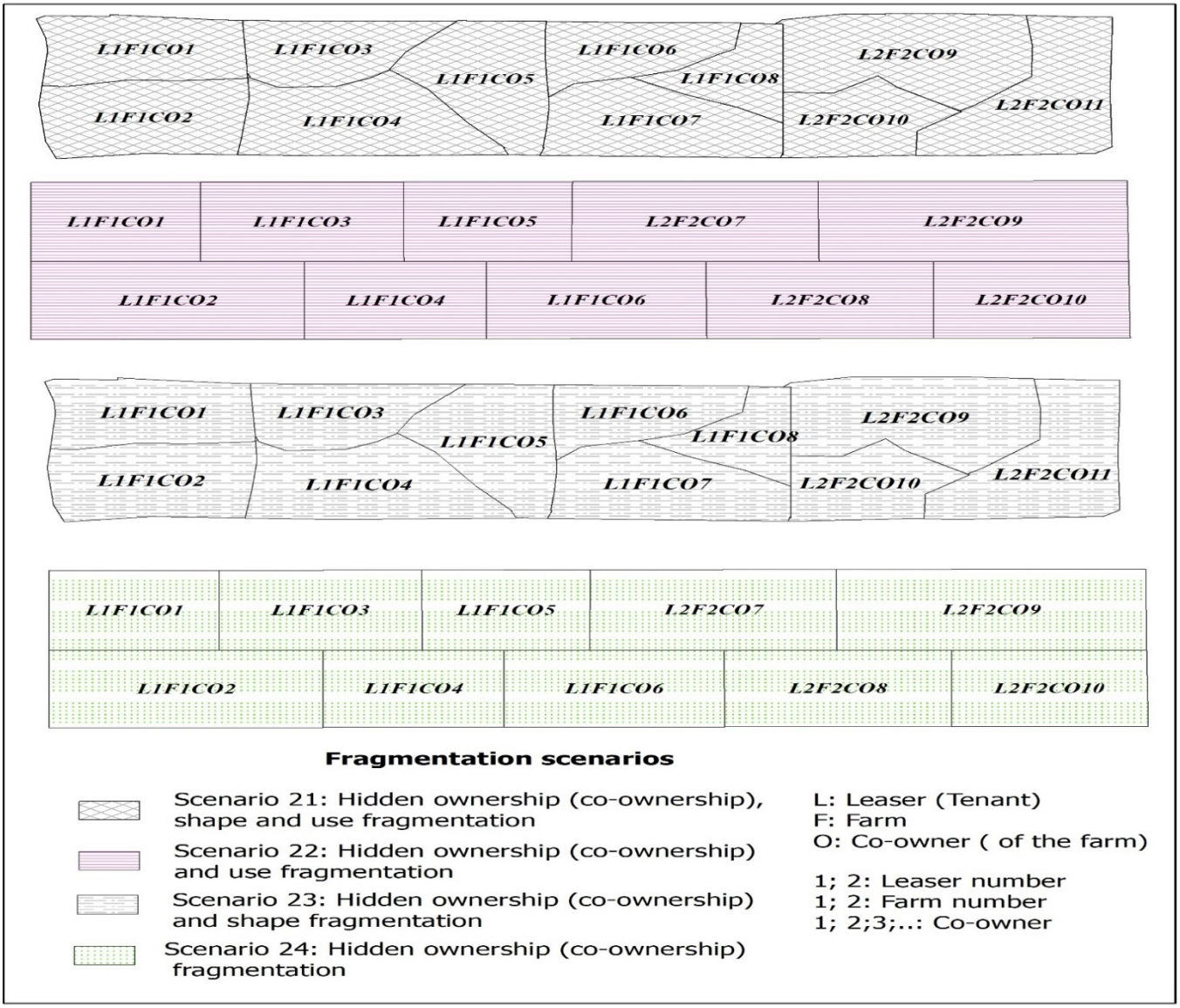

Figure 7A2. Hidden ownership (co-ownership) fragmentation

-Scenario 21: *Hidden ownership (co-ownership), shape and use fragmentation*: Many land co-owners leasing out their farms with irregular shapes and uses (multiculture) to one or few users in a relatively small land block/area: Many small hidden farms with multiple parcel shapes and agricultural uses.

-Scenario 22: *Hidden ownership (co-ownership) and use fragmentation*: Many land co-owners leasing out their farms with regular shapes and multiple uses (multiculture) to one or few users in a relatively small land block/area: Many small hidden farms with regular shapes but multiple agricultural uses.

-Scenario 23: *Hidden ownership (co-ownership) and shape fragmentation*: Many land co-owners leasing out their farms with irregular shapes and regular use (monoculture) to one or few users in a relatively small land block/area: Many small hidden farms with multiple shapes and consolidated agricultural use.

-Scenario 24: *Hidden ownership (co-ownership) fragmentation*: Many land co-owners leasing out their farms with regular shapes and uses (monoculture) to one or few users in a relatively small land block/area: Many small hidden farms with regular parcel shapes and consolidated agricultural use.

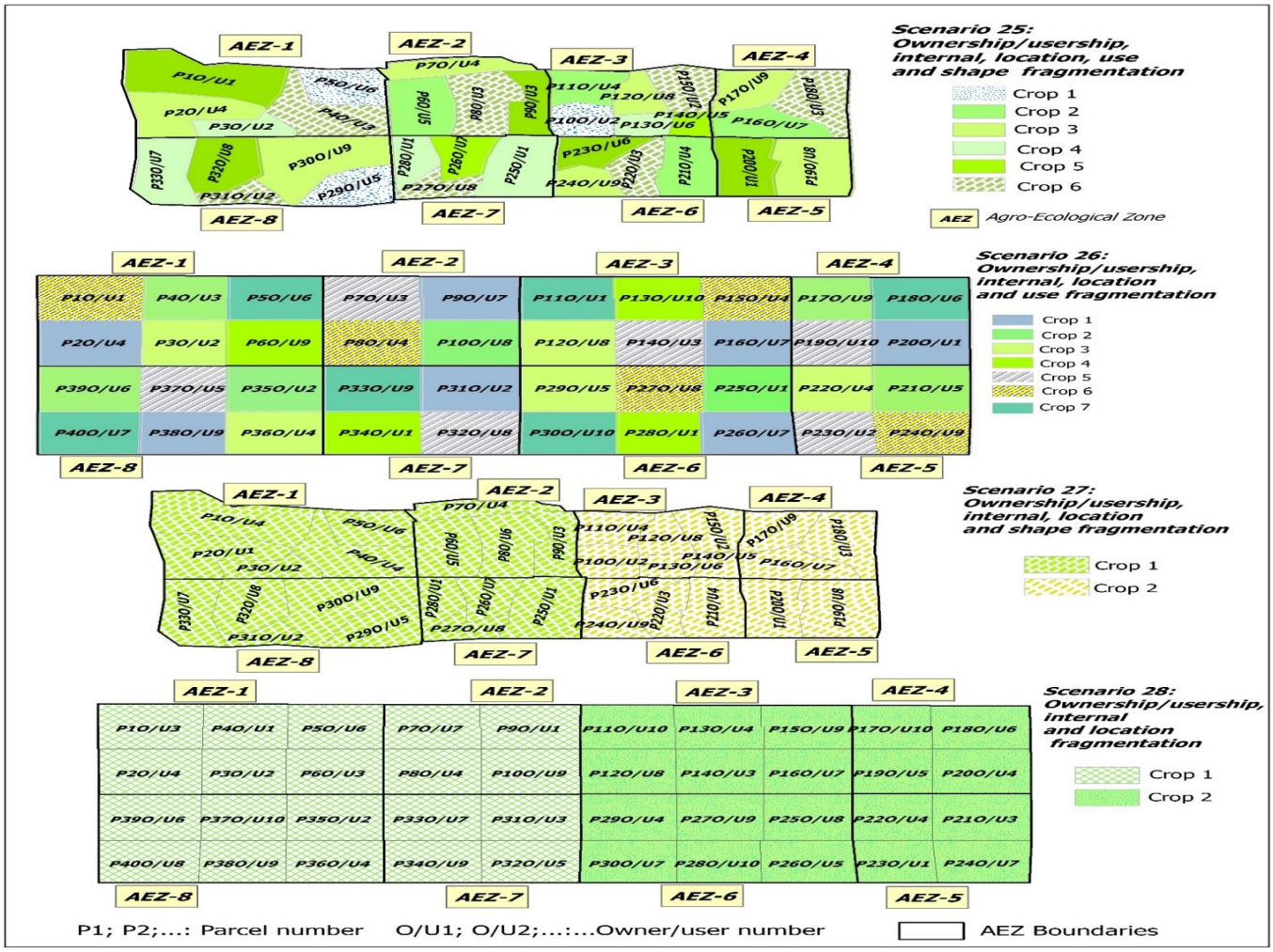

Figure 8A2. Ownership/usership, internal and location fragmentation

-Scenario 25: *Ownership/usership, internal, location, use and shape fragmentation*: Many land owners/users operating many scattered plots with irregular shapes and uses (multiculture) in a relatively small land block/area: Many small farms with many scattered small plots, different agricultural uses and shapes.

-Scenario 26: *Ownership/usership, internal, location and use fragmentation:* Many land owners/users operating many scattered plots with regular shapes and multiple uses (multiculture) in a relatively small land block/area: Many small farms with many scattered small regularly shaped plots and different agricultural uses.

-Scenario 27: *Ownership/usership, internal, location and shape fragmentation:* Many land owners/users operating many scattered plots with irregular shapes and regular use(monoculture) in relatively small land block/area: Many small farms with many scattered small plots, different shapes and consolidated agricultural use.

-Scenario 28: *Ownership/usership, internal and location fragmentation:* Many land owners/users operating many scattered plots with regular shapes and use (monoculture) in a relatively small land block/area: Many small farms with many scattered small plots with regular parcel shapes and consolidated agricultural use.

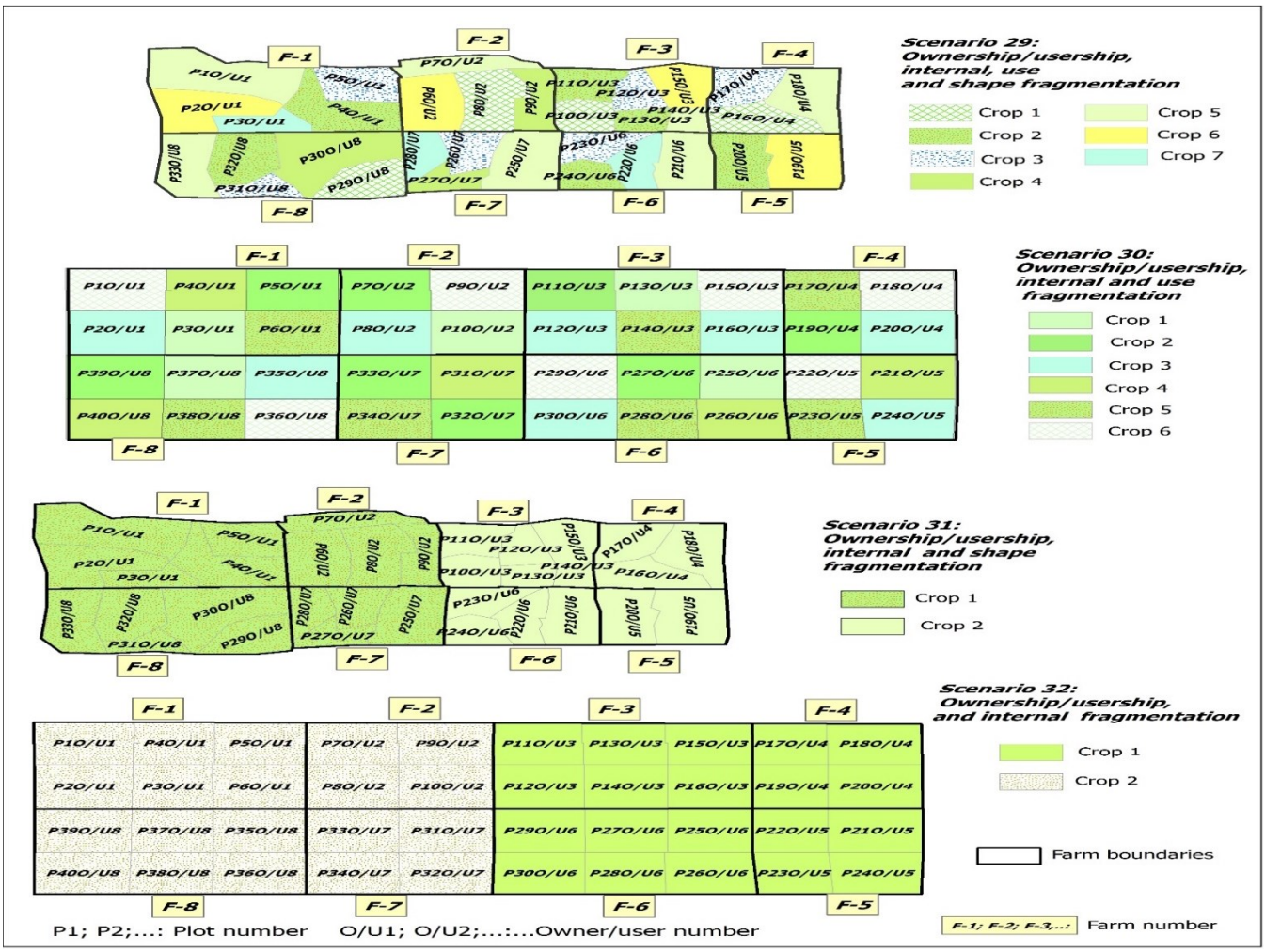

Figure 9A2. Ownership/usership and internal fragmentation

-Scenario 29: *Ownership/usership, internal, use and shape fragmentation:* Many land owners/users operating many contiguous plots to the homestead with irregular shapes and uses (multiculture) in relatively small land block/area: Many small farms with many small plots in the same location close to the homestead with different uses and shapes**.**

-Scenario 30: *Ownership/usership, internal and use fragmentation:* Many land owners/users operating many contiguous plots with regular shapes and multiple uses (multiculture) in a relatively small land block/area. Many small farms with many small plots in the same location close to the homestead with different uses and similar shapes.

-Scenario 31: *Ownership/usership, internal and shape fragmentation:* Many land owners/users operating many contiguous plots with irregular shapes and regular use (monoculture) in relatively small land block/area. Many small farms with many small plots in the same location close to the homestead with different shapes and similar use.

-Scenario 32: *Ownership/usership and internal fragmentation:* Many land owners/users operating many contiguous plots with regular shapes and use (monoculture) in relatively small land block/are. Many small farms with many small plots in the same location close to the homestead with similar shapes and agricultural use.

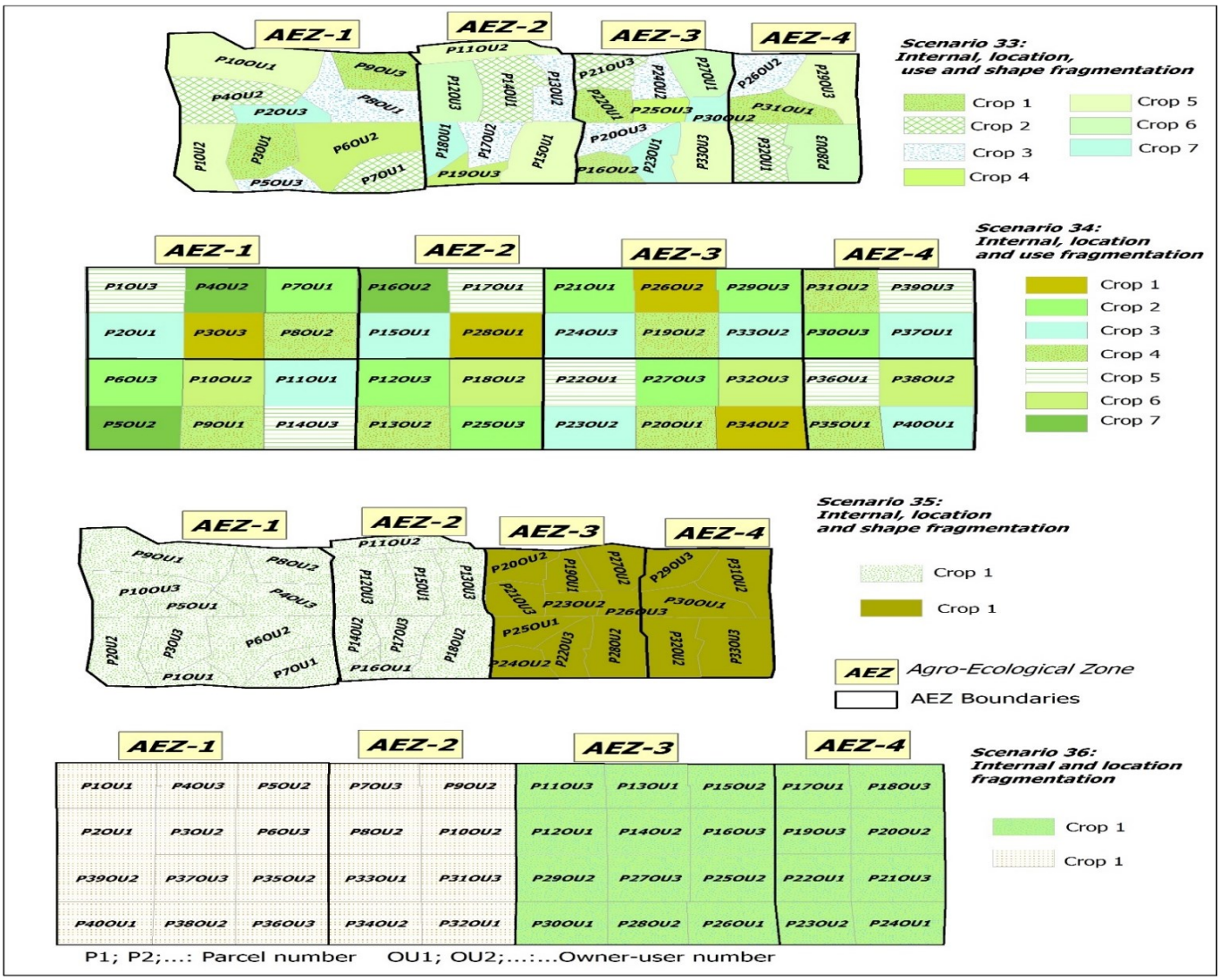

Figure 10A2. Internal and location fragmentation

-Scenario 33: *Internal, location, use and shape fragmentation:* One or few land owner-users operating many scattered plots with irregular shapes and uses (multiculture) in relatively big land block/area. One or few big farms with many scattered small plots with different uses and shapes.

-Scenario 34: *Internal, location and use fragmentation*: One or few land owner-users operating many scattered plots with regular shapes and multiple uses (multiculture) in a relatively big land block/area. One or few big farms with many scattered small plots with different uses and similar shapes.

-Scenario 35: *Internal, location and shape fragmentation*: One or few land owner-users operating many scattered plots with irregular shapes and regular use (monoculture) in relatively big land block/area: One or few big farms with many scattered small plots with different shapes and consolidated agricultural use.

-Scenario 36: *Internal and location fragmentation:* One or few land owner-users operating many scattered plots with regular shapes and use (monoculture) in relatively big land block/area: One or few big farms with many scattered small plots with similar shapes and agricultural use.

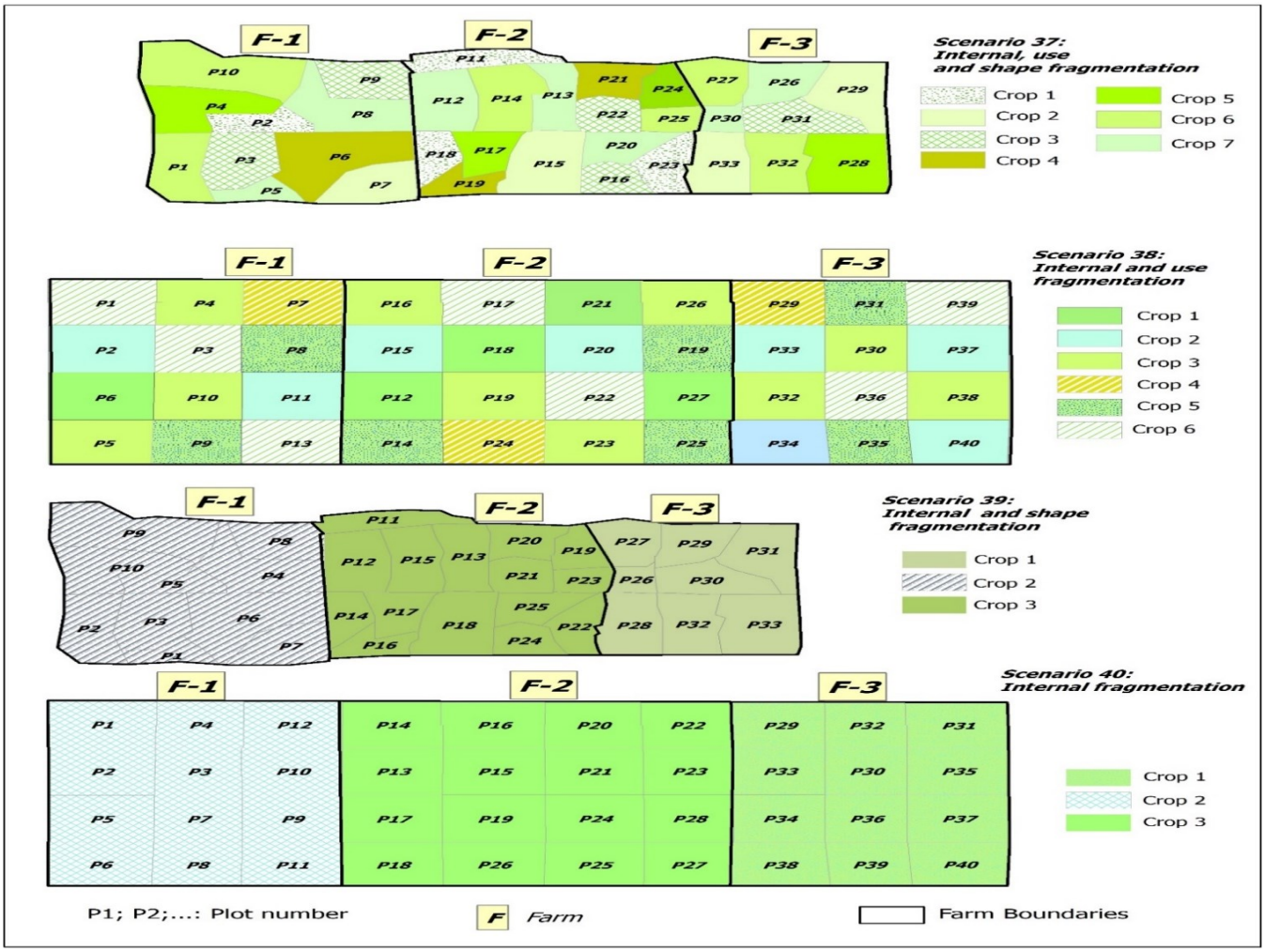

Figure 11A2. Internal fragmentation

-Scenario 37: *Internal, use and shape fragmentation:* One or few land owner-users operating many contiguous plots with irregular shapes and uses (multiculture) in a relatively big land block/area: One or few big farms with many small plots in the same location close to the homestead with different agricultural uses and shapes.

-Scenario 38: *Internal and use fragmentation:* One or few land owner-users operating many contiguous plots with regular shapes and multiple uses (multiculture) in a relatively big land block/area: One or few big farms with many small plots in the same location close to the homestead with similar shapes and different agricultural uses.

-Scenario 39: *Internal and shape fragmentation:* One or few land owner-users operating many contiguous plots with irregular shapes and regular use (monoculture) in relatively big land block/area: One or few big farms with many small plots in the same location close to the homestead with different shapes and consolidated agricultural use.

-Scenario 40: *Internal fragmentation:* One or few land owner-users operating many contiguous plots with regular shapes and use (monoculture) in relatively big land block/area: One or few big farms with many small plots in the same location close to the homestead with similar shapes and agricultural use.

From the above scenarios, it is noted that land tenure (ownership and/or usership) and internal (physical) land fragmentation can coexist in the same small land block. However, referring to the studies of Bentley (1987), Blarel *et al.* (1992), Van Dijk (2004), Van Hung *et al.* (2007), and Asiama *et al.* (2017b) which stipulate that the internal fragmentation decreases with the decrease in the number of parcels per farm and increases with farm size, the increase in the number of owners in a small land block would imply the opposite phenomenon of reduction in farm size and in the number of plots per owner/farm, and obviously the decrease in internal fragmentation. This implies that the two forms cannot theoretically coexist in the same area at the same levels/degrees. For this, their practical coexistance is only possible at different levels (high levels of ownership and/or usership fragmention and moderate to low levels of internal fragmentation, and vice versa) as shown in scenarios 25-32. Furthermore, refering to the belief of land fragmention as a natural phenomenon and a result of the natural diversity (soil,slope, microclimate) (Sklenicka and Salek, 2008), the land type or value fragmentation as a natural or physical form of fragmention can also coexist and interract with all the above mentioned forms at all levels (Ntihinyurwa *et al.*, 2019). Taking into account all the spatial units of land in agricultural land management along with different specific circumstatnces, many other different specific fragmentation scenarios may exist at the parcel, farm and land block levels in a given area, and can be generalized to other areas with similar conditions.

In summary, land fragmentation forms are diverse, and the extent of this diversity is determined by the local conditions in specific countries and areas. Regardless of their variability, they can fall into two categories of either *Physical* or *Tenure fragmentation* which can coexist together in the same area under different fragmentation scenarios and vary from case to case. Nevertheless, with regard to the problems associated with each form, one could categorise them into four different groups of *Size fragmentation* (small size problems), *Location* or *Spatial fragmentation* (distance problems betwen plots and farmstead), *Shape fragmentation* (shape irregularity problems), and *Use fragmentation* (problems of multiple mixed uses or multiculture). For this, its management needs a carefull assessment of all its forms, causes, and impacts (rational and defective) and their detemining conditions.

6. Conclusions

Contrary to the conventional insights in land fragmentation, this study posits new ontologies and epistemologies of farm and parcel as a fundamental basis for describing, measuring and controlling parcel fragmentation, farm fragmentation and farmland fragmentation. Whilst a wide number of studies considers a farm as the total area of land under a single ownership often confused with the parcel and the household landholding, or simply as any continuous land block used for agricultural purposes, in this paper, this concept refers to the total area of land (sum of all parcels) operated or tilled as a single agricultural enterprise (unit), regardless of its tenure (ownership and usership) and its physical characteristics (size, shape, use, value and location). In this regard, the farm fragmentation (internal fragmentation, within farm fragmentation) denotes the situation when a single farm is physically split into many relatively small plots (parcels) either spatially dispersed (non-contiguous) or contiguous (physical fragmentation), or shared by many undocumented co-owners or co-users (hidden tenure fragmentation in terms of ownership or usership), while the farmland fragmentation refers to the split of the farming

structure in a relatively small land block or region into many small farms (visible and hidden tenure fragmentation in terms of ownership and usership), or into many small plots or parcels (physical fragmentation). Following this approach, the extent of the farm (internal) fragmentation indicated by the number or percentage of internally fragmented farms in a given area (land block, village, region, nation) can inform about the status of the farmland fragmentation in both physical and tenure (social) but not vice versa. This implies that the former can exist at both the farm (except the visible tenure fragmentation) and higher (land block, regional, national) levels, while the later occurs at both the parcel, farm and land block (village, regional, national) levels only in forms of physical or landscape fragmentation and hidden tenure fragmentation, and separately at the land block or regional level in form of visible tenure fragmentation regardless of the internal details about the individual farms apart from their number. The parcel fragmentation on the other side refers to any type of physical or social split of the parcel into many small plots in terms of use, shape, location and hidden tenure which can also be considered as internal fragmentation at the parcel level.

Despite previous studies which limit the fragmentation scenarios on physical, ownership, use (tenancy) and the discrepancy between the two last forms as tenure fragmentation, this study adopts 40 different combinations of 6 key fragmentation indicators (descriptors) such as parcel ownership and usership as visible and hidden social or tenure characteristics, along with the number of parcels per farm, their shapes, uses and locations as physical characteristics to create 40 different fragmentation scenarios as an extension to the existing debate on this topic. These range from Internal; Internal and location as physical fragmentation; Ownership (visible and hidden); Usership (tenancy); Visible ownership and usership; Hidden co-ownership and usership; Hidden ownership (co-ownership); Visible ownership and hidden co-ownership as tenure (social) fragmentation to ownership and internal; Ownership, internal and location as both physical and tenure (social) fragmentation, replicated in 4 combinations with variables like parcel use or utilization (monoculture vs multiculture) and shape (regular vs irregular). These 40 scenarios were considered as the most realistic out of the 64 mathematically possible cases in theory, which may separately exist in different areas or coexist in the same area.

We hypothesize that the management of farmland fragmentation can be best done by first identifying all possible land fragmentation scenarios in a given area, their causes, impacts (positive and negative), and the conditions determining their problematic and rational situations prior to the development of any decision about farmland fragmentation conservation or defragmentation policies (strategies) as land management tools. Further research should concentrate on the assessment and development of more detailed specific indicators and harmonized measurements of land fragmentation to determine its extent (when land is too fragmented or not fragmented at all), and guide or support the trade-offs between fragmentation and defragmentation tools for food security purposes under different specific local conditions. Moreover, there should be a distinction among land fragmentation forms at the parcel (internal in the form of both physical and hidden tenure), farm (internal, or within farm, both physical and tenure), and land block, regional and national (fragmentation of the farming structure in a given area or region either in the form of physical or tenure or both, often referred to as farmland fragmentation) levels before devising any fragmentation treatment policy, since the fragmentation forms at these different

spatial units of analysis are theoretically different, which implies their differentiation in practice (in terms of degree and extent). This will facilitate the cross-cultural comparisons of land fragmentation levels (degrees) and prevent the misleading information prior to the development of fragmentation management policies. The findings from this study will inform and guide the decisions of land managers for the design and evaluation of suitable land management interventions aiming at addressing local land fragmentation problems.

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Appendix 3 (A3). Farmland Fragmentation and Defragmentation Nexus: Scoping the Causes, Impacts, and the Conditions Determining its Management Decisions

Abstract

Theoretically, both land fragmentation and consolidation (defragmentation) approaches are considered as tools of land management. However, although a large literature about the relationships among land fragmentation, land consolidation, agriculture production and crops diversification concepts exist, less is known about the linkages among the conditions determining the decisions about the adoption of these tools in a given area. This poses a major dilemmatic challenge to policy makers about whether to devise policies in favour of fragmentation conservation or defragmentation. Therefore, this study identifies the conditions under which one could opt for land fragmentation or defragmentation policies by critically reviewing the documented causal-effects relationships between different fragmentation forms versus defragmentation approaches. The end goal is the development of an explicit comprehensive model indicating when, where and why land fragmentation can be preserved or eliminated for food security purposes within the framework of the Sustainable Development Goals (SDGs 1, 2, 12, 13 and 15). Following the rationalist theory, the study adopts an integrative concept-centric qualitative approach which builds on the analysis of existing literature and deductive logical reasoning to create new comprehensive scientific knowledge about a topic, as an informative guidance for future research and policies. Contrary to the majority of existing literature, this study posits that farmland fragmentation is not necessarily a problem. The scenarios and extent to which it becomes problematic or beneficial are dependent on a combination of a number of local specific external circumstances, ranging from biophysical, social, economic, political, technical to agro-ecological ones. For subsistence motives, labour, risks and conflicts management, climate change adaptation and household food security purposes, both physical in terms of internal and location, and tenure fragmentation of farmland in a given heterogeneous area under the subsistence and middle-income economies can be conserved either in combination with or without agriculture intensification programs. On the other hand, both physical and tenure fragmentation under homogenous agro-ecological conditions, and physical fragmentation under heterogeneous agro-ecological conditions and strong complex economies can be revoked for the purposes of improving farm efficiency and food security. We therefore argue that any policy to adapt the extent of farmland fragmentation should consider both the benefits and costs of such intervention in relation to the specific local context.

Keywords: farm, farmland fragmentation, defragmentation, food security, SDGs, integrative review

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1. Introduction

Farmland fragmentation also known as pulverization (Bentley, 1987;Kadigi *et al.*, 2017), subdivision (Farmer, 1960;King & Burton, 1982), parcellisation (Roche, 1956), scattering and dispersion or distribution (Sorbi, 1952;Farmer, 1960;Sanderatne, 1972;King & Burton, 1982;Bentley, 1987;Kadigi *et al.*, 2017), farm fragmentation (Blarel *et al.*, 1992), agricultural land fragmentation (Brabec & Smith, 2002;Kalantari & Abdollahzadeh, 2008;Sklenicka & Salek, 2008;Vijulie *et al.*, 2012), landscape fragmentation (Lisec & Pintar, 2005;Muchová & Petrovič, 2010;Farley *et al.*, 2012) and field fragmentation (Galt, 1979), has generally been considered as defective and a major threat to agricultural production and food quantity in market-oriented and mechanized agricultural societies through the reduction of farm efficiency by increasing the production costs (FAO, 2003;Tan *et al.*, 2006;Kawasaki, 2010;Latruffe & Piet, 2014;de Vries, 2016;Hiironen & Riekkinen, 2016;Alemu *et al.*, 2017;Dhakal & Khanal, 2018;Zhang *et al.*, 2018;Postek *et al.*, 2019). The protagonists of this view often highlight this phenomenon as an unwanted scenario which needs to be avoided. In line with this claim, most European and some African, Asian, and American countries have adopted strategies of land consolidation to reduce fragmentation (Keeler & Skuras, 1990;Sabates-Wheeler, 2002;FAO, 2003;Van Dijk, 2003;Vitikainen, 2004;Demetriou *et al.*, 2012;Hartvigsen, 2015;Abubakari *et al.*, 2016;Louwsma *et al.*, 2017;Asiama *et al.*, 2019). Alongside classical land consolidation programs, other defragmentation instruments have also been adopted in some areas and specific circumstances. These include land banking (Van Dijk, 2003;Van der Molen *et al.*, 2004;Van Dijk, 2004;Hartvigsen, 2015), cooperative farming, voluntary parcel exchange, farmland subdivision restrictions and Farmland Use Consolidation (LUC) in Rwanda and Malawi (Kathiresan, 2012;Bizoza & Havugimana, 2013;Huggins, 2013;Mbonigaba & Dusengemungu, 2013;Pritchard, 2013;Musahara *et al.*, 2014;Asiama *et al.*, 2017b;Chigbu *et al.*, 2019;Nilsson, 2019;Ntihinyurwa *et al.*, 2019). The success of each of these strategies depends upon different local conditions and factors, which vary from country to country and case to case, since a strategy that works in one country might not work in another. This requires a careful and substantive assessment of the similarity and differences in problems and causes of land fragmentation as well as the prerequisite and operational conditions for the success of any strategy or instrument before its transfer from one country to another (Van Dijk, 2004;Vitikainen, 2004;Abubakari *et al.*, 2016;Asiama *et al.*, 2017a). The documented experience shows that the overlook of the consideration of local conditions when adopting land consolidation programs in Sub-Saharan Africa (Kenya, Malawi, Rwanda, Tanzania) and India has led to insufficient benefits (King & Burton, 1983;Bentley, 1987;Blarel *et al.*, 1992;Huggins, 2013;Pritchard, 2013;Abubakari *et al.*, 2016;Asiama *et al.*, 2017b;Chigbu *et al.*, 2019;Ntihinyurwa *et al.*, 2019).

On the other hand, there are advocates of the opinion which claims that land fragmentation is a farmer's choice or requirement to mitigate risks and weather shocks, by farming in multiple ecological zones and diversifying crops for self-sufficiency (subsistence) in food production and household food security (Bentley, 1987;Blarel *et al.*, 1992;Molle & Srijantr, 2003;Niroula & Thapa, 2005;Sklenicka & Salek, 2008;Di Falco *et al.*, 2010;Ali *et al.*, 2015;Kadigi *et al.*, 2017;Ciaian *et al.*, 2018a;Knippenberg *et al.*, 2018;Cholo *et al.*, 2019;Ntihinyurwa *et al.*, 2019). The collective of these articles posit that not all land fragmentation forms are problematic or defective since there are circumstances where the benefits of fragmentation overweigh the costs of consolidation especially in overpopulated mountainous areas and

subsistence communities with a very high variety of crop-growing conditions, socio-ecological heterogeneities and small farm sizes. Therefore, such areas should be kept fragmented in order to mitigate food market fluctuations and as a risk management strategy to secure the chances of food quality, quantity, accessibility and sustainability (Igbozurike, 1970;Bentley, 1987;Blarel *et al.*, 1992;FAO, 2003;Ciaian *et al.*, 2018a). For them, growing different crops under different growing conditions spreads out the risks of total crops failure and production loss in case of environmental hazards and weather shocks (change in rainfall patterns and temperatures leading to droughts, floods, winds, etc), diseases outbreak, and food price fluctuations under the ever-increasing climate change realities. In this case, land fragmentation is rather considered as an adaptive strategy than a problem. Furthermore, different studies in history revealed the negative relationships between farm sizes and crop yields to discourage the incentives of consolidation in failed labour market management conditions (Blarel *et al.*, 1992;Ali & Deininger, 2014;Kadigi *et al.*, 2017). This explains the persistence of this fragmentation phenomenon in the farming society, and the controversy among farmers whether it is the best choice for them, despite multiple attempts and strategies to eliminate it. In this regard, de Vries and Chigbu (2017) advance that both land fragmentation and land consolidation should be considered as responsible land management instruments.

Following the same debate, different theories ranging from social, economic, and ecological ones have been subjectively advanced to support and justify each of the two approaches of land fragmentation and land consolidation (defragmentation). The Economies of Scale theory stipulating the positive relationship between farm size and crops yield or output (Stigler, 1958;Asiama *et al.*, 2019), Gestalt theory of 1910 stating that the whole is greater than the sum of its parts (Wertheimer, 1938), and the Malthusian theory of 1798 stipulating the inverse relationship between the population growth and food supply (Demont *et al.*, 2007;Desiere & D'Haese, 2015;Burchi & De Muro, 2016) stand for land consolidation or defragmentation approaches; Whilst the Economies of Scope theory stipulating the production as a result of many heterogeneous factors (Teece, 1980;Bentley, 1987;Blarel *et al.*, 1992), the Complexity theory stipulating the adaptation to emerging unpredictable complex phenomena (Norberg & Cumming, 2008;Wim *et al.*, 2015;Salvati *et al.*, 2017), the Ecological Resilience theory stipulating the biodiversity conservation as an adaption to nature shocks (Gunderson, 2000;Lengnick, 2015), and the Boserup's theory of 1965 stipulating the proportional relationship between the population growth and agriculture intensification (Demont *et al.*, 2007;Boserup, 2011;Desiere & D'Haese, 2015) stand for land fragmentation conservation. This poses a major dilemma to policy makers about whether they should devise a policy in favour of defragmentation or fragmentation conservation. This dilemma sometimes leads to the formulation of broad irrelevant farmland fragmentation control strategies regardless of the specific category of its forms (problematic or beneficial) which are often contested or resulting in a failure.

Besides the subjectivity and the contradictions of different previous studies in literature, only few of them sporadically and explicitly show when, where and why one should go for consolidation or keep fragmentation, thereby calling for more comprehensive research about the topic. In this vein, Bentley (1987), Bentley (1990), Kadigi *et al.* (2017), Cholo *et al.* (2019), and Ntihinyurwa *et al.* (2019) commonly

suggest the conservation of any fragmentation scenario in mountainous areas, areas with dramatic micro-climatic contrasts, high production and market risks and fluctuations, costs of consolidation exceed its benefits, high farm population densities, subsistence and heterogeneous socio-economic and environmental conditions for crops diversification, risks and labour management, self-sufficiency in food production and household food security. They on the other hand recommend the consolidation or elimination of any fragmentation occurring in areas with big mechanized farms, homogenous agro-ecological and market-oriented economic conditions for improving farm efficiency and boosting agriculture productivity and food quantity. However, none of these studies holistically links different fragmentation forms and scenarios with various conditions determining their management decisions, despite the advices for prior consideration of the local conditions. Therefore, there is a call for the assessment of more detailed and explicit conditions (Biophysical, Social, Economic, Cultural, Political, and Environmental) under which land should be consolidated or kept fragmented or both, to guide and inform the decisions of policy makers. To this end, different existing land fragmentation scenarios, their causes, impacts (positive and negative) and their magnitude need to be identified, and the appropriate specific case control strategies developed. To fill the above literature lapse and reply to these research calls, this study aims to critically and objectively review and explore existing literature about different farmland fragmentation forms, causes and impacts in different scenarios; identify the knowledge gaps and openings for further research, and reconceptualise the problem to guide policy makers and inform future studies about the right conditions for either fragmentation conservation or defragmentation approaches (Webster & Watson, 2002;Torraco, 2016). It results in a substantive and explicit discussion of both the conditions under which different fragmentation scenarios become defective (problematical) and rational (beneficial) in different specific circumstances.

Being an integrative review, the article builds on the existing body of literature and on logical reasoning from the perspective of the rationalist theory, and on a concept-centric approach as a suitable method to create new comprehensive knowledge about the topic. Moreover, it contributes to and extends the existing debate about land fragmentation and the Sustainable Development Goals (1, 2, 12, 13 and 15) versus the global trends towards market-oriented agriculture. These SDGs stipulate the equal distribution, ownership, access, security, and control of land resources among all the heirs (SDGs 1.4; 2.3), sustainable management and efficient use of natural resources including land (SDG 12.2), the diversification of crops in different fragmented and scattered areas with diverse growing conditions as an adaptive strategy (climate smart or resilient agriculture) to the ongoing new global challenging realities of climate change (SDGs 2.4, 5; 13.1) to end hunger and malnutrition resulting from food insecurity (SDG 2.1, 2, 3, 4, 5), and the agrobiodiversity and ecosystems conservation through the protection of their natural habitats on land (SDG 15.3, 4, 5, 9) in the Agenda 2030. Although land management as a scientific discipline may be somehow linked with all the sustainable development goals, the decisions about farmland use either in fragmented or consolidated forms can only be directly coupled with these five SDGs whose specific targets capture the sustainable land management (ownership and use) and climate change adaption and mitigation, as key factors of sustainable agriculture production and food security to end hunger, malnutrition and poverty. Since land fragmentation and land consolidation are differently conceptualized in diverse contexts, disciplines and levels of analysis, only their relevance for agricultural

production at all scales will be followed in this article. Only the literature written in English about the topic is considered irrespective of the spatial and temporal limitations.

Thus, the article is structured as follow: First, the concepts of farmland fragmentation and farmland consolidation (defragmentation) are introduced, with the motivation of the study thereafter. Second, the methodology of the literature identification, review, analysis, synthesis and reconceptualization is described. Third, the forms and causes of farmland fragmentation are discussed. Fourth, the impacts of different farmland fragmentation scenarios are discussed, and therefrom the conditions for fragmentation conservation or defragmentation approaches developed. Finally, the conclusions and implications for further research are drawn.

2. Methodology

2. 1. Research approach, boundaries, and design

This study adopts an integrative concept-centric qualitative approach whereby deductive logical reasoning from the perspective of rationalist theory is considered the most suitable epistemology and research method for this kind of studies (relying only on secondary data) to create new scientific knowledge and inform future research and policies (Webster & Watson, 2002;Torraco, 2005, 2016). According to Webster and Watson (2002) and Torraco (2016), this approach facilitates a critical review, analysis and synthesis of existing knowledge about a topic, in order to draw the possible relationships/linkages among different variables, identify the gaps, deficiencies, contradictions and opportunities for future research. It deductively uses own reasoning (abstract way of reasoning) without sensory experiences or empirical data to reconceptualise the topic for a better understanding and guide future perspectives. One can use his/her own knowledge about the topic to critically analyse and synthesize the existing knowledge about different concepts, theories and principles, and deduct his/her own new and particular conceptualization of the topic in the form of models, paradigms or frameworks, theories and hypotheses from the reviewed general facts as a novel scientific knowledge (Webster & Watson, 2002;Torraco, 2016). Thus, given the scope of this study (i.e. understanding various conditions under which one can opt for either a land fragmentation or a defragmentation land management strategy to achieve food security), the review only focussed on the literature which addresses the forms, causes and impacts of agricultural land fragmentation and its alternative control measures at all levels as a contextual boundary of the study, since the required information can only evolve from the relationships among these variables. The use of multi-levels of analysis is explained by the fact that farmland fragmentation itself is a multi-level phenomenon, whose causes, impacts as well as control strategies can be identified from the local (individual, household, family and village) to regional, national and international levels. For internal data validity purposes, spatial and temporal limitations were not considered, which led to the geographically unlimited review of both old and new available literature, as a suitable method for this case of research approach. It adopts a synthetic strategy of sense making which suggests the use of multiple cases and broad selection criteria to create a more comprehensive knowledge (Langley, 1999;Webster & Watson, 2002). However, in order to prevent the divergences, misuse, and linguistic bias about different concepts, both the empirical (primary) and review (secondary) literature in English for which the large body of extensive literature exist on this topic was only considered

for the review. The next section explains the processes and methods for literature identification (search, selection criteria and its sources or databases), review, analysis and synthesis techniques, and the reconceptualization or modelling methods and procedures for new scientific knowledge creation on the topic as summarized in the research design (see Figure. 1).

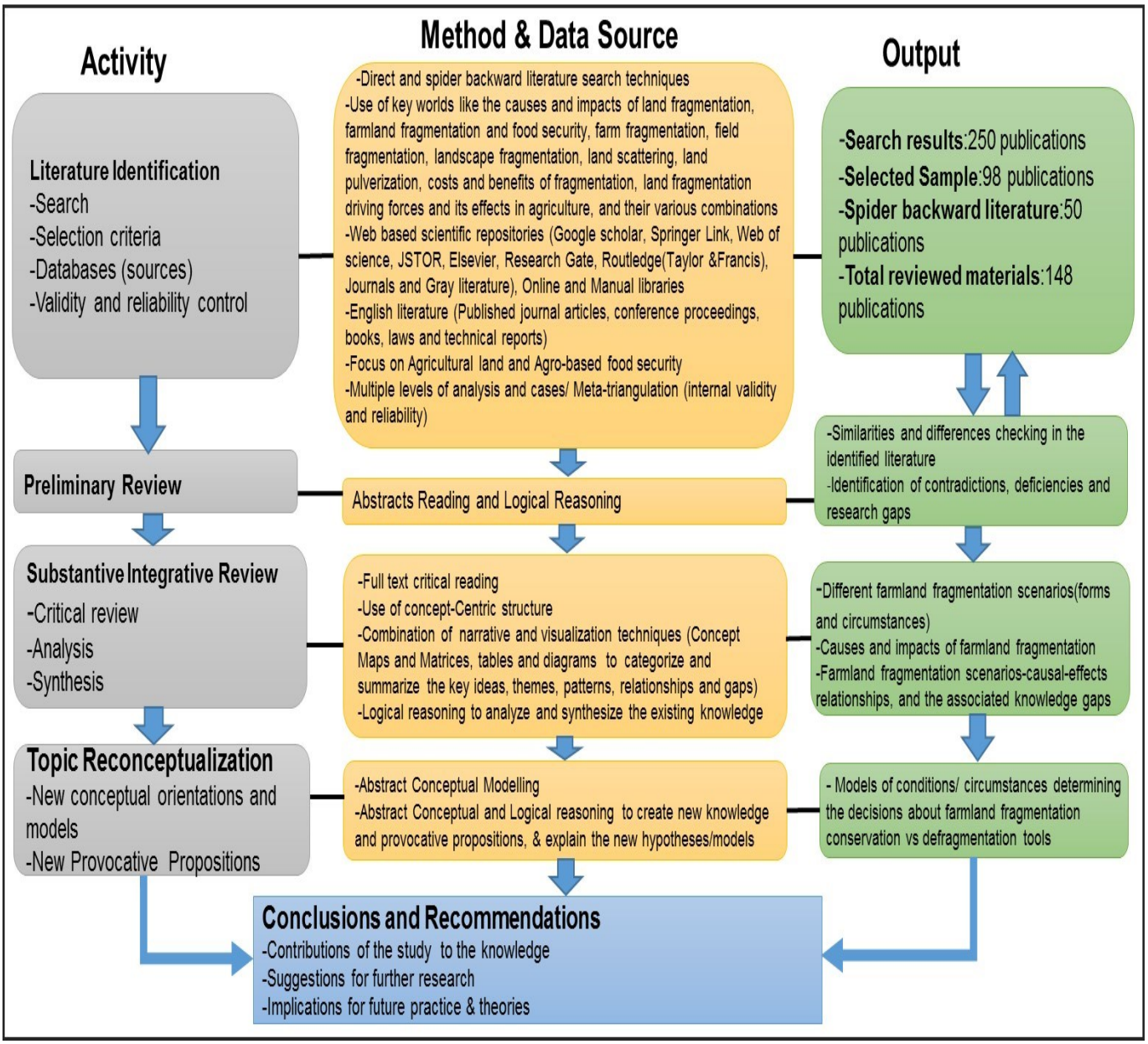

Figure 1A3. Overview of the research process and design

Source: Authors constructs

2. 2. Data sources, analysis, synthesis, and reconceptualization methods

The systematic literature search used the following individual key words and their combinations: causes and impacts of land fragmentation, farmland fragmentation, farm fragmentation, field fragmentation, land fragmentation and food security, landscape fragmentation, land scattering, land

pulverization, costs and benefits of fragmentation, and land fragmentation driving forces and effects in agriculture. It was performed across both different web based scientific repositories including Google scholar, Springer Link, Web of science, JSTOR, Research Gate, Elsevier, Routledge (Taylor &Francis), Journals, and the electronic Grey literature (published and unpublished non-commercial documents from different governmental and non-governmental institutions like FAO, IFPRI, World Bank, GLTN and UN-Habitat), coupled with the online and manual library check-ups for hard documents. The use of multiple synonymous and different key words across many different data sources in literature identification provides an advantage of offering a large variety of documents about the topic for validity and authenticity purposes. The search was nearly complete when no new concepts were found in the articles set (Webster & Watson, 2002;Torraco, 2016). The literature identification process resulted in the retrieval of 250 documents including 237 soft documents ranging from published peer reviewed journal articles, conference proceedings, books, laws and acts, technical reports, theses and press releases, and 13 hard documents from visited libraries. A preliminary review of the search results consisted of critically scanning all titles and abstracts of the articles taking into consideration the research boundaries. This resulted in the selection of 98 relevant materials for a full text review, and identification of similarities and differences, contradictions, deficiencies and research gaps.

Given the scope of the study, we adopted a concept-centric or thematic approach whereby all the articles with similar claims were grouped together and categorized using the combination of narrative (text) and visual representations as suitable organization strategy for integrative literature analysis and synthesis (Webster & Watson, 2002;Torraco, 2016). The content review consisted of both the analysis and synthesis of critical aspects and a listing of new relationships and research gaps. Throughout the review process, new seminal articles and frequently cited relevant references were identified and traced backward from their original articles which were also further considered in the review, using a spider backward literature search technique. This resulted in the selection of 50 additional soft documents, making the total of 148 reviewed publications. These were brought together in a concept matrix (Salipante *et al.*, 1982;Klopper *et al.*, 2007) containing the categorization of ideas and themes across different searched key variables (forms, causes and impacts of farmland fragmentation). These variables were thoroughly reviewed to identify their documented convergences and divergences or contradictions across different disciplines (social, economic, philosophical, agricultural and environmental), and the reasons behind the identified relationships and gaps were discussed, using the authors' existing knowledge about the topic. Different forms of farmland fragmentation, and their causes and impacts were critically reviewed in view of the diversity of the scenarios and conditions by which they were shaped. Besides that, the documented relationships were critically analysed using the logical reasoning method, which follows the rationalist theory (Webster & Watson, 2002;Torraco, 2016). This helped to identify the objective circumstances which derive the decisions for fragmentation conservation or elimination, the strengths, weaknesses, deficiencies, contradictions and problematical situations or gaps in the existing literature which need to be closed by the new knowledge, for the best management of this phenomenon and back the achievement of the Sustainable Development Goals (SDGs1, 2, 12, 13, and 15) within the existing climate change realities. This approach of conceptual reasoning is suitable for integrative theoretical researches like this one, which seek to analyse insights from past experiences and views for the

preparation of future perspectives and guidance. This method has also previously been used by other researchers in this field, such as McPherson (1982), Bentley (1987) and Asiama *et al.* (2017a). The identified relationships and gaps from the critical analysis were summarized in tables, diagrams, concept matrices or weaved together in a unique synthesis for a better presentation of the situation, and basis for a more comprehensive and harmonized reconceptualization of farmland fragmentation phenomenon in synchronized alternative hypothetical propositions and models. The same rationalist approach was also used to justify and explain different combinations and developed propositions about farmland fragmentation management to guide the decisions of policy makers and research scholars. Finally, the implications of the new logic to the existing knowledge and decision makers were explained, and the suggestions for future research to fill the newly revealed gaps and empirically test the new relationships and scenarios were derived.

3. Farmland fragmentation forms, causes and driving factors

Farmland fragmentation is conceptualized in diverse ways across the literature. The first aspect of this variation concerns the forms of fragmentation. There is a variation in *physical fragmentation* (internal, use, shape, value, and location), *tenure fragmentation* (both visible and hidden ownership and usership) and *spatial unit fragmentation* (parcel, farm and land block or zone) (Sabates- Wheeler, 2002;Van Dijk, 2004;Hartvigsen, 2014;Asiama *et al.*, 2017b;Ntihinyurwa *et al.*, 2019;Postek *et al.*, 2019). The reasons for this variety are often contextual. Bentley (1987) argues that agricultural land fragmentation is a result of a combination of factors, rather than being monolytical. McPherson (1982) has categorised the causes (factors) of land framentation as well as their effects (impacts) as twofold, in both demand (voluntary causes versus positive impacts) and supply factors (imposed or involuntary causes versus negative or problematic impacts). These authors argue that the causes and effects of land fragmentation are therefore also closely connected. The supply-side explanations stipulate that fragmentation has adverse effects on agricultural production, while the demand-side explanations reason from the presumption that farmers' choice is guided by their individually perceived benefits of the levels of fragmentation (Blarel *et al.*,1992). However, these explanations only make sense at a level whereby farmers can oversee to which extent internal fragmentation has a positive or negative effect on their agricultural production targets (in both quantity and quality), and on their food preferences and dietary needs for food security purposes. For Igbozurike (1970), McPherson (1982), and Blarel *et al.* (1992), the supply side reasoning alone cannot explain the persistence of land fragmentation in the farming sector, as it has also been documented in areas where both land consolidation programs, vacant and abundant lands co-exist, which justifies the existence of the demand side. In such situations, the supply-demand logic alone does not explain this land fragmentation phenomenon.

King and Burton (1982) and Hartvigsen (2014) provide alternative causes of land fragmentation such as: (1) socio-cultural variations (Egalitarian based ascending partible inheritance laws, population growth, marriage, dowry culture, private and customary land tenure systems); (2) variations in economic efficiencies (land market, land transactions, agricultural systems); (3) physical variations (soil qualities, topography, location, shapes, exposure, waterways, and other natural features); (4) operational variations (land reforms like land sharing programs, land redistribution and restitution programs, land

policies, laws and regulations, grouped resettlements programs, urbanization and infrastructure development). Asiama *et al*. (2017b) categorise the causes of land fragmentation in Ghana into socio-spatial variations (customary tenure which differs per region) and operational (technical) variations (susbsistance agricultural system). Van Dijk (2003) attributes land fragmentaion to economic opportunities and efficiencies (in the land market) and normative aspects (efficacy of agriculture policies). These subsequent factors derive both positive and negative impacts of land fragmention in one way or another, since many authors found them to be polarized, regardless of their categories and resultant fragmentation forms. Figure. 2 displays a summary of these various generic causes and driving factors of farmland fragmentation.

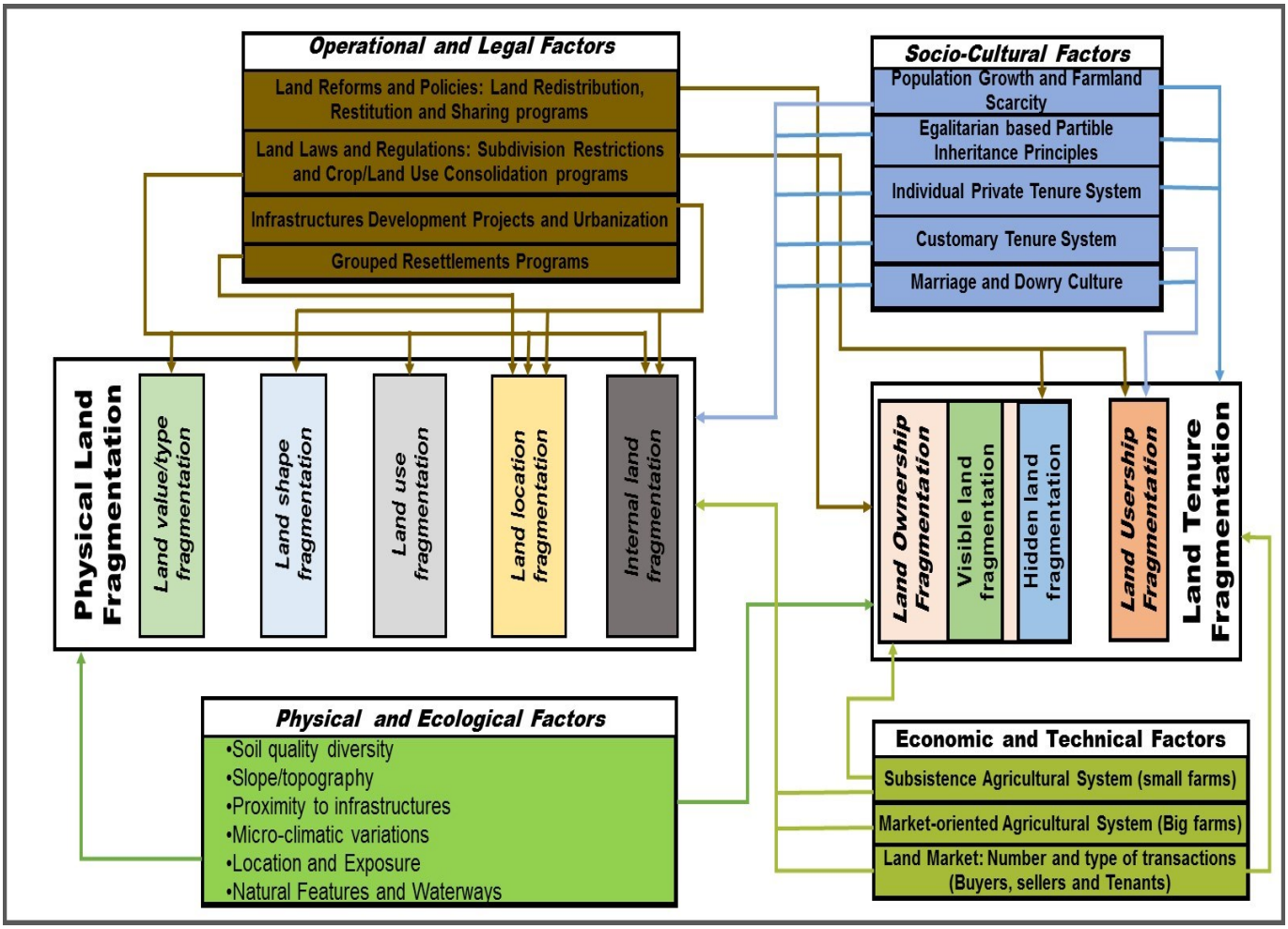

Figure 2A3. Generic causes and driving factors of farmland fragmentation

Source: Authors constructs from the analysed literature

In supply-side explanations for land fragmentation, both physical and tenure fragmentation forms are mainly linked with the demographic features, human activities, socio-economic and historical transformations. These include the farming population growth on scarce and stable land resources, partible egalitarian inheritance principles and culture, individual private land tenure system, along with land reforms such as land redistribution, land restitution and land sharing programs in different countries

after the conflicts (King, 1977;Bizimana *et al.*, 2004;Gomes *et al.*, 2019). The argument in these discourses is that high population growth in areas of limited land resources increases the agriculture population density, the number of land owners and users, the household size, the household food demands and needs, the desire to expand the farm through the acquisition of additional contiguous (adjacent) or non-contiguous parcel to meet these demands. This leads to land scarcity, which decreases the ratio of land per person as an indicator of internal (within farm) fragmentation in both physical and hidden tenure at the farm level, and tenure fragmentation (in both visible and hidden ownership and usership) at the land block, community, regional and national levels (Binns, 1950;Farmer, 1960;Farley *et al.*, 2012;Ntihinyurwa *et al.*, 2019). Binns (1950) argues that the population growth only leads to problematic land fragmentation when it is combined with partible egalitarian based inheritance and results in non-contiguous (scattered) small parcels from the homestead. Overpopulation alone cannot lead to land fragmentation when combined with land subdivision restrictions and impartible inheritance laws. In contrast, Farmer (1960) argues that land fragmentation can only be due to overpopulation and land shortage, and cannot be a result of partible inheritance, since the partible inheritance in abundant land and low population growth does neither lead to the increase in the number of owners and users, nor to small farm sizes as indicators of tenure fragmentation in terms of both ownership and usership. However, this view ignores the possibility of internal fragmentation which can result from egalitarian based land distribution through partible inheritance, land market, and land reforms in both scarce lands (small farms) and abundant lands (big farms) conditions. To back this stance, Bentley (1987) and Blarel *et al.*(1992) note that big farms are even internally more fragmented than small ones.

Existing land tenure systems have also been documented as direct drivers of land fragmentation. For Bentley (1987), Blarel *et al.*(1992), Abubakari *et al*.(2016), and Asiama *et al*.(2017b), the introduction of individual-based land tenure and registration systems has broken down the existing common and customary tenure systems in many African countries (Kenya, Zambia, Malawi, Ghana, Rwanda, Uganda, Nigeria, Gambia, Tanzania). This immediately led to the subdivision of family lands among different family members and many small individual farms indicating ownership fragmentation, many small parcels and plots per farm indicating internal fragmentation in case of the purchase of additional parcels and plots non-contiguous to the existing ones. Similarly, the customary tenure system itself can be an indirect driver of land fragmentation, as it prevents family members with only use rights to sell their land parcels and conserve farmland for future generations. In this case, any farmer willing to expand his/her farm is forced to buy or lease additional non-contiguous parcels to his/her farm, which in turn increases the internal and land location fragmentation as physical forms, and tenure fragmentation in the form of usership. Additionally, Abubakari *et al.* (2016) noted that the allocation of parcels and/or uses at the family levels under customary tenure systems in Ghana are not known by the chiefs nor documented at all, which leads to the occurrence of hidden use and ownership fragmentation.

The economic status coupled with agricultural systems and policies have as well been reported as key determinants of land fragmentation in many countries. Both opportunity costs and transaction costs dictate any land owners' decisions on how and when to transact in a land market (sales and purchases). McCloskey (1975) argues that land market itself is fragmented, which explains the existence of land

fragmentation. Van Dijk (2003), Vitikainen (2004), Hartvigsen (2014), and Asiama *et al.*, 2017a,b) in their respective works on Central Europe and Ghana, argue that the number of land transactions and the type of actors (buyers and sellers) influence the level and type of land fragmentation in a given area, by determining the significance and the type of transaction (market activity). For them, the physical land fragmentation in forms of internal,use and location occurs any time a farmer expands his farm by acquiring (buying/purchasing) new non-contigous parcels to his existing farm, as a result of restricted land market under the growing or strong market-oriented agricultural systems for the purpose of boosting the agriculture production and the income from the farm, or crops diversification. In this scenario,the value of land and the profit from it is high under the circumstances of good economic status of the country (high economic land value) due to the market perfection,which in turn leads to the willingness of big farmers to buy additional parcels to expand their farms (high purchasing power) sometimes for land speculaltion purposes, and the small farmers to sell their small plots at higher prices. In case of failed economic incentives especially in subsistance economies with free but uncertain or imperfect land market, land is not considered by farmers as an economic asset or commodity, rather a social resource (social land value) characterised by high attachment of farmers to land as their means of survival or subsistance. In this case, due to the low productive value of land (low income), and low purchasing power of inputs and additional parcels, there are few investments in farming. This in turn leads to the reduction in the number of users as tenants of big farms, and the maintenance of small plots by many small farmers in a relatively small area for subsistance farming in a so-called free survival scenario (Van Dijk,2003), thereby keeping land tenure (in terms of ownership) and physical fragmentation. Simply put, while the market-oriented agricultural system is well known for its big consolidated farms (in case of unrestricted land market) and big internally fragmented farms (in case of restricted land market), the subsistence one is characterised by small and sometimes internally fragmented and scattered farms (tenure and physical fragmentation) as a result of subsistence motives, traditional farming methods (shifting cultivation), physical, social and demographic factors explained above (Van Dijk, 2003;Van Hung *et al.*, 2007;Asiama *et al.*, 2017a).

Moreover, land reforms, laws, regulations and policies, infrastructure development, and urbanization are identified as key normative drivers of both land tenure and physical fragmentation at all spatial levels (both parcel, farm and land block levels). Land redistribution and restitution programs in Central and Eastern European countries which followed the political reforms and separation from the Socialist Soviet Union led to changes from cooperative farming and common land ownership (collectivisation), to systems favouring individual private land tenure system (privatisation). This resulted in the subdivision of big commonly used farms into many very small parcels operated by many owners and tenants leading to many small farms (Van Dijk, 2003;Hartvigsen, 2014). One of the most visible result of this process is the high levels of tenure fragmentation in both land ownership (indicated by many land owners) and usership in case of many absentee owners leasing out their small farms to many users (tenants) in a relatively small area, and internal fragmentation in case of application of egalitarian based principles in the distribution process (ibid). Another frequent outcome of these reforms is the scenario of the discrepancy between ownership and usership fragmentation (Ntihinyurwa *et al.*, 2019) or between ownership and use referred to as tenure fragmentation (Van Dijk, 2003;Hartvigsen, 2014;Sklenicka *et al.*, 2014;Jürgenson, 2016;Asiama *et al.*, 2017b;Muchová, 2019;Muchová & Raškovič, 2020) indicated by

the small number of land owners using their own farms or small share of the interaction between the number of owners and the number of tenants (users) in a given area. This happens when many farms are restituted to former owners who are no longer interested in farming or redistributed among all the residents including non-farmers who may decide to lease or sell their farms to many different users (tenants). It can also happen in case of farmers living far away from some of their remote parcels, when they decide to lease them to their close neighbours. These owners are often referred to as absentee owners. Likewise, the land sharing programs in Rwanda (1994-2012) after the 1994 Genocide against Tutsis left many farms subdivided between their then owners and their former (previous owners returning from the exile) nationwide, and between big farmers and landless people in the Eastern province. This resulted into many small farms and increased land tenure (in form of ownership) fragmentation (Bizimana *et al.*, 2004;Ntihinyurwa *et al.*, 2019).

Land tenure fragmentation in terms of hidden ownership fragmentation is also documented as a result of land policies and restrictions like land use consolidation program (LUC) and the article 30 of the law governing lands in Rwanda which forbid the subdivision of agricultural land into parcels of less than 1ha. Such policies encourage the cooperative use of land by family members for the purpose of enhancing the production of 8 nationally selected priority crops in a synchronized way, based on the national Agro Ecological Zones (AEZ) (Pritchard, 2013;Chigbu *et al.*, 2019;Nilsson, 2019;Ntihinyurwa *et al.*, 2019). It is also argued that consolidation practices leading to localized mono-cropping systems may push the farmers to the desire of acquiring other parcels in different sites which could give them the possibility to grow diverse crops for risks and labour management, and food diversity and security purposes (ibid). This paradoxically leads to land tenure fragmentation in terms of both visible usership and hidden ownership, and physical fragmentation in the forms of internal, use, and location. In the same vein, Bentley (1987) and Blarel *et.al* (1992) attribute to the construction of infrastructure (roads, railways, etc) and other development activities the subdivision of land parcels into small irregularly shaped fragments, which obviously increases the physical (internal and shape) land fragmentation. Similarly, the ever-increasing urbanization in developing countries is found to put a lot of pressure on land parcels for expansion of the existing farms to meet the food demand of the increasing urban population, thereby increasing their continuous subdivision into small non-contiguous parcels resulting in internal fragmentation. Furthermore, King and Burton (1982) argue that the grouped settlements programs are linked with increased land location fragmentation or plots scattering problems by increasing the distance between those plots and the farmstead, whereas the scattered settlements inside more compact farms reduce the distance-based fragmentation issues.

On the demand side, given the belief that land is not homogenous, its qualitative variations (in soil types, slopes, microclimates, topography, exposure, and growing conditions, etc) result in both physical and tenure fragmentation, when the Egalitarian principles are considered during inheritance and land reform processes, as pointed out by different researchers like Keeler and Skuras (1990), Tan *et al.* (2006), Sklenicka and Salek (2008), Hristov (2009), Sikor *et al.* (2009), and Ciaian *et al.* (2018a) in their respective studies. For them, land units are different and diverse in physical (flat versus mountainous and water holding capacities) and biochemical (various soil fertility statuses and agrobiodiversity) properties,

locations (far from the homestead, close to the house, close or far from irrigation facilities and roads, etc), and types (arable versus grasslands, wet versus drylands etc), with different production potentials and suitability classes or grades, and therefrom different values. Thus, the Egalitarian principle applied in many countries throughout the partible inheritance and land reform processes stipulates the distribution of land among all the heirs in qualitative and quantitative equal shares. All the members receive pieces of land of the same sizes and qualities from all locations, classes and grades. Therefore, for equity, conflicts prevention, subsistence motives, self-independency in food production, and risk and labour management purposes, family members prefer to have lands of all grades or classes through inheritance, land reforms, and land market, which leads to the subdivision of lands into small pieces scattered in different locations with various uses, thereby increasing both land tenure and physical fragmentation (Herzfeld, 1980;Heston & Kumar, 1983;Bentley, 1987;Bentley, 1990;Blarel *et al.*, 1992;Kadigi *et al.*, 2017;Ciaian *et al.*, 2018a;Knippenberg *et al.*, 2018;Ntihinyurwa *et al.*, 2019). Being a farmers' choice for different purposes, this strategy has been rather closely linked with the demand side of causes of land fragmentation than the supply one. In subsistence heterogeneous agriculture societies, farmers prefer to have different heterogeneous land parcels in different locations with different values, suitability and growing conditions for their crops diversification to meet their various dietary preferences, spread the production and prices risks, and the labour management (ibid). However, this strategy can also be considered as an external imposition to farmers by the social cultural practices such as egalitarian partible inheritance, and natural conditions (topography, soil type, climate change) which result in adverse fragmentation to them. While the majority of studies point out the population growth as the major problematic cause of land fragmentation, Bentley (1987) and Blarel *et al.* (1992) rather view it as an abundant labour source which acts as a positive factor of agricultural production in scarce land conditions with no off-farm employment opportunities.

The marriage and dowry culture in some countries also exacerbates and worsens farmland fragmentation issue, especially when the female household members get married and are assumed to relocate and join their partners for conjugal family life in places far away from their parcel shares in family lands. This increases the internal and location fragmentation by adding new non-contiguous parcels to their respective farms, along with usership fragmentation in case one member of the couple (absentee owner) decides to lease his/her distant land from the homestead to its closest users or tenants. However, this can also reduce the visible ownership fragmentation by merging or pooling two or more different farms from both spouses or their siblings, under one consolidated farm with a single ownership or operatorship (McCloskey, 1975;Bentley, 1987;Bentley, 1990).

In summary, agricultural land fragmentation results from a combination of factors, some of which deliberately chosen by farmers for different beneficial purposes, whilst others are considered as external detrimental impositions of the nature and the society. This polarized nature of land fragmentation causes explains its persistence in agriculture, even under the conditions where its coping strategies exist. The coexistence of different land fragmentation forms proves the causal interlinkages among them, since some forms have been found to induce each other (i.e. soil quality and ownership fragmentation versus internal fragmentation and vice versa) (Sklenicka & Salek, 2008;Ntihinyurwa *et al.*, 2019), as shown on

Figure. 3. However, the analysed literature shows that these fragmentation causes vary from country to country, and case to case. This implies that their significance depends upon the nature (problematic or beneficial) of their resultant land fragmentation forms under different circumstances (explained later in the next sections). What makes the issue more complex is that some aspects can result in both fragmentation and consolidation forms under different specific circumstances (i.e. grouped settlements, land market, inheritance, etc). For this, any policy to address land fragmentation should consider different case specific forms and their particular causes (Van Dijk, 2003;Asiama *et al.*, 2017a).

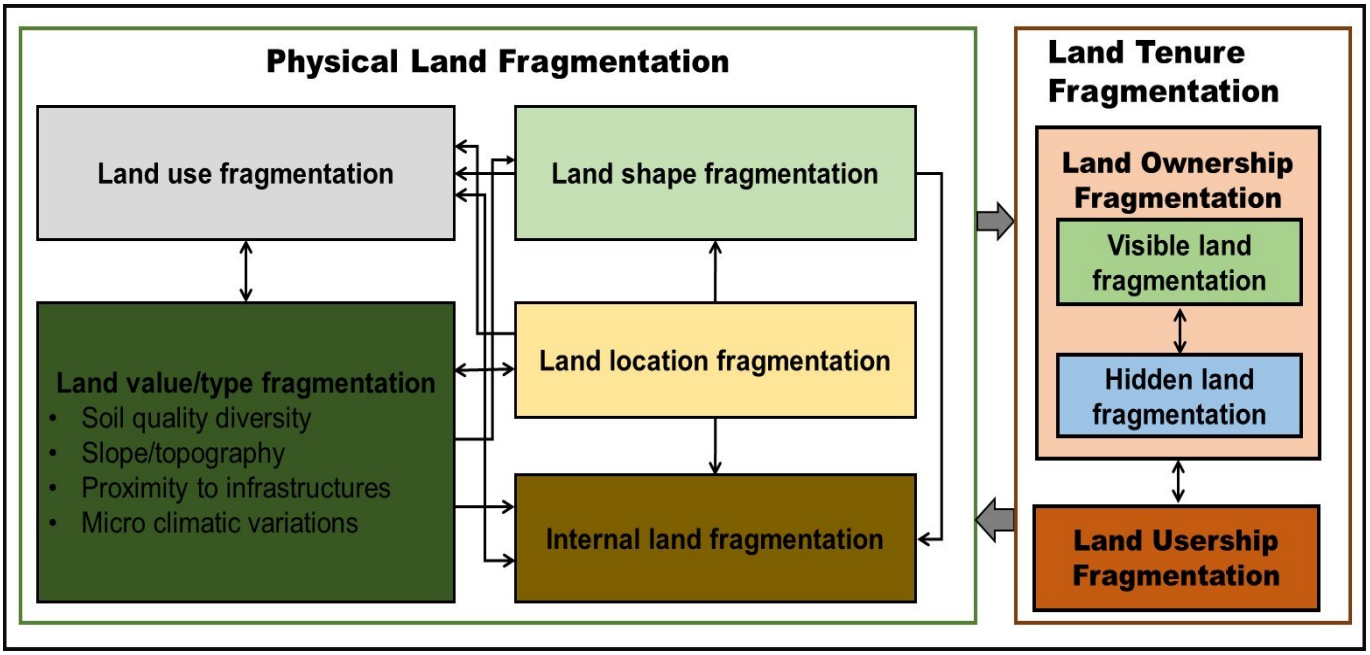

Figure 3A3. Causal interactions among land fragmentation forms

Source: Authors constructs adapted from Ntihinyurwa *et al*. (2019)

4. Farmland fragmentation impacts

The impacts of land fragmentation are contested in the literature across multiple scientific disciplines especially economy, geography, agriculture policy, environment, sociology, anthropology, ecology and agronomy (Bentley, 1987;Demetriou *et al.*, 2013). The contradictions reside in its polarized nature and mainly originate from the assumption that fragmentation hampers economies of scale. As such, it is assumed to reduce agricultural development and production efficiency (Binns, 1950;Pihkala & Suomela, 1952;Sorbi, 1952;Karouzis, 1971;Lusho & Papa, 1998;Van Dijk, 2003;Van der Molen *et al.*, 2004;Niroula & Thapa, 2007;Su *et al.*, 2014;Hiironen & Riekkinen, 2016;Janus & Markuszewska, 2017;Akkaya *et al.*, 2018). A contrasting viewpoint is that fragmentation benefits farmers, by serving as an adaptive strategy through production and prices fluctuations risks management, food and labour market strategy, and agricultural production diversification for food security purposes (Connell & Lipton, 1977;Heston & Kumar, 1983;McPherson, 1983;Bentley, 1987;Blarel *et al.*, 1992;Howden *et al.*, 2007;Tan *et al.*, 2008;Jia & Petrick, 2014;Alexandri *et al.*, 2015;Ciaian *et al.*, 2015;Janus *et al.*, 2017;Cholo *et al.*, 2018).

The proponents of the defective side of land fragmentation (mostly economists, agriculture policy makers and geographers) argue that small scattered irregularly shaped parcels reduce the agriculture production efficiency and effectiveness. An increase of distance between plots and the farmstead increases travel time, transport and supervision costs. Furthermore, there is a loss and/or wastage of effective land area through both regular and irregular boundaries as well as in plot patchworks, and such boundaries increase the risks of conflicts and disputes among neighbours, hamper the mechanization of agriculture and the development of irrigation and drainage infrastructure. Moreover, small fragmented farms reduce the cultivation of more profitable crops which normally require big farms, and the willingness of the banks to offer credits to farmers with small plots as collateral. This hinders the investments in agriculture and its modernization, and therefore limits the economies of scale. Hence, the costs of agriculture production and fragmentation alleviation outweigh the monetary benefits, which reduces the farm efficiency and the income of farmers (McPherson, 1982;Sabates-Wheeler, 2002;FAO, 2003;Demetriou *et al.*, 2013;Hartvigsen, 2014;Sklenicka *et al.*, 2014;Sikk & Maasikamäe, 2015;Dhakal & Khanal, 2018;Janus *et al.*, 2018;Muchová, 2019;Postek *et al.*, 2019). An additional pitfall is that parcels at greater distances are less intensively cultivated, even abandoned in some cases (Bentley, 1987;Van Dijk, 2003;Sikor *et al.*, 2009). As explained in section 3, land tenure fragmentation in both ownership and usership may result from the breakdown of the existing common and customary tenure systems, egalitarian based partible inheritance laws and different land reforms aiming at equal distribution of land resources, which leads to individual or private land ownership and use rights, restrictions and responsibilities.

The experience from the studies of Bentley (1987), Van Dijk (2003),Sklenicka *et al.* (2014), Hartvigsen (2015), Asiama *et al.* (2019), Ntihinyurwa *et al.* (2019), and Muchová and Raškovič (2020) shows that this scenario may have 3 main controversial implications: First, it may increase the number of land ownership and use related conflicts among family and community members, due to the increase in the number of farms, parcels and boundaries, and therefore reduce the social cohesion in the community. Second, it may become a barrier to agriculture mechanization, expansion, and the economies of scale, thereby decreasing farm income and food security. Third, it may be considered as positive for equity and subsistence motives, since it provides equal or equitable distribution of land among all heirs which guarantees the independent ownership and use rights, restrictions, and responsibilities thereby increasing their food and tenure security. Besides that, the discrepancy between the use and ownership fragmentation indicated by a small share of farmers using their own land, and a big number of absentee owners and tenants also limits the incentives of investments in defragmentation projects. These owners believe that these projects would only directly benefit the users (tenants) of land or farmers. However, these tenants do not have the ownership rights over these lands which prevents their use as collateral to get credits from the banks. They may also feel less incentives to engage long term investments in land fragmentation projects that are not theirs and require the consent of the owners, which leads to the persistence of this fragmentation problem. The main problem with land fragmentation in Central and Eastern European countries is the emergence of small sizes and irregular shapes of parcels as a result of the increased number of owners and users in a relatively small area (Van Dijk, 2003;Hartvigsen, 2014), although it has generally been found to be related to farm size. These authors posit that the use of modern

machinery is facilitated by big rectangular or square shaped parcels, which makes it difficult or even impossible on tiny irregularly shaped parcels indicating physical fragmentation, since it may require an excessive amount of manual work in the corners and along the boundaries, and justifies the need for land consolidation or defragmentation instruments. Furthermore, the irregular shapes of parcels hinder the cultivation of some more profitable crops (e.g. Vines, Olives) which need to be cultivated in series, the implementation of soil conservation work, and the construction of the roads network which meet the international geometrical standards (Demetriou *et al.*, 2013;Hartvigsen, 2014;Cholo *et al.*, 2018). These proponents of the negative side are subject of a common criticism of considering agriculture production for food security only in terms of quantity and availability at the higher levels (national and regional), thereby ignoring the diversity, quality, sustainability (stability), accessibility, acceptability, and usage (utilization) aspects of food security at the lower levels (household and individual).

The ones who consider land fragmentation as positive (mostly anthropologists, ecologists, environmentalists, sociologists, agriculture policy makers, subsistence farmers) argue that it offers to farmers the possibilities to cultivate in many environmental zones, minimise the production risk and optimise the schedule for cropping activities. The key feature on this side is the exploitation of land parcels of differing qualities with the variety of soil and growing conditions for subsistence motives, including the household's self-sufficiency in food crops production for food security (Netting, 1972;Galt, 1979;McPherson, 1982;Bentley, 1987;Blarel *et al.*, 1992;Van Hung *et al.*, 2007;Di Falco *et al.*, 2010;Kadigi *et al.*, 2017;Ciaian *et al.*, 2018a;Knippenberg *et al.*, 2018;Cholo *et al.*, 2019;Ntihinyurwa *et al.*, 2019). These recognized advantages are closely related to the demand-side causes of this phenomenon, which justifies its persistence in agriculture sector (Kadigi *et al.,*2017). For these researchers, many different scattered plots in different locations allow farmers access to land of different qualities when it comes to soil, slope, and micro-climatic variations. This facilitates the crop diversification through an easy matching of soil types with their suitable food crops, reduces production and price risks resulting from the fluctuating climatic conditions, and spreads labour requirements all over the growing season, since different crops ripen at different times. In this regard, farmland fragmentation has advantages when it comes to reducing the risk of total crop failure on the variety of soil and growing conditions. Further, it can be a method to increase food security in the context of climate change in heterogeneous areas, as it has been revealed by the studies of Knippenberg *et al.* (2018) and Cholo *et al.* (2019) in Ethiopia. As an explanation to their point of view, all the above proponents of this position emphasise the importance of land fragmentation in heterogeneous communities with varying land and soil conditions, when farmers find land fragmentation as desirable for social and environmental reasons. It acts against the risks of total harvest loss (total crop failure through disease, hail, droughts, floods, winds, and other natural disasters) in case of climate change, and factor for diversification in various soils and growing conditions. In this regard, it reduces and controls the diffusion or spread of pests and other crops diseases across the entire farm. Moreover, fields with high yields in one year may in the following year generate much lower yields, thus several plots of the same crop also spread out the risk. In addition, a holding with several plots facilitates the crop rotation and the ability to leave some land in fallow (Igbozurike, 1970;Netting, 1972;Galt, 1979;Bentley, 1987;Blarel *et al.*, 1992;Ciaian *et al.*, 2018b;Cholo *et al.*, 2019). They also find it as a tool for equal distribution of resources through the Egalitarian principles

which in turn reduces the number of land ownership related conflicts and disputes, and the preservation of biodiversity (permanent boundaries provide cover for wildlife, fruit for humans, and windbreaks for crops) in some countries and specific cases (ibid).

5. Conditions determining farmland fragmentation management decisions

Despite the above polarized claims about farmland fragmentation, there are few studies which aim to reconcile these opposite positions. Since not all land fragmentation forms are problematic or defective, there is a need to determine when, where, to whom and under which conditions this phenomenon becomes problematic or beneficial, and the specific fragmentation forms or scenarios involved. Pingali *et al.* (1987), Eastwood *et al.* (2010), Headey and Jayne (2014), and Asiama *et al.* (2017b) in their respective studies note that although land fragmentation has been prevalent in agricultural systems for long time, it has become more problematic with the expansion of agriculture mechanization and commercialization in market-oriented agricultural systems. Igbozurike (1970), Bentley (1987), and Blarel *et al.*(1992) posit that the harm caused by land fragmentation is overrated. However, the results from our substantive scrutiny review reveal that only 4 studies (McPherson, 1983;Bentley, 1987;Van Dijk, 2003;Ntihinyurwa *et al.*, 2019) explicitly analyse the beneficial and problematical situations of land fragmentation under different contexts. They point out several factors and circumstances which help to determine the nature of impacts of different forms of land fragmentation in agriculture. These range from the economic status (modern versus subsistence economy, perfect versus imperfect land, labour and food market), social (customary or community versus private land tenure systems), demographic (high versus low population density), agriculture systems and policies (market-oriented versus subsistence agriculture, monoculture versus polyculture, terraces, agricultural intensification programs, and risks management strategies like agricultural insurance, etc), physical or spatial (abundant versus scarce land, flat versus mountainous topography),to ecological or environmental ones (homogeneous versus heterogeneous soil, slope, and climatic conditions). Land fragmentation therefore does not always denote the generic inefficiency, but depends more on the context and situation within which one sees it (Kadigi *et al*.,2017). FAO (2012) stipulates that any fragmentation resulting in positive impacts should be kept. In this regard, Bentley (1987) and Van Dijk (2003) present a series of circumstances under which land fragmentation can be beneficial or problematic. Nevertheless, none of them clearly shows the specific aggregated combinations of the forms, their driving factors, circumstances and impacts, and the analysis level of land fragmentation (parcel, farm, village, regional, national and international) under specific scenarios, in order to inform the decisions about the suitable management strategies. To bridge this gap, we deductively developed different possible fragmentation scenarios representing the combinations of circumstances and drivers, fragmentation forms at different spatial levels (parcel, farm, land block or landscape), their impacts and recommended management strategies between fragmentation conservation and defragmentation. Table 1 summarizes these relationships.

Table 1A3. Summary of farmland fragmentation scenarios, impacts, and its management decisions

Fragmentation Scenarios		***Impacts (Positive and Negative)***	***Management Decisions***	***References***
Forms and spatial levels	***Circumstances***			
-Physical Fragmentation (internal and shape) ***-Tenure (ownership and Usership) fragmentation*** ***-Both parcel, farm and land block levels***	-Small heterogeneous areas (high diversity of ecological conditions like microclimate, soil, slope, and growing conditions in many micro-zones) -High climate change risks prone areas -High agriculture population densities (scarce land and abundant labour) -Subsistence economy and agriculture -Imperfect food, labour, and land market -Hilly as well as flat topographies -Land conflict prone areas	-Agriculture production diversification -Food market imperfections and erosion control strategies -Household food security -High costs of defragmentation -Equitable distribution and use of land -Land ownership and use conflicts, labour and production risks management strategies -Climate change adaptation strategy -Land use and tenure security -Agrobiodiversity conservation	***Fragmentation Conservation*** *(Beneficial/Rational fragmentation)*	(Farmer, 1960;Igbozurike, 1970;Netting, 1972;Galt, 1979;King & Burton, 1982;McPherson, 1982, 1983;Bentley, 1987;Bentley, 1990;Keeler & Skuras, 1990;Blarel *et al.*, 1992;FAO, 2003;Van Dijk, 2003;Tan *et al.*, 2006;Van Hung *et al.*, 2007;Sklenicka & Salek, 2008;Hristov, 2009;Sikor *et al.*, 2009;Di Falco *et al.*, 2010;Kawasaki, 2010;FAO, 2012;Demetriou *et al.*, 2013;Ali & Deininger, 2014;Alexandri *et al.*, 2015;Ali *et al.*, 2015;Ciaian *et al.*, 2015;Kadigi *et al.*, 2017;Cholo *et al.*, 2018;Ciaian *et al.*, 2018a;Ciaian *et al.*, 2018b;Knippenberg *et al.*, 2018;Cholo *et al.*, 2019;Ntihinyurwa *et al.*, 2019)
-Physical (internal, use & location) fragmentation ***-Farm level***	-Mountainous and hilly lands (high diversity in microclimatic, soil, slope, and growing conditions, many heterogeneous micro-zones), either abundant or scarce -Regularly shaped bench terraces	-Agriculture production diversification -Food security -Production risks management -Erosion control and Agrobiodiversity conservation		
Physical (internal & shape) fragmentation ***- Farm level***	-Flat as well as mountainous lands (abundant and scarce) with dramatic micro-environmental differences or contrasts -High climate change risks vulnerability -Absence of other alternative risks management strategies like insurance, credits, and pesticides -Presence of land saving technology (fertilizers, high yielding crop varieties) and perfect inputs and outputs market	-Production risks management and climate change adaptation -Agriculture production diversification -Crops rotation and fallow for soil fertility management -Food security -Agrobiodiversity conservation		
-Physical (internal, location, use and shape) fragmentation ***-Tenure (ownership and Usership) fragmentation*** ***-Both Parcel, farm and land block levels***	-Areas with scarce land (high agricultural population density and abundant labour) -High climate change risks -Dramatic microclimatic variations -Strong complex economy (market-oriented agriculture, perfect labour, inputs, outputs and food market) with no alternative risks management strategies (insurance) -Presence of land saving technology (fertilizers, high yielding crop varieties)	-Risks and labour management -Farm Employment -Agriculture production diversification for food security -Equitable distribution and use of land -Land use and tenure security		
-Physical (internal, use, shape & location) fragmentation ***-Farm level***	-Heterogeneous areas with many micro-zones -Low farming population density (abundant land) -Complex strong economy (perfect land, labour and food market, higher economic land value than its social value) -Mechanized market-oriented agriculture -Presence of off-farm employment -Presence of risks management strategies (insurance, pests control, risks resistant varieties, etc)	-High production costs (travel and supervision costs) -Low farm income -Barrier to mechanization of agriculture through irregular shapes and boundaries	***Defragmentation*** *(Defective/Problematic fragmentation)*	(Binns, 1950;Pihkala & Suomela, 1952;Chisolm, 1967;Clout, 1968;Karouzis, 1971;King, 1977;King & Burton, 1982;McPherson, 1983;Bentley, 1987;Keeler & Skuras, 1990;Lusho & Papa, 1998;FAO, 2003;Van Dijk, 2003;Bizimana *et al.*, 2004;Van der Molen *et al.*, 2004;Vitikainen, 2004;Niroula & Thapa, 2005;Tan, 2005;Niroula & Thapa, 2007;Demetriou *et al.*, 2013;Manjunatha *et al.*, 2013;Hartvigsen,

-Physical Fragmentation -Tenure fragmentation -Both parcel, farm and land block levels	-Homogeneous areas (similar socio-economic and ecological conditions) -Many small scattered irregularly shaped parcels belonging to many or few owners/users -Subsistence as well as complex economies -Abundant as well as scarce land -High rate of tenancy (many users and absentee owners)	-High production costs (travel costs and labour supervision costs) and low farm income -Barrier to agricultural mechanization through irregular shapes, small plot sizes, boundaries and absentee owners -Many boundaries related conflicts -Break down of collective tenure system and social cohesion -Barrier to the economies of scale -Wastage of land through boundaries -Household Food Insecurity (low food quantity, diversity, quality, accessibility and sustainability)	2014;Abubakari *et al.*, 2016;Hiironen & Riekkinen, 2016;Alemu *et al.*, 2017;Janus *et al.*, 2017;Janus & Markuszewska, 2017;Akkaya *et al.*, 2018;Dhakal & Khanal, 2018;Asiama *et al.*, 2019;Muchová, 2019;Ntihinyurwa *et al.*, 2019;Muchová & Raškovič, 2020)

Source: Authors constructs drawn from McPherson (1983), Bentley (1987), Van Dijk (2003), and Ntihinyurwa *et al.* (2019)

The advantages or benefits of land fragmentation are mostly linked with internal physical land fragmentation at the parcel and farm or household level. The only exceptions concern the reduction in land ownership and use based conflicts, and tenure security assigned to ownership fragmentation as a result of equal distribution and independent use of land resources through the strict application of egalitarian based principles in land transactions. On the other hand, the disadvantages can be linked with both physical and tenure fragmentation at all levels. As table 1 shows, a combination of socio-economic and ecological circumstances as external factors dictates the sort of impacts of land fragmentation and its management decisions for either keeping fragmentation or defragmentation. These include: the ecological conditions of the area (homogeneous versus heterogeneous), the presence or absence of risks management strategies in the area, the demographic status (high versus low population densities), the status of the market (perfect versus imperfect), the spatial dispersion of the parcels, and the type of agricultural system in the area (market-oriented versus subsistence agriculture). The idea is that different circumstances regulate the magnitude of negative impacts of land fragmentation merely associated with farm and parcel sizes for tenure fragmentation, along with distance, shape and use for physical fragmentation, thereby determining the need for keeping fragmentation or defragmentation.

Chisholm (1967) and Bentley (1987) argue that the problem of distance associated with the internal land fragmentation can be eliminated by a perfect market of inputs and labour. They posit that the production costs associated with distance depend upon the prices of inputs and outputs, and the market strategies. This position is further supported by Van Dijk (2003) in his/her study about the Central European land consolidation scenarios. For them, the better the market perfection; the smaller the prices of inputs and high prices of outputs; the higher the value of production; the smaller the production costs; the higher the income from fragmented parcels; the better the viability of the farm regardless of its size. Furthermore, the strategy of selling the production of distant plots on field reduces the transport costs of the production. Besides that, according to Farmer (1960), Connell and Lipton (1977), Bentley (1987), and Blarel *et al*. (1992), small farms mitigate the negative effects of land fragmentation by reducing the labour costs including the supervision and employment costs through high labour use intensity and high labour per land ratio. They argue that the smaller the farm; the lower the internal fragmentation; the higher the labour use intensity; the higher the productivity of the farm. In small countries with small farms, abundant labour, and scarce land, farmers seek to maximise the returns through scarce factors (land and capital), rather than abundant factors (labour), by improving farming technologies through land saving strategies such as insurance, high yielding varieties and different agriculture intensification programs to increase the farm efficiency and meet the food needs of this growing population (Farmer,1960). Apart from this, fragmentation in this case is considered by farmers as a source of employment for household members. This paradoxical scenario explains the persistence of land fragmentation under the conditions of subsistence economies and growing population characterised by scarce land and sufficient local labour to handle labour peaks, as a source of employment and farm efficiency.

Moreover, under the circumstances of ecological diversity indicated by high heterogeneity or variations in soil, slope, microclimate, exposure, and growing conditions especially in mountainous areas or alpines, high production and market risks prone areas, and the absence of risks management

strategies such as insurance, pests control measures, credits and high yielding varieties, internal land fragmentation serves as a risk management strategy, and factor of production diversification for food security (ibid). This has been empirically proved by many different studies in different countries and at different times. Alexandri *et al.(*2015), Ciaian *et al.* (2015), Ciaian *et al.* (2018), Knippenberg *et al*.(2018), and Cholo *et al.*(2019) found that land fragmentation significantly stimulates more diversification for subsistence farm households than for market-oriented households in Romania, Albania and Ethiopia respectively, and contributes to food security improvement by increasing the variety of foodstuffs produced by these subsistence farm households. They have revealed land fragmentation as an opportunity for food security rather than a challenge.

In the same vein, Blarel (1992) argued that land fragmentation leads to production diversification of food basket for self-sufficiency among subsistence farmers to meet their nutritional requirements and food security at cheap prices, as the cheapest strategy to meet the household food security in case of food market imperfection circumstances. According to Maxwell and Smith (1992), Pinstrup-Andersen (2009), Manjunatha *et al.* (2013), and Ntihinyurwa *et al.* (2019), although the popular logic is that land consolidation (especially due to increased farm size and reduced distances) has direct positive effects on increasing food security by boosting food production, this only makes sense when food security is viewed from the lens of quantity. Nevertheless, food security is much more than quantity of food production. It has the quality, accessibility, utilization, acceptability and sustainability perspectives which can be achievable even under land fragmentation scenarios, when everyone in the household has access to regular safe, nutritious and enough acceptable food to meet his (her) food preferences. It is about more than growing enough food, since it implies the demand for it, as well as the supply, the quality as well as quantity, an adequate diet (acceptable quality and quantity) today and assurance of one tomorrow (Sen, 1981;Campbell, 1991;FAO, 1996;Pinstrup-Andersen, 2009;Pangaribowo *et al.*, 2013;FAO, 2014;Leroy *et al.*, 2015;Burchi & De Muro, 2016;Chigbu *et al.*, 2019;Ntihinyurwa *et al.*, 2019). Due to the ever growing fluctuations in climate and food prices directly affecting the household's food acquisition (domestic and wild agriculture and animal production, purchase, aids, imports) and allocation (distribution and usage), and food safety concerns, the achievement of food security at the micro levels requires the shift from the mass food production systems and consumption patterns prioritizing the quantity, towards more diversified food stuffs through sustainable, climate resilient and smart agriculture systems by growing wide diversity of crops. This will help to meet the dietary needs and food preferences of acceptable quality, safety and quantities for all people in a sustainable way, as an adaptive strategy for ending hunger and malnutrition stipulated by many policy initiatives and goals like the SDGs 1.4; 2.1, 2, 3, 4, 5; 12.2; 13 & 15.3, 4, 5, 9 (Rosegrant & Cline, 2003;Di Falco *et al.*, 2010;Lipper *et al.*, 2014;Prasad *et al.*, 2014;Thornton & Herrero, 2015;UN, 2015;Bailey, 2016;Conceição *et al.*, 2016;Chigbu *et al.*, 2019;Cholo *et al.*, 2019;Fan *et al.*, 2019;Lazíková *et al.*, 2019).

Simply put, the more the differences, diversity or heterogeneity in land and soil qualities which can be indicated by various suitability classes and production potentials; the more the crops can be diversified; the higher the food stuffs diversity and the nutritional balance; the higher the food quality and sustainability; the higher the food security. This position is backed by the tenets of the Economies of

Scope theory stipulating that the production is a result of many heterogeneous factors (Teece,1980;Bentley,1987;Blarel *et al*.,1992), the Complexity theory stipulating the adaptation to emerging unpredictable complex phenomena (Norberg & Cumming, 2008;Wim *et al*.,2015;Salvati *et al*., 2017), the Ecological Resilience theory stipulating the biodiversity conservation as an adaption to nature shocks (Gunderson,2000;Lengnick,2015), and the Sustainable Development Goals (1, 2, 12, 13, 15). These theories and SDGs stipulate the diversification of crops in diverse fragmented and scattered areas with different growing conditions as an adaptive strategy to the ongoing new global challenging realities of climate change to end hunger and malnutrition resulting from food insecurity, conserve the agriculture biodiversity, and equal distribution, ownership, sustainable management and efficient use of land resources (Griggs *et al.*, 2013;Keesstra *et al.*, 2016). Due to erosion control purposes and high costs of alleviating fragmentation in mountainous areas, Farmer (1960) suggests the farming of these areas only in fragments. Moreover, in cases of failed economic incentives in subsistence communities characterised by higher agricultural population densities on scarce lands conditions where the social value of land is higher than its economic one, land ownership fragmentation plays an important role in food and tenure security through a certain level of independency in ownership and use. The family members prefer to get their own small pieces of land for their independent uses to meet their independent food preferences (Van Dijk, 2003, 2004). This directly connects with the third targets of SDGs 1 and 2 which stipulate the equal distribution, ownership, access, security, use and control of land resources among all the heirs. Therefore, Bentley (1987) recommends that any land fragmentation under these circumstances should be conserved for the benefits of farmers in terms of land tenure security and household food security.

Nevertheless, this adaptive strategy of land fragmentation continues to be challenged and is considered outdated by some economists and geographers in view of the presence of other risks management strategies (insurance, pests control measures, credits, high yielding and resistant crop varieties, etc), the growing technology in market-oriented agriculture, low population densities (scarce labour on abundant land), and homogenous ecological conditions (Bentley,1987). Chisholm (1967) and Bentley (1987) hypothetically posit that the production of any crop is identical at all sites of any homogenous area with similar soil, slope, microclimatic and growing conditions, and uniform fertility. Therefore, keeping fragmentation under these conditions would be useless, since it does not offer any advantage to farmers, rather increases the production costs for transport, supervision, mechanisation, etc., thereby declining the farmer's income. Besides that, Bentley (1987) claims that although high farming population growth under subsistence and scarce land conditions leading to tenure fragmentation can serve as a source of employment with more income for the growing population in the household farm in case of the existence of land saving technology, it would not be beneficial to keep such fragmentation under the absence of such technology since it decreases the returns to labour ratio. In this case, he/she recommends the management of this fragmentation scenario through the adoption of farming technology, creation of off-farm employment, and curbing the population growth, since consolidation programs would only benefit the ones who retain land and leave out a part of the population expelled from farming under unemployment and misery. Furthermore, under the conditions of scarce labour, abundant land, and market-oriented agriculture policies, fragmented spatially and topographically dispersed parcels regardless of their sizes obstruct the mechanization and commercialization of agriculture by hindering

the cultivation of more profitable crops which require big sizes, and the economies of scale, which in turn reduce the farm viability and profitability (Clout, 1968;FAO, 2003;Van Dijk, 2003;Van der Molen *et al.*, 2004;Niroula & Thapa, 2005;Tan, 2005;Rahman & Rahman, 2009;Hartvigsen, 2014;Sundqvist & Andersson, 2014;Asiama *et al.*, 2019). This Economies of Scale theory stipulating the positive relationship between farm size and crops yield (output) has been broadly documented in land fragmentation and consolidation literature as a goal of many consolidation projects to eliminate the obstacle of fragmentation (Binns, 1950;Stigler, 1958;Thompson, 1963;Edwards, 1978;Bizimana *et al.*, 2004;Van Dijk, 2004;Vitikainen, 2004;Kawasaki, 2010;Hristov *et al.*, 2012;Manjunatha *et al.*, 2013;Saint-Cyr *et al.*, 2016). This position is also supported by the Gestalt theory stating that the whole is greater than the sum of its parts (Wertheimer, 1938).

Moreover, in cases of strong rural-urban linkages, rural migration for off-farm employment increases the urban population, thereby reducing the rural labour supply. This in turn increases the demand for food to meet the needs of the growing urban population, which requires the maximization of returns (yields) per parcel by either reducing the production costs and/or increasing the labour use efficiency (higher yield per small labour) through agriculture mechanization. Fragmented holdings become an obstacle in this case, hence the need for consolidation as a facilitator to mechanization and agriculture expansion on big parcels through the reduction of the production costs (Asiama *et al.*, 2017a). Under the conditions of high land related tensions especially in subsistence economies and customary or communal tenure systems, land tenure fragmentation may increase the number of land ownership and use related conflicts among family and community members, due to the increase in the number of farms, parcels and boundaries, and therefore reduce the social cohesion in the community, thereby increasing the risks of land tenure insecurity (Ntihinyurwa *et al.*, 2019). Similarly, Van Dijk (2003) argues that a big number of tenants indicating the usership fragmentation or the discrepancy between the ownership and use in an area obstructs long term investments in agriculture, due to the lack of tenure security over the leased lands since there are no or limited incentives to invest in long term projects like land consolidation on such lands as explained in paragraph 2 of section 4. Therefore, Bentley (1987), Van Dijk (2003, 2004), and the above mentioned authors recommend the consolidation or elimination of any fragmentation form under such circumstances in order to reduce land boundaries related conflicts, improve tenure security and social cohesion, and increase or boost the quantity of agricultural production and food security in terms of food quantity and availability in a given area,as stipulated by the third target of SDG 2.3 in terms of doubling the agriculture production of small scale farmers by 2030.

In contrast to the provisions of the above mentioned economies of scale, many researchers empirically revealed the inverse farm size and productivity relationships along with the lack of significant empirical evidences for a positive association between land fragmentation and farm inefficiency in different countries like Rwanda (Blarel *et al.*, 1992;Byiringiro & Reardon, 1996;Ali & Deininger, 2014), Ethiopia (Cholo *et al.*, 2018;Paul & wa Gĩthĩnji, 2018), Tanzania (Kadigi *et al.*, 2017), China (Wan & Cheng, 2001;Tan *et al.*, 2008), Ghana (Blarel *et al.*, 1992), Indonesian island of Java (Benjamin, 1995), Vietnam (Nguyen, 2014), and Albania (Deininger *et al.*, 2012). This has been attributed to the market imperfection, labour and technology use inefficiency as an explanation to the diseconomies of scale

(Blarel *et al.*, 1992;Eastwood *et al.*, 2010;Ali *et al.*, 2015;Abubakari *et al.*, 2016;Asiama *et al.*, 2017a). It is argued that, the higher the fragmentation, the fewer the inputs and needed labour, the smaller the production costs and the higher the income. Farmer (1960), Chisholm (1967), and Bentley (1987) advance that small farms per hectare tend to be more productive than big farms, due to their high labour use intensity. This justifies the conservation of fragmentation in subsistence economies.

In summary, land fragmentation as a concept is not a problem per se. Its problematical and beneficial situations are determined by a number of external circumstances. In general, land fragmentation is considered good when farms are composed of many small non-contiguous scattered plots in different locations with heterogeneous ecological conditions under the absence of risks management strategies, presence of Egalitarian principles, intra-familial conflicts, high climate change vulnerability, high population densities, subsistence agriculture and market imperfections circumstances (Ntihinyurwa *et al.*, 2019), and therefore subject for conservation. It is considered bad when there are many/or few owners/tenants operating many small non-contiguous irregularly shaped parcels scattered over large distances from the homestead on a small/or big land unit with more homogeneous ecological conditions and less vulnerability to climate change risks, in the presence of risks management strategies and high land boundaries related tensions, under market-oriented or mechanized agriculture with perfect labour, land and food market (ibid), and henceforth subject for elimination. Therefore, land fragmentation management strategies should depend upon the type/form and the level of fragmentation involved and its type of impacts under different local conditions. With the growing concern on climate change from food production side, attention should be kept on the trade-offs between the role of food crops diversity on food stuffs diversification as a source of sustainable and resilient food systems on one hand, and the quantity of agriculture production to meet the food needs of the growing population at the micro and local level (community, village, household and individual) irrespective of its quality on either fragmented or consolidated land parcels on the other hand.

6. Conclusions

Building on the existing literature and the logical reasoning, this study critically assessed the forms, causes and impacts of farmland fragmentation and derived various scenarios both problematical and beneficial under which one could opt for fragmentation conservation or defragmentation strategies as a new contribution to the existing knowledge in the field of farmland management (including its administration, policy and governance).

Contrary to the provisions of existing literature, the study reveals that farmland fragmentation as a concept is not necessarily problematic. Instead, it highlights that the problematic and beneficial scenarios are determined by a combination of local specific external circumstances ranging from social, economic, political, technical to ecological ones. In this regard, the findings hypothetically disclose that farmland fragmentation can be conserved in cases of the dominance of many subsistence farms composed of many small non-contiguous spatially scattered plots in different locations and topographies, irrespective of the ownership, farm size, uses and shapes indicating the internal and location as physical fragmentation, and tenure fragmentation in a given heterogeneous area with various ecological

conditions for subsistence, equality and self-independency motives, risks, labour and land ownership based conflicts management, and household food security purposes in terms of food diversity, accessibility, quality and sustainability. The fragmentation scenarios in this case become rational in circumstances of subsistence and middle-income economies characterised by the absence of modern risks management strategies (insurance, credits, high yielding and resistant crop varieties), presence of egalitarian principles in land distribution, land saving technology (i.e. agriculture intensification strategies), intra-familial conflicts, high climate change vulnerability, high population densities, subsistence agriculture, and market imperfections in a given area. This rationality is founded on the farmers' choice for farmland fragmentation, and supported by the Economies of Scope theory, the Complexity and Climate Resilience theories, and the Boserup's theory of 1965 on population growth and agriculture intensification, for its socio-economic and ecological benefits over consolidated farms. In specific cases like mountainous areas where the costs of alleviating land fragmentation may far exceed its benefits, keeping fragmentation would be more beneficial than its alleviation. On the other hand, farmland fragmentation becomes defective and subject to defragmentation measures in cases of both tenure and physical fragmentation scenarios under homogeneous ecological conditions (similar topography mostly flat slopes, microclimates, soils and growing conditions) with less vulnerability to climate change risks, by increasing the farm efficiency and the income from agriculture at all levels (parcel, farm, land block, local, regional, and national). Furthermore, in cases of strong economies characterised by market-oriented or mechanized agriculture, perfect labour, land and food market, and the presence of risks management strategies in agriculture, there is no rationale for keeping physical fragmentation under heterogeneous ecological conditions, since its costs may far outweigh its benefits. This position is backed by the stipulations of the Gestalt theory of a whole, the Economies of Scale theory, and the Malthusian theory of population growth and food supply, which collectively argue for agriculture expansion on bigger consolidated farms than on fragmented ones.

For the best management of farmland fragmentation phenomenon and the empirical test of the above proposed model, this study recommends the identification of all the possible land fragmentation scenarios in a given area, their causes, impacts (positive and negative), and the conditions determining their problematic and rational situations prior to the development of any decision about farmland fragmentation conservation or defragmentation policies and strategies as land management tools. To this end, a careful feasibility study should be conducted to assess the problematic and beneficial land fragmentation forms under specific local conditions, prior to the development of their suitable, desirable, adaptable (dynamic), sustainable, climate resilient and multidimensional food security responsive coping strategies at the local level. An attention should be given to the improvement of food security status at the household and individual levels, rather than the existing focus on food productivity at the regional and national levels. Further research should concentrate on the assessment and the development of more detailed specific indicators which could support the trade-offs between land fragmentation and defragmentation tools for food security purposes under different specific local conditions, and specific control strategies suitable to each fragmentation scenario.

The findings from this study will inform and guide the decisions of policy makers, research scholars and the general scientific community for the devise of the suitable policies and tools for the best management of local farmland fragmentation scenarios and extend the existing knowledge about farmland management. Moreover, it will contribute to the extension of the existing debate about the achievement of the Sustainable Development Goals (SDGs 1, 2, 12, 13 and 15) of ending hunger and malnutrition within the framework of the agenda 2030 through the diversification of crops in different fragmented diverse and scattered areas with different growing conditions as an adaptive strategy to the global challenging realities of climate change (climate smart or resilient agriculture), sustainable management, equal distribution, control and efficient use of land resources to boost the agriculture production of small scale farmers (agriculture intensification), versus the global trends towards market-oriented agriculture on big farms (agriculture expansion), for the household food security purposes.

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Appendix 4 (A4). Farmland Fragmentation, Farmland Consolidation and Food Security: Relationships, Research Lapses and Future Perspectives

Abstract

Farmland fragmentation and farmland consolidation are two sides of the same coin paradoxically viewed as farmland management tools. While there is a vast body of literature addressing the connections between farmland fragmentation and farmland consolidation on the one hand and agriculture production and crops diversification on the other hand, their relationship with variations in food security is still under-explored. This challenges policy makers about whether and how to devise policies in favour of fragmentation conservation or defragmentation. Therefore, drawing on the multiple secondary data and the deductive logical reasoning through an integrative concept-centric qualitative approach following the rationalist theory, this study critically reviews and analyses the existing body of literature to identify how farmland fragmentation versus defragmentation approaches relate to food security. The goal is to develop and derive an explicit model indicating when, where, how and why farmland fragmentation can be conserved or prevented and controlled for food security motives as a novel alternative comprehensive scientific knowledge generation, which could guide and inform the design of future research and policies about farmland fragmentation management. The findings show that both fragmentation and consolidation variously (positively and negatively) impact on food security at different (macro, meso and micro) levels. While farmland fragmentation is highly linked with food diversification (food quality), acceptability, accessibility, and sovereignty at the local (household and individual) levels, farmland consolidation is often associated with the quantity and availability of food production at the community, regional and national levels. Theoretically, the best management of farmland fragmentation for food security purposes can be achieved by minimizing the problems associated with physical and tenure aspects of farmland fragmentation along with the optimization of its potential benefits. In this regard, farmland consolidation, voluntary parcel exchange and on-field harvest sales, farmland realignment, and farmland use (crop) consolidation can be suitable for the control of physical fragmentation problems under various local conditions. Similarly, farmland banking and off-farm employment, restrictions about the minimum parcel sizes subdivision and absentee owners, joint ownership, cooperative farming, farmland use (crop) consolidation, agricultural land protection policies, and family planning measures can be suitable to prevent and minimize farmland tenure fragmentation problems. On the other hand, various agriculture intensification programs, agro-ecological approaches, and land saving technologies can be the most suitable strategies to maximize the income from agriculture on fragmented farms and parcels (plots) under the circumstances of beneficial fragmentation. Moreover, in areas where both rational and defective fragmentation scenarios coexist, different specific strategies like localized and multicropping based land consolidation approaches in combination with or without agriculture intensification programs, can provide better and more balanced optimal solutions. These could simultaneously minimize the defective effects of fragmentation thereby optimizing or without jeopardizing its potential benefits with regard to food security under specific local conditions.

Keywords: farmland fragmentation; farmland consolidation; food security; food sovereignty; agro-ecology; integrative review

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1. Introduction

Farmland fragmentation has generally been considered as negative for agricultural production and food security and equivalent to the increase in production costs leading to farm inefficiency [1–11]. Consequently, most contemporary agricultural land policies aim to reduce fragmentation through land consolidation as a panacea to this quandary [12–18]. Besides the classical land consolidations programs, other instruments such as land banking [19–21], voluntary parcel exchange, land restrictions, cooperative farming, and land use consolidation (LUC) in Rwanda and Malawi [11,22–27] have been applied in some specific areas and situations. The success of each strategy depends on local conditions of a country and specific management and governance factors, since the strategy which works well in one country might not succeed in another [11]. Such idiosyncrasies necessitate each time a careful and substantive assessment of how and where farmland fragmentation patterns (forms, causes and both problematic and beneficial impacts) are similar or different. This assessment similarly applies to the success requirements and operational conditions of farmland fragmentation management strategies (as specific farmland management instruments) and their anticipated impacts prior to their transfer between countries [11,12,16,28]. The documented experience shows that the disregard of local conditions when designing and implementing land consolidation programs in sub Saharan Africa (Kenya, Malawi, Rwanda, Tanzania) and India led to failures and unintended harmful consequences in some areas [11,12,24,29–35].

On the other hand, there are counter arguments which consider farmland fragmentation as a demand-driven farmer's choice and strategy for risk management, exploitation of multiple ecological zones, labour bottlenecks management and self-sufficiency or independency in food production in subsistence communities through crops diversification for household food security [6,31,33,36–42]. These advocates argue that not all land fragmentation forms are equally problematic or defective. There might indeed be situations where the benefits of fragmentation outweigh the costs of consolidation, especially when it comes to areas which are overpopulated by communities relying on self-subsistence (agroecological) agriculture and/or mountainous characterized by diverse crop-growing conditions, socio-ecological heterogeneities and small farm sizes [11]. In such cases, fragmentation would be more favourable to support the management and mitigation of food production and market risks for the motives of local food security through its components of quality, accessibility, quantity and sustainability [4,11,30,31,43–45] and food sovereignty [46]. For these research scholars, a strategy which favours diverse and multi-cropping systems (polyculture) under varying crop-growing conditions manages better the risks of total crops failure and production loss resulting from the consequences of the ever-increasing climate change scenarios (manifested in changes in rainfall patterns and temperatures) leading to environmental hazards (droughts, floods, winds, etc), diseases outbreak, and food price fluctuations, than a mono-cropping systems-based one (monoculture) [11,33]. Furthermore, being one of the key agroecological principles and elements, the spatial and temporal crops diversification at both field/plot, farm and landscape levels increases the resilience of local farmers against various climate change, prices fluctuations and other global risks thereby acting as the sustainable strategy for achieving food diversity, self-sufficiency in the production of culturally acceptable food diets and food sovereignty as the local approach of achieving food security [46–48]. Hence, farmland fragmentation in this situation is rather

viewed as a rational choice which adapts to the environmental variations and generates local food security than a drawback [11]. Moreover, in the line of disheartening land consolidation initiatives, various studies over time disclosed negative correlations between farm sizes and crop yields when labour market management conditions are unfavourable [11,31,49,50]. According to Ntihinyurwa and de Vries [11], this stance explains why farmland fragmentation persists, and the choice dilemma of farmers about fragmentation conservation for its positive sides and/or its prevention and banishment for its negative sides, in spite of various consolidation initiatives to combat it. In this respect, de Vries and Chigbu [51] and Ntihinyurwa and de Vries [11] posit that both land fragmentation and land consolidation are equally responsible land management instruments, given the circumstances in which they are carried forward.

As part of the same debate, there exist various contrasting social, economic, and ecological theoretical constructs and models, which favour, explain and support the claims of each side, i.e., deriving and proving the benefits of land fragmentation or of land consolidation. On land consolidation side, Ntihinyurwa and de Vries [11] highlight for example the economies of scale theory which states that farm size and crops yield or output are positively related [17,52], the Gestalt theory stipulating that the whole is greater than the sum of its parts [53], along with the Malthusian theory which stipulates the existence of an inverse relationship between the population growth and food supply [54–56]. On the other hand, the economies of scope theory asserting that the volume of production is the result of many heterogeneous factors [30,31,57], the complexity theory which argues for adaptation to emerging unpredictable complex phenomena [58–60], the ecological resilience theory which highlights the role and relevance of biodiversity conservation as an adaption to nature shocks [61,62], the agroecology stipulating the crops diversification, resilience to natural shocks, and responsible governance of land and natural resources [47,48], and the Boserup's theory which stipulates the existence of a proportional relationship between the population growth and agriculture intensification [55,56,63], support land fragmentation position. This polarized duality poses a crucial dilemma to policy makers and research scholars about whether they should devise and advise policies in favour of defragmentation (consolidation) or fragmentation conservation [11]. As stated by Ntihinyurwa and de Vries [11], this dilemma sometimes leads to the design of irrelevant farmland fragmentation control strategies which overlook the idiosyncrasies of specific fragmentation scenarios and its both contextual problems and benefits, and as a consequence derive disputed results leading to the failures.

Despite the subjectivity and the contradictions of various studies in literature, none of them has previously attempted to reconcile the above polarized views about farmland fragmentation and consolidation, and devise an explicit comprehensive relationship between these two concepts and food security as an end result instead of the existing focus on agriculture production and food quantity, since food security goes beyond the quantity. Chigbu et al. [32], Maxwell and Smith [64], Pinstrup-Andersen [65], Manjunatha et al. [66], Ntihinyurwa et al. [33], and Ntihinyurwa and de Vries [11] argue that although the popular logic is that land consolidation (especially due to increased farm size and reduced distances) has direct positive effects on increasing food security by boosting food production from conventional agriculture, this makes sense when food security is viewed from the lens of quantity. However, food security is much beyond the quantity of food production. It has the quality, accessibility, utilization,

acceptability, sustainability, and sovereignty perspectives which can be achievable even under land fragmentation scenarios [11,32,33,46,67]. It is about more than growing enough food, since it implies the demand for it as well as the supply, the quality as well as quantity, an adequate diet (culturally acceptable quality and quantity meeting the local food preferences and needs) today and assurance of one tomorrow [11,32,33,46,54,65]. Following Sen's food entitlement theory [68], food security is achieved when everyone has access to regular, safe, nutritious and enough food [11,32,65,69]. For the advocates of food sovereignty, food security is achieved when local peasants have self-sufficiency in the production of their own food based on their cultural food preferences through local and sustainable agroecological approaches [46,70]. Furthermore, only few sporadic studies such as Bentley [30], Blarel et al. [31], Abubakari et al. [12], Kadigi et al. [50], Ntihinyurwa et al. [33], and Ntihinyurwa and de Vries [11] explicitly show when, where, how, and why one should keep fragmentation or opt for consolidation approaches, thereby calling for more comprehensive and holistic studies about this subject. In light of these arguments, there is a need to identify and compare categories and attributes of farmland fragmentation scenarios. For each of such scenarios one can describe which causes their constitution have, their impacts (positive and negative) on external variables like food security, and which control strategies would be most appropriate to them.

To address this specific research lapse and respond to these research calls, this study aims to:

- critically review (by exploring and synthesizing) the existing documented conceptual relationships between farmland fragmentation and its control interventions (including land consolidation), and food security;
- identify the knowledge gaps and openings for further research;
- reconceptualize the relationships between farmland fragmentation, its control strategies, and food security;
- propose a new theoretical model of farmland fragmentation management which may better help policy makers than current subjective and disaggregated ones, and guide and inform future solutions-oriented and evidence-based studies about appropriate and suitable alternatives for dealing with farmland fragmentation.

It explicitly results in a substantive explanation of different farmland fragmentation scenarios, the conditions under which they become defective or beneficial, and proposes the suitable potential strategies for their sustainable management under various specific circumstances. Moreover, the development and comparison of farmland fragmentation scenarios and food security extends the existing debate about farmland fragmentation and consolidation, and multiple UN sustainable development goals, namely SGDs 1, 2, 12, 13 & 15, versus the global trends towards market-oriented agriculture. Specifically, SDGs 1.4 and 2.3 address land rights and how farmers own, access, secure and control land resources among all the heirs; SDG 12.2 refers to the sustainable management and efficient use of natural resources (including land); the diversification of crops in different fragmented and scattered areas with diverse growing conditions as an adaptive strategy (climate smart, agro-ecological or resilient agriculture) to the ongoing new global challenging realities of climate change and the core of SDGs 2.4,5; 13.1 to end hunger and malnutrition resulting from food insecurity, is addressed by SDG 2.1, 2, 3, 4 & 5); and

the agrobiodiversity and ecosystems conservation through the protection of their natural habitats on land comes as focus of SDG 15.3, 4, 5 & 9), in the framework of the Agenda 2030 [11,71]. The decisions about farmland use either in fragmented or consolidated forms can be most directly linked with these five SDGs whose specific targets capture the sustainable land management (ownership and use) and climate change adaption and mitigation, as key factors of sustainable agriculture production and food security to end hunger, malnutrition and poverty, even though land management as a scientific discipline may be connected with all the SDGs [11]. Since the terms of land fragmentation, land consolidation, and food security are variously conceptualized in different contexts, scientific disciplines and levels of analysis, in this article, only their meaning in the context of agriculture production at all levels is followed. The focus is given to the concept of food security from the lens of agriculture-based food stuffs, with little attention on the animal-based ones for the purpose of nutritional balance and food quality. Irrespective of the spatial and temporal limitations, only the literature about this topic in English language is considered.

The article is shaped in the following structure: The first section introduces the concepts of farmland fragmentation, farmland consolidation, and food security. The second section addresses the methodology of the literature identification, review, analysis, synthesis and reconceptualization. The subsequent third section categorizes and discusses farmland fragmentation scenarios and how these relate to their existing generic control (management) strategies (instruments) and interventions. Thereafter in fourth section, the concept of food security is discussed, and its relationships with farmland fragmentation and farmland consolidation approaches are assessed and synthesized. This section subsequently derives the new model of farmland fragmentation management and the re-conceptualized relationships which are discussed and motivated in section 5. Finally, the conclusions and implications of the study for further research and policies are drawn.

2. Methodology

2. 1. Research Approach and Boundaries

As an integrative review article (relying only on secondary data), this research opts for an integrative concept-centric qualitative approach which draws on the deductive logical reasoning following the rationalist theory through the exploratory research design, to create new scientific knowledge from the existing general facts in literature and inform future research and policies [11,72–75]. This approach is considered by Ntihinyurwa and de Vries [11] and Ntihinyurwa and de Vries [75] as the most suitable research epistemology for this kind of study, since it deductively uses the researchers' own reasoning (abstract way of reasoning) without sensory experiences or empirical data to create novel scientific knowledge. The researchers use their own knowledge about the topic to critically analyse and synthesize the existing knowledge about different concepts, theories and principles, and deduct their own new and particular conceptualizations (models or frameworks) from the reviewed general facts [11,72–76]. Webster and Watson [74] and Torraco [73] argue that this approach fosters the critical review, analysis and synthesis of existing knowledge about the topic under research, with the objective of devising possible relationships among various research variables, identify knowledge gaps and contradictions, and seek opportunities for future research. The main aim of this approach is the re-conceptualization of

the topic in a more understandable way for the guidance of future perspectives and expansion of the existing theories or creation of new knowledge in a particular scientific domain [11,72–76].

Hence, given the scope of the study of understanding various farmland fragmentation scenarios and proposing their suitable management strategies and interventions to achieve food security, only the literature about the forms, causes and impacts of agricultural land fragmentation and its alternative control measures across contexts and disciplines at all spatial levels was considered as a contextual boundary of the study, since the required information can mostly be derived from the relationships among these research variables. The use of multiple spatial levels of analysis is explained by the fact that farmland fragmentation itself is a multi-level phenomenon, whose causes, impacts as well as control strategies can be identified from the local (individual, household, family, village) to regional and national levels [11]. Spatial and temporal limitations (boundaries) were not considered throughout the review process for internal data validity purposes. This led to the review of both old and new geographically unlimited available literature materials on the topic, as a suitable method for this case of research approach which requires a comprehensive and broad literature. This review technique adopts a synthetic strategy of sense making which suggests the use of multiple cases and broad selection criteria to create a more comprehensive knowledge [11,74,75,77]. Nevertheless, for the purpose of preventing various conceptual divergences, misuse, and linguistic bias, both empirical (primary) and review (secondary) literature only in English language in which a large body of extensive literature on this topic exist [11,75], was considered for this review. This approach was recently used in quite similar studies and contexts by Asiama et al. [29], Asiama et al. [28], Ntihinyurwa and de Vries [11], and Ntihinyurwa and de Vries [75]. The following subsection explains the processes and methods for literature identification (search, selection criteria and its sources, scientific repositories or databases), review, analysis and synthesis techniques, and the reconceptualization or modelling methods and procedures as summarized in the research design (see Figure 1).

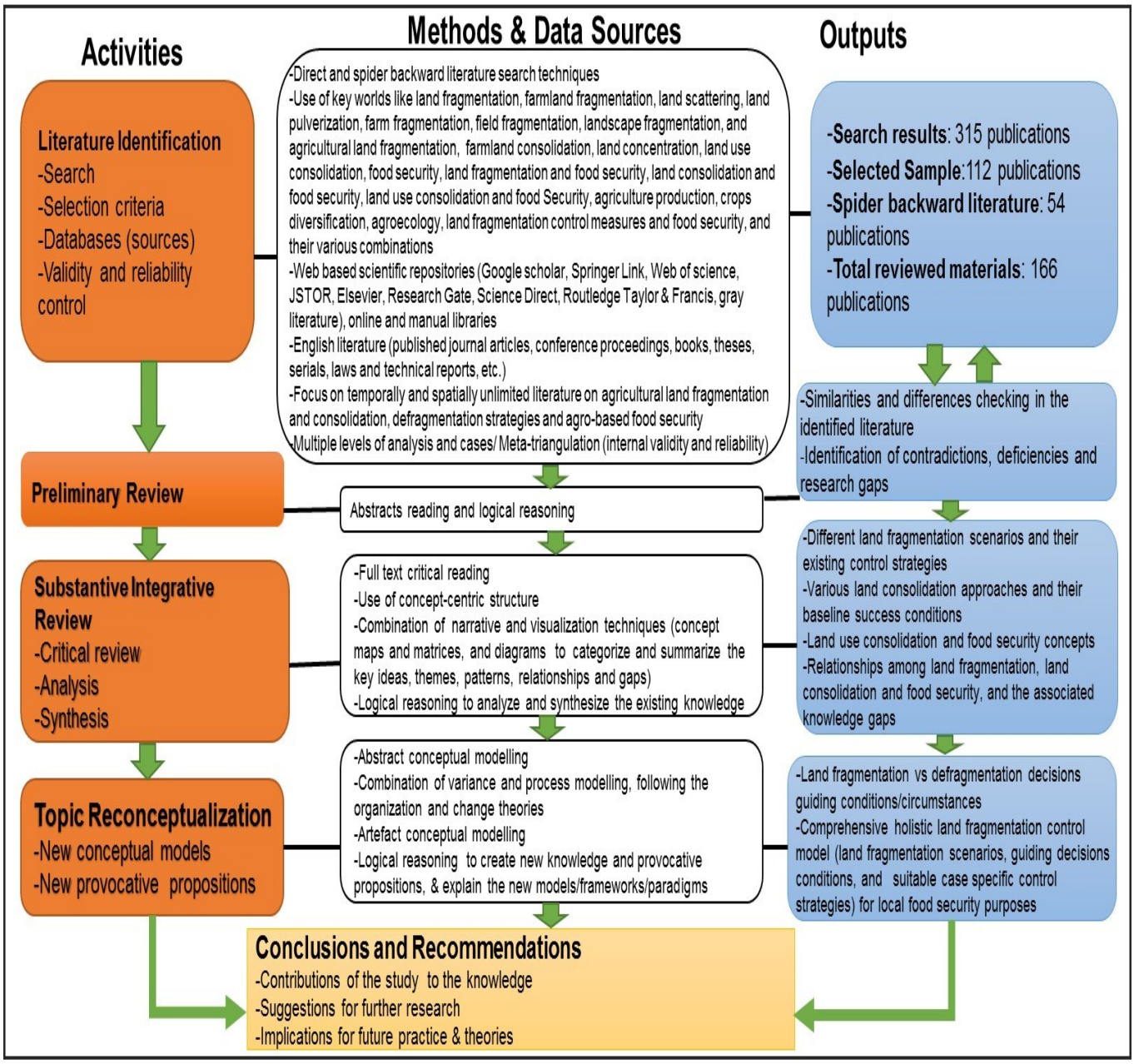

Figure 1A4. Overview of the research process and design

Source: Adapted from Ntihinyurwa and de Vries [11] and Ntihinyurwa and de Vries [75]

2.2. Data Sources and Research Methods

Once the boundaries of the literature were set up, we proceeded with the literature identification (search and selection). The following key words combinations were the basis for the search strategy: farmland fragmentation, farm fragmentation, land fragmentation, landscape fragmentation, field fragmentation, land pulverization, agricultural land fragmentation, land scattering, land fragmentation control measures, land consolidation, farmland consolidation, land concentration, land use consolidation (LUC), farm land use consolidation, crop consolidation, food security, farmland fragmentation and food

security, farmland consolidation and food security, land use consolidation and food security, land banking and food security, agriculture production and food security, crops diversification and food security, land fragmentation control measures and food security, agro-ecology and food security, and agriculture intensification and food security. These key word combinations were chosen based on their closeness to the topic and the likelihood of generating the desired information. Individual instances of these key words and their diverse combinations were the systematic search strategies across different well-known web based scientific repositories (for soft documents) and the online and physical library visits (for hard documents) in English language (see sub section 2.1 and Figure 1 for detailed search and selection criteria). These web-based scientific repositories include among others: Web of Science, Google Scholar, Springer Link, Research Gate, Routledge (Taylor & Francis), JSTOR, and Journals websites. Additionally, throughout the literature search process, relevant grey literature (published and unpublished non-commercial literature materials) from various governmental and non-governmental multilateral and bilateral organizations and institutions (such as FAO, GLTN, USAID, IFPRI, World Bank Group, UN and UN-Habitat amongst others) was taken into account. According to Webster and Watson [74], Torraco [73], Ntihinyurwa and de Vries [11], and Ntihinyurwa and de Vries [75], the use of multiple synonymous and diverse key words across many different data sources in literature identification provides a benefit of offering a large variety of documents about the topic for the motives of data and findings validity and authenticity. The search was nearly complete when no new concepts were found in the records set [11,73–75]. The literature identification process resulted in the retrieval of 315 written records including 292 soft documents varying from published peer reviewed journal articles and review papers, magazine articles, books, book sections, conference proceedings, laws and acts, technical reports, theses to press releases and serials, and 23 hard documents from visited libraries. The screening and preliminary review of the search results was done through critically scanning all titles and abstracts of the retrieved literature materials taking into account the above-mentioned review boundaries (see subsection 2.1 and Figure 1) and elimination of duplicates. This process resulted in the selection of 112 relevant materials eligible for a full text review.

In the light of the aim and the scope of the study, a concept-centric (thematic) approach was adopted as the most suitable organization strategy for integrative literature review, analysis and synthesis [11,72–75]. Following this approach, all the articles with similar claims and views were grouped together and categorized through the combination of textual (narrative) and visual representations [11,73–75]. In this regard, throughout the reading session, a concept matrix [78,79] was developed to categorize different ideas and themes across various research variables encapsulating the concepts of farmland fragmentation, farmland consolidation, and food security in a more understandable, precise and narrow way. The content review consisted of both the analysis and synthesis of key and critical aspects of the research variables, and a listing and display of new relationships and research gaps [11,75]. During the review process, new seminal articles and frequently cited relevant references were identified and traced backward from their original materials using a spider backward literature search technique for further consideration in the review [11,75]. This technique resulted in the selection of 54 additional eligible documents for full text review, which therefrom generated the total number of 166 reviewed materials. In order to identify the strengths, weaknesses, deficiencies, contradictions, problematical situations and

research gaps which need to be closed by the new knowledge [11,75], various farmland fragmentation scenarios and their existing control strategies were thoroughly reviewed, and their spotlighted relationships with food security critically analysed using our existing knowledge about the topic through the logical reasoning following the rationalist theory [11,73–75].

This approach of conceptual reasoning is suitable for integrative theoretical studies which seek to analyse insights from past experiences and views for the preparation of future perspectives and guidance [11,72–75], and has been previously used by many research scholars in quite similar context with this one including McPherson [80], Bentley [30], Asiama et al. [29], Asiama et al. [28], Ntihinyurwa and de Vries [11], and Ntihinyurwa and de Vries [75]. The identified theoretical relationships and research gaps from the critical analysis were exhaustively summed-up in different diagrams and alternative models, or weaved together in a unique synthesis for a better presentation of the situation and basis for a reconceptualization of farmland fragmentation, farmland consolidation and food security nexuses. This also helped to inform the design of a new comprehensive and holistic conceptual thinking about farmland fragmentation management to support the achievement of the sustainable development goals (SDGs 1, 2,12,13, and 15) within the existing climate change realities. An abstract conceptual modelling combining both variance and process graphical models in artefact format [77,81] and textual models following the organization theory, theory of change, complexity theory and the soft systems methodology of thinking (SSM) [59,60,82,83], and the dynamic systems theory [84–86], was used to develop a new model. This model shows different farmland fragmentation scenarios, their proposed specific managerial decisions and strategies under different conditions, and their hypothetical impacts on food security and other aspects of livelihoods. The logic conceptual reasoning approach [74,87] combined with the reviewed theoretical foundations and documented empirical findings of the reviewed materials were used to justify various combinations and propositions of the model [75]. Finally, the implications of the new model to the existing knowledge and decision and policy makers were explained, and suggestions for future research to fill the newly identified gaps and empirically test the new relationships were derived [11,72–74,76].

3. Farmland Fragmentation Scenarios and its Management Strategies: Land Consolidation as a Controversial Multi-layered and Progressive Panacea to a Multidimensional Quandary

The concept of farmland fragmentation may at first glance seem very complex, fluid and multidisciplinary, as it refers to both a spatial structure and a management strategy [75]. As a multidimensional concept, it has been variously and subjectively defined in the existing literature [30,88]. Some research scholars commonly define it as the situation where a single farm consists of numerous spatially separated (non-contiguous) small parcels often scattered over a wide area [2,4,30,37,75,88–93]. Igbozurike [94] provides a more holistic and objective conceptualization by defining it as the process by which a contiguous block of land is split into two or more parts [75]. It has been simultaneously described as a natural and socio-economic phenomenon that occurs at different spatial levels (parcel, farm, land block and landscape). Thus, its conceptualization and derived forms should draw from the existing relationship between land parcel (object) and people (subject) in land management paradigms [33,75]. Following this approach, any fragmentation in the physical characteristics of a land parcel as an object (size, use, shape, type, location) dictate the existence of different physical fragmentation forms

[75]. Similarly, any fragmentation derived from the social relationships (rights, restrictions and responsibilities) between land parcel (object) and people (subject) implies the occurrence of various social or tenure fragmentation forms (both visible and hidden ownership and usership) at different spatial levels [75]. Moreover, the economic characteristics of land (value and market) often dictated by social and physical traits may also imply some fragmentation forms and scenarios.

Therefore, referring to the study of Ntihinyurwa and de Vries [75], physical farmland fragmentation stands for any type of fragmentation in physical characteristics of land either internal or external at all spatial levels, while tenure fragmentation refers to any fragmentation form derived from the split in the social characteristics of land in terms of its relationships with people, irrespective of the exclusive internality and externality criteria. Hence, in this context, farm fragmentation (often referred to as internal or within farm fragmentation) denotes the situation when a single farm is physically split into many relatively small plots (parcels) either spatially dispersed or contiguous (physical fragmentation), or shared by many undocumented co-owners or co-users (hidden tenure fragmentation in terms of ownership or usership) [33,75]. On the other hand, according to Ntihinyurwa and de Vries [75], farmland fragmentation refers to the split of the farming structure in a relatively small land block or region into many small farms (visible and hidden tenure fragmentation in terms of ownership and usership), or into many small plots or parcels (physical fragmentation). When the split into many plots happens at the parcel level, this phenomenon is denoted as parcel or field fragmentation. The land value (social and economic) fragmentation and land market fragmentation exist when a land block is split into smaller subunits like land parcels and plots with different socio-physical peculiarities dictating the diversity in value and market of the land. Irrespective of various contradictory theories of Earth creation, it is obvious that the landscape is naturally fragmented (in soil type, size, location, shape, topography), which ontologically explains the existence of physical fragmentation at the landscape level as a natural phenomenon, independent of human activities and land-people relationship. This relationship is often defined at the parcel level [95,96], which dictates the existence of physical, social (tenure), and economic fragmentation forms. Despite the dynamic nature of this fragmentation concept, King and Burton [97] and Ntihinyurwa and de Vries [75] assert that the above fragmentation forms can coexist in the same area at different levels, and its extent is determined by the local conditions in specific countries and areas [75]. This entails the existence of different possible generic and specific fragmentation scenarios from various combinations of its indicators [75]. Notwithstanding various conceptualizations of this fragmentation phenomenon from the socio-economic and physical perspectives and different subjective levels of analysis, all the analysed literature materials have a commonality of referring to agriculture land fragmentation (see Ntihinyurwa and de Vries [75] for more details on various farmland fragmentation forms and scenarios).

The causes and impacts of farmland fragmentation in the literature have always been subject to contradictory and multidisciplinary debate by considering it either beneficial (voluntary) to farmers (as risk management strategy for household food security) or defective (derived from external imposition which leads to the reduction of farm efficiency through the increase of production costs) (see Ntihinyurwa and de Vries [11] and Ntihinyurwa et al. [33] for more details). However, recent studies revealed that its problematical and beneficial scenarios are dictated by a combination of local specific external conditions,

varying from economic, socio-cultural, political, ecological, technical to environmental ones, which therefore similarly implies the variation of their management strategies [11,12,17,18,30,33,90]. According to [75], with reference to the problems linked with farmland fragmentation, its problematic forms can be categorized into four distinct groups: i) *farmland location or spatial fragmentation* (problems of long distance between plots and farmstead); ii) *farmland size fragmentation* (problems of small plots and farm sizes); iii) *farmland shape fragmentation* (problems of shape irregularity), and iv) *farmland use fragmentation* (problems of multiple mixed uses or multiculture).

Whether problematic or beneficial, agricultural land fragmentation needs a certain level of management for sustaining the quality and quantity of agriculture production for food security purposes in a given area. In this regard, various strategies have been developed over time to control this complex phenomenon. Demetriou [98] grouped them into three main categories as follows:

- Legal provisions and restrictions relating to inheritance, minimum size of parcel subdivision, joint ownership, absentee landowners, prevention of transfer to non-farmers, leasing, and imposition of a maximum limit on the size of a holding to prevent the rational drivers of fragmentation phenomenon from worsening the situation.
- Land management approaches including land consolidation, land funds and land banking, voluntary parcel exchange, and cooperative farming to reverse and inhibit the harm of the existing fragmentation.
- Agricultural land protection policies which embrace the Purchase of Development Rights (PDR), the Transfer of Development Rights (TDR), and the Cluster Development Programs (CDP) in USA to prevent its use for other purposes or development activities like residential, commercial, etc. These are described below.

a) *Land Consolidation*: Even though the concept of land consolidation has its roots in the medieval ages with the first initiative in the 1750's in Denmark as a social reform [4] and was implemented in different countries for millennia, there is no common definition for it, as it varies across contexts and by country with respect to the end goals and objectives. It is generally known as a process of arranging parcels together in order to make them more productive and reduce the adverse effects of fragmentation in agriculture [4,19,98,99]. In the German Land Consolidation Act (1976), it is considered as an instrument of improving production and working conditions in agriculture and forest lands as well as promoting the general use and development of land in rural areas and the living conditions of rural livelihood, through the re-arrangement of agricultural land by restructuring the shape, size, ownership and location of farmland parcels and forestry [10,16,97,100–102]. FAO [4] defines it as a land management activity that involves all the procedures for exchanging, rearranging, realigning, and expanding farm parcels in rural areas with the goal of increasing food productivity. In this context, the parcel boundaries, ownership, size and location of the land are restructured for its best use and management. Since the reallocation of new parcels as a core for land consolidation procedures is rather value than shape, use, size and location based, land valuation based on soil evaluation is considered as the basic activity which should be given a special attention and management to reduce the pace of resultant conflicts in this strategy [12,15–17,103–106]. Land consolidation started as a monofunctional concept with a single objective of improving

agriculture production which is still kept in Scandinavian countries like Sweden (*fastighetsreglering*), Norway and Denmark. It gained its momentum in 1970s, and started to integrate other objectives of rural development like village renewal, landscape and natural resources management, and forests management afterwards [16,20,107]. It is currently implemented with success as a comprehensive rural development strategy in many western European countries like the Netherlands (*ruilverkaveling*), Germany (*Flurbereinigung*), France (*remembrement*), Luxembourg, Spain, Belgium, Switzerland and Austria, as well as Finland (*uusjako*), and in Asian countries like China, India, Nepal, South Korea and Japan, where it is embedded in large national and regional development programs [16,101,102,107]. Van der Molen et al. [20] argue that land consolidation also called concentration [39] as an ambivalent concept (instrument and principle) following different principles (parcel reallocation and improvement of physical conditions) has a common objective of making the parcelling of one farm more compact (few contiguous parcels close to the homestead) and the farming structure in a given region denser (few farms per land block with higher average farm size), in order to create more operational and viable farm units. In this context, it is theoretically and commonly understood as a process of making the parcelling of one farm or a farming structure of any region more compact with few parcels per farm or land block, and higher average parcel and farm sizes respectively [4,16,18,20,108,109]. FAO [4] advances that any modern land consolidation should follow the following principles:

- The objective should be to improve the rural livelihoods rather than only the primary production of agricultural products.
- The end result should be the whole community renewal through its sustainable economic and political development, and the protection and sustainable management of natural resources.
- The process should be participatory, democratic and community-driven not only in concept, but also in practice.
- The interventions should be to assist the community to define new uses for its resources and then reorganize the spatial components accordingly.
- The approaches should be comprehensive and cross-sectoral, integrating elements of rural and broader regional development including the rural-urban linkages.

Several other studies indicate that the local agricultural, economic, social, cultural, environmental, agro-ecological and political conditions of the area dictate the procedures, objectives and models of land consolidation in different countries, although the implementation principles remain the same everywhere [12,13,16,18,19,28,33,110]. They argue that the variations in local conditions make it necessary to allow the creation of different local versions or approaches of land consolidation, based on the available problematic land fragmentation forms and needs of rural local population. A successful consolidation approach of flat areas cannot necessarily apply in mountainous areas. This idea is guided by the FAO principles stipulating that a good land consolidation strategy must recognize the diversity of rural society and the non-problematic scenarios of land fragmentation [4,111]. This dictates the need for diverse local solutions, including keeping the beneficial fragmentation for crops diversification motives for food security and sovereignty, and risks and labour management under multiple agroecological zones [30]. In this vein, different land consolidation forms (approaches) have been developed over time. The most commonly

known include the comprehensive, simplified, voluntary, individual, government-led, private company-dominated, and farmland use consolidation among others [4,16,23,99,108,112,113] as described below:

- *Comprehensive land consolidation*: It embraces the re-shaping and re-allocation of parcels together with a broad range of other measures and activities that support and promote the rural development [4,16,114]. Examples of such activities include extension services for rural communities, the village renewal, the construction of rural roads and water infrastructure, the co-construction and support to community based alternative agro-processing techniques, the erosion control measures, the construction and rehabilitation of irrigation and drainage systems, the creation of social infrastructure including sports grounds and other public facilities, along with the environmental protection and improvement measures including the designation of nature reserves [4,16,114]. This model prevailing in Germany and the Netherlands presents the drawback of taking too long in implementation, due to the complexity of involved activities and large coverage. It is mostly *government-led*, and somehow involves a certain level of compulsion in participation [4,16,114]. It is more effective when it is combined with land banking programs to counter the challenges of unwilling participants in order to enlarge the parcels and landholdings [4,16,114]. Although its implementation procedures vary from country to country, they generally involve the following phases: initiation or the design of the project (feasibility study); inventory of existing 3Rs (rights, restrictions and responsibilities like ownership, tenancies, easements, usufructs, mortgages and conflicts) and values over land (land valuation); elabouration of the detailed consolidation plan showing the new parcels layout and their reallocation which shall be presented to the public for claims consideration and accepted by all land owners before the final plan; implementation of the final plan and appeal proceedings; and finally a concluding phase in which the final records are produced [4,16]. Drawing from the recent study of Veršinskas et al. [114], the *mandatory* and *majority-based* (the decisions to compulsorily consolidate are based on the votes of the majority) *land consolidation* types fall in this category. The same study groups the consolidation process in this model in three phases of the feasibility phase, the re-allotment phase, and the registration and implementation phase. Notwithstanding its multifunctionality, when flexible and participatory, the comprehensive land consolidation can be subject to different changes and take different approaches to adapt it to the local collective needs and objectives, contrary to the government-centered one [115].
- *Simplified land consolidation*: To overcome the challenges of long duration due to the complexity of activities in comprehensive consolidation models, the simplified land consolidation has been created to optimize the conditions in agricultural sector through the exchange or re-allocation of parcels, and the provision of additional lands from land banks [4,16]. These simplified projects are often combined with minor public works like the rehabilitation of infrastructure and sometimes the provision of minor facilities with the primary objective of improving the working conditions in agriculture. They are mostly implemented on a small coverage and follow similar but simplified procedures as comprehensive land consolidation [4,16]. This is the case of German special land consolidation proceedings and Swedish forest re-allotment projects [4,16].
- *Voluntary group consolidation*: It is based on the mutual agreement among close land owners to consolidate their adjacent plots with no element of compulsion in some countries [4]. Since the consolidation is entirely voluntary, during the process, all participants must fully agree with the proposed

project [4,16,114,116]. In the light of this, such voluntary projects tend to be small, usually with less than ten participants and best suited to address small and localized fragmentation problems with less harm to the environment [4,16,28]. In Denmark, this option is most common and almost all land consolidation projects are carried out in a completely voluntary process, and typically involve the negotiations with up to 50 land owners, even though some few projects may involve about 100 participants [4]. Countries like Lithuania and others are currently following this approach [4,16,28,116].

- *Individual consolidation*: In this form, the consolidation of holdings takes place on an informal and sporadic basis without a direct involvement of the state and the provision of public facilities [4,117,118]. Nevertheless, the state can play a significant role in encouraging consolidations that improve agriculture by promoting instruments such as joint land use agreements like cooperative farming, scattered parcels exchanges among farmers to create compact farms, farmland use or crop consolidation, and leasing and retirement schemes [4,16,117].
- *Land Use Consolidation (LUC) or Consolidation of crops*: LUC program also known as Farm Land Use Consolidation in USAID reports, and land consolidation in the Ministerial order on land consolidation models in Rwanda (2010), refers to the consolidation of the use of farmlands where all farmers with close parcels grow one same crop in a synchronized way up to the minimum size of 5ha from the 8 priority food crops (maize, beans, wheat, rice, Irish potatoes, banana, cassava and soybeans) chosen by the government at the national level based on the Agro Ecological Zones (AEZ) of the country [23,26,32,33,117,119]. Contrary to other land consolidation programs, the individual land rights in LUC remain intact [32,33,117]. It is a national program implemented in the whole country as one of the pillars of the Crop Intensification Program (CIP) with the objectives of increasing agricultural production, improving the living conditions in rural areas, and meeting food security [23,26,28,32,33,117]. Huggins [24] and Pritchard [34] call it “Crop Consolidation”. Similar programs have been previously documented in Malawi, and in Europe in case of viniculture consolidation programs [16,26,120].

Although land use consolidation (LUC) is conceptually considered as a special form or approach of land consolidation, from the practical perspective in Rwanda and Western Europe, the two terms do not have much in common in terms of activities involved. While in land consolidation the sizes, shapes, boundaries, locations and ownership of land parcels are rearranged with no control on the use, and the parcel values kept intact, only the use of farmlands for priority crops is consolidated in the case of land use consolidation in Rwanda, with all the other attributes remaining unchanged. Nevertheless, the two strategies share the same objective of improving agriculture production and the rural livelihoods, even though LUC has been criticized to only lead to the monoculture (mono-cropping) system resulting in food insecurity at the household level in case of climate change, natural shocks, and market imperfection scenarios [24,32–34,119,121]. Furthermore, one could wonder whether it is the most suitable strategy to the problematic land fragmentation scenarios in Rwanda, considering the heterogeneous local social, economic, physical and ecological conditions of the country. In support to this doubt, recent findings of Isaacs et al. [122] revealed the benefits of improved intercropping system to outperform the ones from the government-led mono-cropping through LUC in terms of household food security and risks management insurance. Niyonzima [123] found that the national farming programs including LUC encouraging the monoculture and environmental policies have failed to address the local farmers needs

in the Eastern Province of Rwanda mainly due to the market imperfections, thereby recommending the support to mixed farming systems as a promising solution for agricultural production and household food security concerns. Therefore, contrary to the studies of Laepple [120], Vitikainen [16], Musahara et al. [26], and Asiama et al. [28], we claim that there is no rationale for considering *land use consolidation* as part of conventional *land consolidation approaches*, rather a particular type of agricultural land use management, and a tool for farmland management like land consolidation as well.

With regard to the emergence of new issues in the implementation of *government-led land consolidation* projects in China, a new approach of *company-dominated pattern of land consolidation* programs [113] has been developed as an efficient strategy for both physical and tenure fragmentation problems. In this approach, the private companies act as land bank institutions and acquire large lands through the negotiations-based expropriation programs from small farmers to create big land funds which could later be farmed as single consolidated viable operational units, or leased to big farmers [113]. The commonality of these consolidation models is that most of them are regulated and facilitated by land professionals [114].

Whereas the success conditions of different land consolidation approaches vary from country to country, the common key feature is that the relative economic value and ownership of land should be kept constant before and after consolidation following the surrogate principle of land valuation, with the benefits from such consolidation exceeding the costs of its establishment [16,30]. Similarly, Van Dijk [18], Hartvigsen [19], Asiama et al. [28], and Asiama et al. [17] argue in their respective studies on Central and Eastern Europe and Ghana, that the economic value of land should exceed its social value (perfect land market leading to high land mobility) as a key precondition for success of land consolidation programs. In this regard, various researchers have highlighted and documented the general baseline conditions which need to be considered before the development of any specific land consolidation approach in an area [4,12,18,19,28,30,107,108,124–127]. These include:

-Land tenure system: It dictates the decisions about the parcels reallocation process as a core for land consolidation. The customary or community land tenure system has been considered to be an obstacle to this activity, since farmers only have use rights over their lands, with no allocation rights without the consent of the chiefs who hold the custodian rights (allodial title) to control and allocate the use of land on behalf of their community [12,17,28]. Furthermore, in customary tenure systems, land is considered as a sacred property of the family which should be preserved for future generations (ibid). This increases the social attachment to land and social land value, which in turn reduces land mobility as an obstacle to land reallocation and land market [18,19]. Likewise, the absentee owners in case of usership fragmentation obstruct the reallocation process since they do not find any direct interests from consolidation. On the other hand, the users (tenants) do not have the ownership and allocation rights, which decreases their willingness to invest in long term projects like land consolidation [11,18]. The failure of previous land consolidation attempts in customary lands has been attributed to the focus on technical and economic aspects, thereby ignoring this important social benefit [28]. Asiama et al. [17] found that the exchange of parcels in the Ghanaian customary lands is only possible among family members within the same community, with very limited mobility among communities. For this, the statutory individual

private tenure system with individual ownership rights has been pinpointed as a suitable success condition for modern land consolidation projects by facilitating the decision making about reallocation with consent from one or few owners [12,18,19,28,104].

-*Economic status and land market*: They dictate the approach of land consolidation to be adopted, and the reallocation process. A perfect land market increases the economic value of land (land as an economic commodity), which in turn reduces the social attachment to land (social value), thereby easing land mobility and the reallocation of land during land consolidation. This is explained by the theory of land mobility stipulating that when the economic value of land is higher than its social value, the mobility of land through any kind of transfer increases [18,28,109]. Furthermore, the macro economic conditions have been found to facilitate the adoption of modern comprehensive land consolidation approach, which needs considerable financial capacities from both farmers and the state, while the subsistence economies favour more simplified and cheap approaches [16,28].

-*Willingness of farmers to participate*: This is crucial for the success of any land consolidation project and the type of approach to follow. It is dictated by land psychology (i.e., sense of social attachment to land), economic status, land availability, and land market. From a rational perspective, farmers accept to participate when the economic benefits from the project outweigh the costs and its social ones. Participation also relates to the degree to which project managers have an affinity with the area [128]. FAO [4] suggests that land consolidation process should be demand-driven by farmers, and the government should intervene to assist them in choosing the suitable approaches to their land use needs. In case a big number of farmers accept the participation, the reluctance of few farmers is overcome by a certain level of compulsion in some cases and the expropriation processes through land banking. The subsistence farmers in risks prone areas with scarce land and absentee owners often resist land consolidation programs which rearrange the ownership structure, sizes, locations and boundaries, due to the fear of losing their original rights over land [4,12,17,30,97,129].

-*Availability of land banks*: Although not a sine qua non condition for all land consolidation projects, it is very important during the reallocation process, as it provides additional lands from the governmental land funds to bridge the lapse of unwilling participants. Land banks provide an opportunity for expansion, shaping of farmlands and creation of adjoining infrastructure; facilitates the increase in land mobility; and creates the room for a flexible land consolidation design and reallocation process [4,12,21,28,109,125,127].

-*Existence of a legal framework*: It determines the success of land consolidation projects by regulating the whole process from the initiation to the concluding stage. Since land consolidation projects involve the exchange and reallocation of land rights, there is a need for a strong legal basis to regulate the interferences among different private property rights by the state, for the sake of transparent protection of the rights of landowners and users, and prevention of the prevalence of any conflicts from the process. It also provides the procedures for resolution of any conflict resulting from the sensitive land valuation and reallocation processes, and regulates the modalities of participation in the projects [4,12,28,106]. According to Bullard [99], the legislation is not only meant to address land fragmentation, but also to prevent its reoccurrence in future. For this, the absence of the legal frame is considered as a major obstacle to the success of any land consolidation project.

-*Level of political structure*: It determines the political will of the state to support land consolidation projects, which in turn dictates the type of approach to follow, the duration of the project, its implementation procedures and success. When there is a high level of political will, the government takes a primary initiative to finance land consolidation programs at large scale, which in turn stimulates the willingness of voluntary participation of farmers and reduces the duration and costs of implementation. In contrast, the lack of political will slows down the process, and induces farmers to adopt cheap approaches on voluntary basis with no direct influence of the state [16,28].

-*Existence of problematic land fragmentation*: Since land consolidation is designed to solve the existing problems of land fragmentation, there is a need to know the available forms of land fragmentation in a specific local area, and their problematic circumstances to inform the suitable land consolidation and other approaches, since not all land fragmentation problems need land consolidation control strategies, neither are all fragmentation forms problematic [4,11,20,21,30,31,33,75,130]. The review of existing documents has revealed that the modern land consolidation is only suitable for physical (internal) fragmentation problems of big farms. Expanding the stipulations of Abubakari et al. [12] and Asiama et al. [28] for the availability of a certain type of land fragmentation as a precondition for an introduction of land consolidation projects in a given area, we argue that there should be a problematic land fragmentation suitable for land consolidation strategies since some fragmentation forms like tenure fragmentation might need other different strategies for their control. It has further been found that the adoption of non-suitable land consolidation strategies to the existing local land fragmentation problems has led to their failure in many countries like Kenya, Malawi, Japan, and others (ibid).

-*Biophysical/geographical/agroecological/environmental conditions*: Variations in topography (slope distribution), soil quality and water distribution, and the microclimatic conditions determine the forms of land fragmentation and which control strategies are suitable in a given area with respect to the benefits and costs associated with the valuation and reallocation activities. Contrary to hilly and mountainous topographies characterized by high diversity or heterogeneous microclimatic conditions and soil qualities, flat terrains with quite homogeneous conditions make it easy to exchange parcels with similar characteristics and values [12,28,30]. Furthermore, the hilly and mountainous areas with sharp variations in surface characteristics hinder the creation of regular shapes and infrastructures as land boundaries may naturally follow the physical characteristics of the terrain like hill tops or valleys [12,13,28,40,107]. King and Burton [97], Bentley [30], and Janus et al. [108] argue that due to the sharp variations in soil quality, and agroecological conditions in mountainous and hilly lands, the costs of consolidation may exceed its benefits, which dictates the development of different consolidation approaches rather than focusing on economic profitability, or keeping fragmentation in such areas. Prior to the development of any land consolidation approach, one needs to consider its anticipated effects on the environment, since previous experience has shown that large comprehensive consolidation projects have led to the loss of biodiversity. There should be measures to conserve the environment within the projects, or the development of environmental friendly approaches like simplified or voluntary or small localized land consolidation projects involving few people and activities [16,28,131–133].

-*Technical aspects (existence of land information system and consolidation experts)*: Since the consolidation of parcels involves the restructuring and rearrangement of socio-spatial land characteristics like ownership, use, size, shape, location, value and boundaries, there is a need to have a well-

functioning and updated land information system (LIS) to provide such information for a successful reallocation [4]. However, it is not a prerequisite prior to the establishment of consolidation projects, since the experience has shown that this database can be created later within the project [4]. Furthermore, since the implementation procedures of land consolidation vary from country to country with specific success conditions, the creation or adoption of new specific approaches adapted to the local societal needs requires some technical capacity and infrastructure, which can be provided from experts' technical knowledge [28,134]. Therefore, a team of experts made of land use planners, land surveyors, estate valuation surveyors, land administrators, land managers, agricultural engineers and agronomists, lawyers, socio-economists, agroecologists and environmentalists need to be in place to assist the farmers in the preparation and execution of the suitable land consolidation projects tailored to the local needs [12,16,28,30].

b) *Land Banking:* It is explained as the process of transferring and acquiring the ownership of small parcels from small farmers to big farmers to enlarge their holdings through sales, and/or to the government or private investors through expropriation procedures in order to use them as land funds (land banks) for the development of infrastructure and land buffer during land consolidation projects, with an overall objective of creating more operational and viable farm units [18,98,125,127]. Land banks provide an opportunity for expansion and shaping of farmlands, and the creation of adjoining infrastructure [18,125,127]. It follows the principle of ownership exchange, and targets to eliminate the size related land fragmentation problems and reduce the number of boundaries and its related conflicts [20,21]. It has been implemented in Western Central European countries like Germany and the Netherlands, often integrated in large land consolidation projects, although recent studies have also found it suitable to the Eastern and Central European land fragmentation problems [4,19,21,98,125,127]. It can be voluntary by old farmers to young active farmers willing to enlarge their farms, or compulsory through governmental agencies for agriculture and infrastructure developments projects (ibid).

c) *Voluntary parcel exchange:* It involves the exchange of distant non-contiguous parcels from the farmsteads among two or more landowners, resulting in more compact farms from adjacent parcels of each landowner with more efficient spatial layout [30,98]. The main target is to reduce the distance related costs, irregular shapes, and the number of boundaries by decreasing the number of scattered plots per farm under the circumstances of subsistence economies and scarce land. This strategy has been used with success in smaller land consolidation areas with a limited number of farmers in Germany (§ 103a FlurbG-) and the Netherlands (through a notarial agreement) where the primary benefit is in agriculture, and can be combined with land banking activities for its effectiveness [17,21]. More recently, it has also been considered for areas with other land uses than agriculture, most notably to suit the preservation of nature and merging ecological areas.

d) *Restrictions of the minimum parcel size subdivision, Joint ownership and Cooperative farming***:** For the purpose of reducing the negative effects of small farm sizes, different countries have established the legal provisions restricting the subdivision of parcels into small non-economically viable units and partible inheritance, thereby encouraging their joint ownership by many co-owners or heirs, and their cooperative farming. In *joint ownership*, a big piece of land is owned by many co-owners but operated by

one or few farmers, where in many cases one of the co-owners (heirs) later buys the shares of other heirs, or the co-owners lease their shares to one big farmer or cooperative (tenants) under specific use rights, restrictions and responsibilities [30,97,135,136]. Farmers may prefer the subdivision of the title over a piece of land in terms of shares without affecting its physical characteristics (ibid). With regard to the *cooperative farming*, a group of farmers jointly operate one big co-owned or leased farm together or agree to cultivate one type of crop on their small plots in a given area in order to create big and more economically operational and viable farms. In both cases, farmers retain their rights over land, whereas in the latter case, the boundaries of their parcels are kept intact, which has been found as a barrier to agriculture mechanization since it is difficult to move the machinery on small separately owned plots with many boundaries [3,97,98]. This is the case of Rwanda, where the article 30 of the law governing land forbids the subdivision of agricultural and livestock land which would result into small pieces of less than 1ha, thereby encouraging the joint ownership of such parcels and their cooperative farming through *land use consolidation (LUC) program* or cultivation of the same priority crop [26,33,117] as explained above in section 3 (a). However, although these strategies have been used with success in many countries (i.e., joint ownership in Taiwan) with subsistence economies and growing population under land scarcity conditions to tackle and reverse the problems of land fragmentation [136], different studies report their failure in countries like India, Nepal and Rwanda, as a result of the reluctance of farmers against them [8,24,30,32–34,97,98,123,137,138]. These studies decry these strategies to obstruct/deprive the full enjoyment of use rights over land for independent purposes, thereby inducing many ownership and use related conflicts viewed as a result of spatial injustices [139] leading to tenure and food insecurity in cases of compulsory participation and compliance to them. Moreover, the minimum parcel size subdivision restrictions have been criticized to lead to hidden ownership fragmentation thereby increasing farmland use fragmentation and the ownership and use related conflicts over land [32,33].

e) *Land realignment***:** It refers to the adjustment of land boundaries between two or more land parcels with the aim of remedy to the existing encroachment problems and or land management problems. It only implies minor changes in boundaries structure of adjacent plots thereby affecting the changes in sizes and shapes of parcels. It has been applied with success under the circumstances of internal fragmentation with contiguous parcels under the same operatorship to eliminate the problematic boundaries for the purpose of merging small plots into larger economically operational units [20,28].

Besides the above commonly known strategies to control the problematic land fragmentation, various studies have documented several other socio-economic and agronomic strategies to optimize the benefits from fragmented holdings by minimizing their defective effects on agriculture production without their elimination. These include different agriculture intensification programs (intensive use of labour and inputs in small heterogeneous farms and parcels); risks management strategies (agricultural insurance, agroecological approaches, food storage, pests control measures, credits, high yielding and resistant varieties) [11,30]; on-field harvest sales and off-farm employment [30,130]; the relocation of very distant farmsteads to close the best farms [97]; and many different case specific strategies parallel to the rational farmland fragmentation conservation under different circumstances like the cases of

consolidation of one agricultural use type or crop (land use consolidation in Rwanda and viniculture in Europe) [16,24,27,120] as explained above in previous paragraphs.

Despite the variety of these documented land fragmentation control strategies, land consolidation has been broadly and commonly used as a panacea to this quandary, regardless of its different forms and specific cases [21,33]. Although both land consolidation and land fragmentation are theoretically considered as land management instruments, the dominant discourse in the literature and practice presents a common weakness of tending to show the traditional land consolidation as the appropriate tool and solution to land fragmentation problems thereby ignoring the possible benefits of the later [30,33]. However, some studies revealed that land consolidation alone does not solve all land fragmentation problems. Whereas it is suitable to address land fragmentation problems of Western European and Scandinavian countries in areas characterized by big farms with many irregularly shaped and spatially dispersed parcels (internal fragmentation), it does not suit the Central and Eastern European countries which have many small farms (small size problems as an indicator of tenure fragmentation), and failed to be adapted to some African and Asian countries with complex traditional land tenure systems [20,21,28,33,88,109]. Furthermore, empirical evidence has critically proven that it tends to favour (benefit) big farmers with many scattered plots by increasing their income from agriculture at the expense of small farmers with small plots as an important pitfall, probably due to the diseconomies of scale [27,30,119,121]. In this vein, Nilsson [27] and Muyombano and Espling [121] found land use consolidation (LUC) not relevant to the fragmentation problems of small farms in Rwanda. Besides that, it has been largely criticized by many researchers for resulting in the loss of employment in case of its introduction in densely populated countries with subsistence economies thereby leading to the increase in rural urban migration, the loss of agrobiodiversity, and food insecurity through monoculture [30,31,37,38,124,133,140–142]. For this, land banking, voluntary parcel exchange, land realignment, joint ownership and cooperative farming have been proposed as suitable strategies for other land fragmentation problems than internal fragmentation of big farms [12,16,17,20,21,26,98,127]. Apart from that, Bentley [30] and Blarel et al. [31] argue that the problems of land fragmentation should be eliminated by focusing on Figurehting its root causes through curbing the population growth, creation of off-farm employment, and increasing agriculture technology.

However, in spite of the large body of literature about land fragmentation control strategies, only few studies explicitly address how, when, where and why different land fragmentation forms and specific control strategies can be inter-related and mutually conducive. The hesitation to study these interlinkages are connected to the inherent complexity and country-specificity of land fragmentation problems. These studies argue that land fragmentation issues are complex and vary from country to country and case to case with strong dependency on local social, economic, political, cultural, agricultural, agroecological and environmental conditions. Hence, there is no standard objective strategy or measure to control this phenomenon, nor is there a successful transfer of specific strategies in different areas with different characteristics [12,19–21,28,127]. This makes it difficult to objectively compare and assess the effectiveness of these strategies [108]. The empirical evidence revealed that the failure to consider the local conditions prior to the transplantation of land consolidation programs has previously led to their

failure in some African (Kenya, Malawi, Tanzania) and Asian countries dominated by customary and communal land tenure systems [12,18,21,29]. Therefore, there is a need to take into account specific local land fragmentation forms, their causes and impacts (problematical and beneficial) under specific conditions, and analyse the similarities and differences prior to any attempt to transfer any fragmentation control strategy among different areas, and/or create new progressive tools and responsible approaches suitable (adapted and updated) to the existing dynamic local conditions [12,18,28,143]. The idea behind is that a successful strategy in one area might not succeed in another due to the differences in operational conditions. One needs to know the factors of its success prior to its broad transplantation elsewhere. Abubakari et al. [12] in their study on land consolidation in the Ghanaian customary lands strongly argue that the success of any land consolidation program depends on the suitability of local conditions with its baseline conditions, with respect to land characteristics like its tenure, use, value, location, size and shape. For them, the information about the convergence or divergence of these conditions needs a careful feasibility study in specific areas under consideration. Bentley [30], Van Dijk [18], and Van Dijk [21] note that land fragmentation is minimized or reduced, when the number of owners, users or farmers (tenants) and farms in a given area (tenure fragmentation) declines, the number of irregularly shaped parcels per farm and the overall distance between them and the farmstead (physical fragmentation) drops, the number of uses/crops per farm (use fragmentation) declines, and the number of farmers who are operating/using their own lands (discrepancy between usership and ownership or tenure fragmentation) increases.

To this end, our review of the defragmentation strategies shows that land consolidation instruments are suitable to control internal (location and shape) land fragmentation of big farms through the creation of compact farms with one or few close regularly shaped big parcels, and tenure fragmentation (ownership and usership) through the creation of compact farming structure in a given region by reducing the number of owners and increasing farm sizes with regular shapes). Voluntary parcel exchange suits for internal fragmentation of small farms through the reduction of distances between parcels and homestead. Land banking is suitable for size or tenure fragmentation to reduce the number of farms/owners and increase the farm sizes in a given area, while cooperative farming is suitable for internal fragmentation in case of boundaries and shapes realignment through the joint ownership, and tenure fragmentation in case of consolidation of one use type or crop as it happens in land use consolidation in Rwanda and viniculture in Europe. The risks management strategies (insurance, resistant varieties, etc) and on field sales can be used to minimize internal fragmentation. agriculture intensification programs (inputs and labour use intensity) and off-farm employment can be suitable for reduction of land tenure fragmentation problems, while agricultural land protection policies can be suitable to prevent and reduce land tenure and size fragmentation problems. Finally, the restrictions about partible inheritance, minimum size of parcel subdivision and absentee landowners, the prevention of transfer to non-farmers and leasing suit for dealing with land tenure fragmentation, whilst the imposition of a maximum limit on the holding size suits for preventing internal physical fragmentation [4,16,18–20,30,98,120,127,144,145]. These strategies can be categorized into two groups of preventive (legal provisions and protection policies for agricultural land) to spot the root causes of fragmentation), and

mitigation (land management approaches, socio-economic and agronomic measures) to manage the impacts of an already occurred fragmentation.

Recognizing both the potential benefits and problematic situations of land fragmentation, Bentley [30] and Asiama et al. [17] suggested a specific model of land consolidation in blocks or localized land consolidation where only spatially dispersed parcels within the same microzone with homogenous soil and agroecological conditions are consolidated. This helps to conserve and give farmers access to all types of parcels in different sites with diverse microclimates and growing conditions, for both increasing the agricultural production efficiency as well as crops diversification for risks and labour management and food security purposes through food sovereignty at the local level. In this case, land consolidation does not necessarily result in a single parcel, rather in few parcels located in different sites to keep the topographical advantages of fragmentation. Likewise, Cholo et al. [41] proposed a consolidation of small parcels into larger heterogeneous plot clusters to enhance food security by exploiting synergies between agroecological adaptation practices and land fragmentation. Adversely, Ntihinyurwa et al. [33] proposed a consolidation approach which provides farmers with single contiguous farmlands or parcels that can be cultivated with multiple crops to answer the desire to meet food diversification, risks management, labour bottlenecks management as land fragmentation claims, and agriculture production efficiency by minimizing the time and travel costs as land consolidation claims. For this, there is a need for a strong objective land capability and suitability classification prior to the development of any local specific land consolidation approach. Figure 2 summarizes our findings on various documented instruments, strategies and policies to control different problematic land fragmentation scenarios.

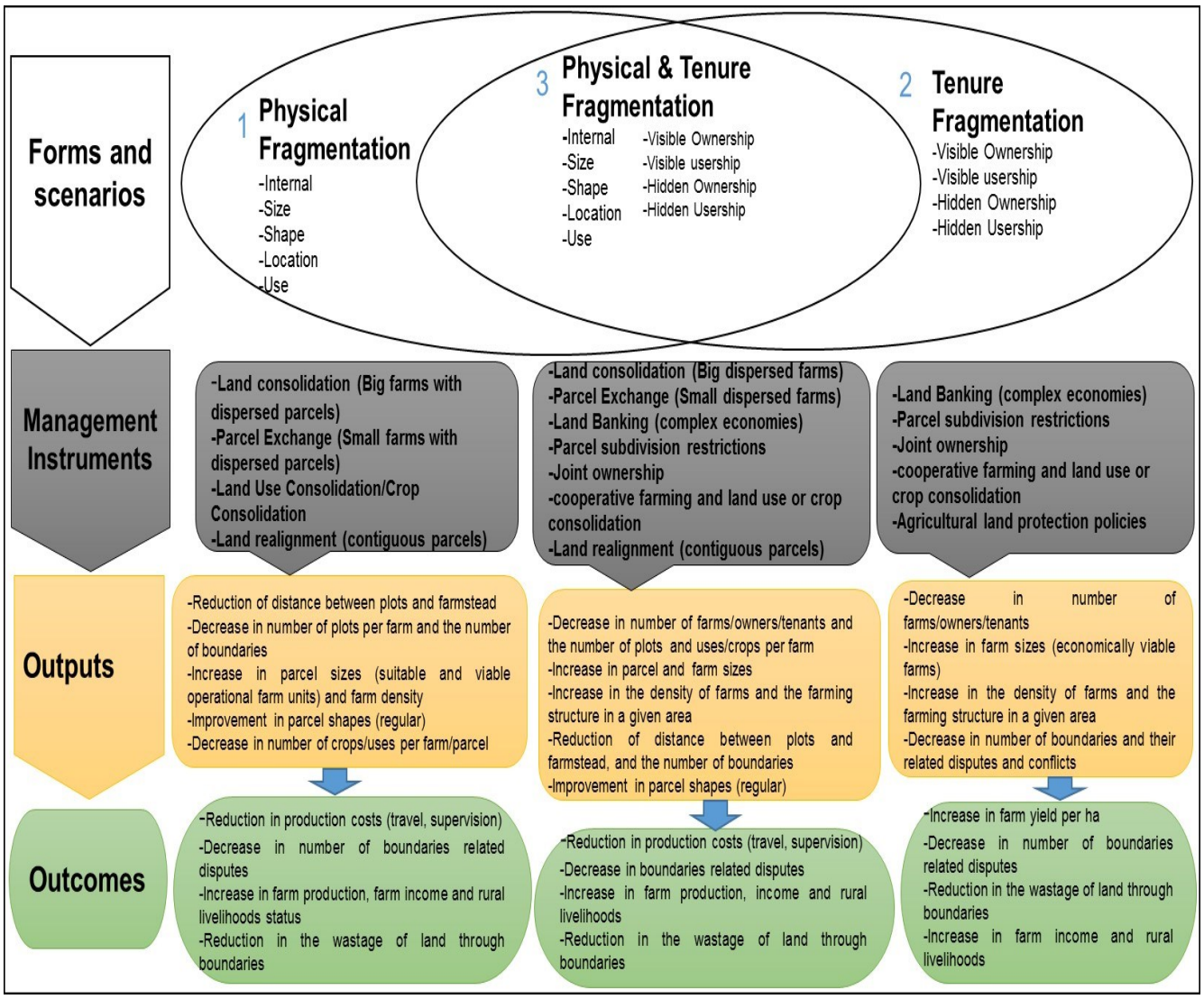

Figure 2A4. Synthesis of the problematic land fragmentation control strategies (instruments)

Source*:* Developed from the reviewed literature

In summary, both the problematic and beneficial or rational land fragmentation scenarios need a certain level of management in order to optimize the income from agriculture. However, the complexity of this phenomenon makes it difficult to choose the suitable instruments (strategies) for specific circumstances, which calls for trade-offs among different alternatives and their right combinations under various local conditions. For this, the analysed literature has on one hand revealed that the problems related to *physical land fragmentation* (internal, location or distance, shape, use, plot or parcel size and boundaries) can be minimized by land consolidation for large heterogeneous farms (under complex strong economies), voluntary parcel exchange and on-field harvest sales for small heterogeneous farms (under moderate and subsistence economies), land realignment for homogenous farms (contiguous plots) to eliminate and reorganize boundaries, and land use consolidation or crop consolidation for multiple uses on small plots and farms. *Land tenure fragmentation* problems (ownership, usership, small farm sizes, and boundaries) are reduced by land banking for small farms under complex strong

economies, parcel sizes subdivision and absentee owners' restrictions, joint ownership, cooperative farming, land use (crop) consolidation, and agricultural land protection policies for small farms under moderate and subsistence economies. Furthermore, the introduction of insurance systems and mechanization in agriculture, and the market perfection (for food and labour) have been used as strategies to eliminate the fundamental reasons for internal fragmentation in complex strong economies with market-oriented agriculture (use of multiple zones for production diversification, risks and labour management strategies).

On the other hand, different agriculture intensification programs such as the combined use of soil mineral and organic fertilizers and amendments, pests control measures, labour use efficiency and intensity, and high yielding and resistant crop varieties have been documented as suitable strategies to maximize the income from agriculture on fragmented plots under the beneficial or rational fragmentation, subsistence and moderate economic conditions (market imperfections) for risks management, labour schedule, production diversification and control of ownership and use related conflicts over land. In some special cases like mountainous areas, the costs of alleviating land fragmentation may far exceed its benefits [11,30]. In such cases, keeping fragmentation is more beneficial than its alleviation (ibid). Therefore, Bentley [30], Van Dijk [18], Van Dijk [21], Asiama et al. [28], Asiama et al. [17], and Ntihinyurwa and de Vries [11] suggest that any attempt to control land fragmentation should consider different local and case specific social, cultural, economic, political, environmental, and agroecological conditions of an area, and the benefit-cost analysis to guide the decisions about the suitable strategies for the sake of their success. In this regard, there is a need to develop strategies which simultaneously minimize the defective effects of fragmentation thereby optimizing or without jeopardizing its potential benefits [33,75] for food security purposes. Local agroecological approaches tailored to the needs of local peasants (farmers) should be given a key place in the management of local farmland fragmentation scenarios of subsistence communities for sustainable agriculture production, farm resilience, self-sufficiency in culturally acceptable (desirable) food production, increase in food sovereignty and the household food security motives. The next section discusses this food security concept.

4. Food Security as a Multidimensional, Multilevel and Multisource Concept

The concept of food security has been variously defined over time across different disciplines for particular interests and goals at different spatial levels and social scales. Chigbu et al. [32] and Dam Lam et al. [146] found that by the end of 2015, there were more than 200 different definitions of food security. However, despite the subjective and sometimes contradictory conceptualizations of the term, most of these definitions are oriented towards the supply of sufficient (enough) food availability (quantity of calories) at all times (stability) to meet the needs (demands) of the growing population from domestic and wild production, stocks, food imports or purchase from the markets, and food aids [32,54,147–151]. The majority of them were following the 1789 Malthusian food availability theory, stipulating the balance between the population growth and food availability (food growth rate should not be below the population growth rate) at the macro and meso spatial levels (community, regional, national, global). This tendency persisted till the introduction of Sen's theory of food entitlement in 1981 stipulating the notions of access, affordability, allocation (distribution) and utilization of food at the micro spatial levels (household and

individual) [54,64,65,68,150]. With an attempt to reconcile different conceptualizations of this term, FAO [69] from the World Food Summit (WFS) in November 1996 developed a more comprehensive widely accepted definition of food security as a status/situation: “when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life”, and vice-versa for food insecurity. The same definition was extended later in 2009 in the world summit on food security, where the four pillars (dimensions) of food availability, food accessibility, food usage (utilization) and food stability (sustainability) through which food security can be measured at both national, regional, community, household and individual levels were linked to this concept, while the nutritional dimension was added to it as an integral part [33,54,65,146–148,150–152]. With respect to the nutritional dimension, the concept implies that food and nutrition security is achieved when adequate food (in terms of quantity, quality, safety, and socio-cultural acceptability as components of food security) is available and accessible, and satisfactorily utilized by all individuals at all times to live a healthy and happy life [54,67,150,151]. This stipulates the consideration of the aspects of availability, accessibility and stability of food of acceptable quantity, quality, safety and diversity, based on the social and cultural preferences of any society or an individual at all levels [67]. Whenever one of these aspects is not met, people may suffer from hidden and visible hunger [33] and malnutrition, which negatively affect the health and livelihoods of the population. Since the aspect of availability in this definition stands for the supply of enough food of acceptable quality and quantity to broadly meet the demands of the population, it is mostly used to measure food security at the meso and macro levels (community, global and national); Whilst the accessibility and utilization entailing the capacity of individuals or households to meet their preferred food needs for an active healthy life, stand for the micro levels (household and individual). The same concept of food security highlights the chronic and the transitory food insecurity at all these levels/scales, as a result of instability of all the other aspects/pillars. The household food security is the application of this concept to the family level, where individuals within the households are the hub of concern [33,54,65,69,148,151,153].

The achievement of food security at all levels following the FAO definition is function of different factors including the economic status of the household, socio-cultural norms and values, demographic characteristics, agricultural system, education level, and environmental and agroecological characteristics of the area, to cite only few [32,33,65,69,154]. Surprisingly, the popular logic of achieving food security has over time focused on reducing the population growth through different family planning policies, and boosting agriculture production to keep the balance between the food demands of the growing population and food availability (supply) at the macro and meso levels (national, regional and community), thereby ignoring its entitlement and sovereignty at the local (household and individual) levels [46,47,54,65,68,149,155]. However, since food security is a very complex, multidimensional and multilevel concept, difficult to achieve in silos, this can only be possible if other external economic, socio-cultural, political, agroecological, and environmental factors are overlooked. Food security entails more than growing enough food, since it implies the demand for it, as well as the supply, the quality as well as quantity, diversity as well as accessibility, an adequate diet (culturally acceptable quality and quantity) today and assurance of one tomorrow [11,32,33,54,65,67–69,148,150,153]. It has the aspects of quality, access/affordability, acceptability, utilization/usage and stability/sustainability which can only be achieved

when everyone in the household has access to regular, safe, nutritious and enough acceptable food to meet his/her food preferences [11,32,33,65,68,69,150]. Therefore, in the existing critical context of the ever growing fluctuations in climate and food prices which directly affect the household's food acquisition (domestic and wild agriculture and animal production, purchase, aids, and imports) and allocation (distribution and usage), and food safety concerns, the achievement of food security at the micro levels requires the change of food production paradigms. This needs the shift from the mass food production systems through conventional agriculture and monoculture, and consumption patterns prioritizing the quantity and availability, towards more diversified and locally produced food stuffs through sustainable, climate or natural risks resilient and smart agriculture systems, following various agroecological approaches including the polyculture (growing wide diversity of food crops in space and time) [11,32,33,37,41,45–48,71,156,157]. This can help to sustainably meet the cultural dietary needs and food preferences of acceptable quantity, quality and safety for all local people, as the suitable method of achieving food sovereignty, an adaptation strategy to the existing climate change realities for ending hunger and malnutrition, and local approach of meeting food security stipulated by many policy initiatives and goals like the SDGs 1.4; 2.1,2,3,4,5; 12.2; 13 & 15.3,4,5,9 [11,32,37,38,41,46–48,71,141,155,157–165].

Being the main factor of food production in many countries, the agriculture production of enough staple food crops as the basic component of food systems for food security (food supply side) requires the focus on agriculture intensification of small scale farms or agro-ecological strategies on fragmented land, and agriculture expansion of large scale farms on consolidated land, to meet the local needs and food preferences of the growing population. Recent studies and social movements advocate for the achievement of local food security by focusing on the concept of food sovereignty, which stipulates the self-sufficiency and autonomy in food production by local small scale farmers through various agro-ecological methods and agricultural systems tailored to their needs, knowledge, cultural values and traditions, and other particular circumstances [46–48,155,165]. Nonetheless, this does not alone guarantee the complete solution to the problem of food insecurity, since other aspects like food utilization and food market entail more than that [32,65,150]. The evidence has shown that food insecurity may exist in cases of high availability and accessibility of food in sufficient quality and quantity, mainly due to the lack of knowledge about the right preparation and combination of balanced nutritional diets, and the basic health and hygienic services like clean water (ibid). To this end, one needs to focus on a holistic and careful assessment of food security status, by considering all its underpinning factors at all levels. Figure 3 summarizes these various factors of food security.

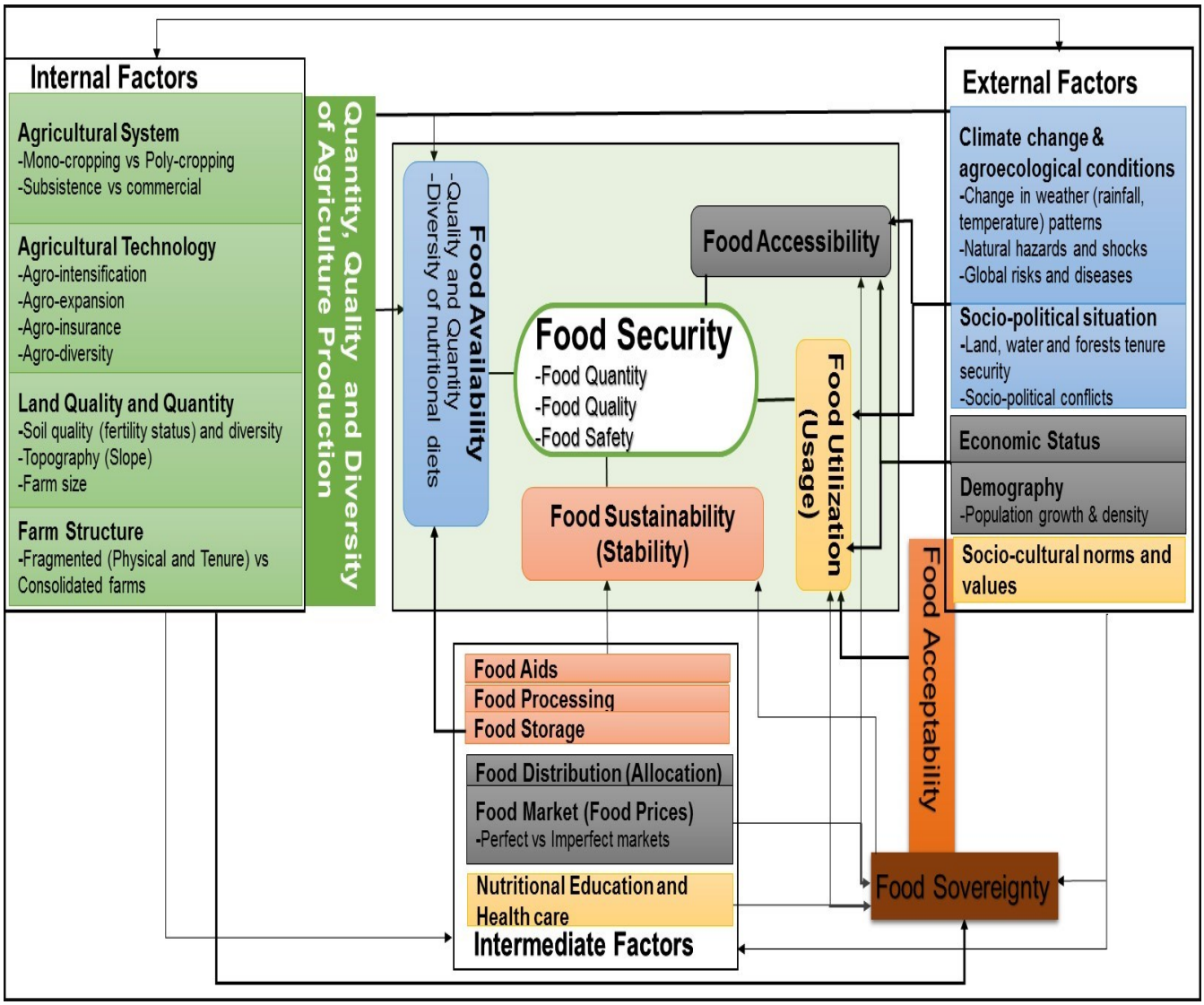

Figure 3A4. The multidimensionality of food security as influenced by internal and external factors

Source*:* Developed from the reviewed literature

As Figure 3 summarizes, food security as a multidimensional and multilevel concept cannot only be achieved by a single instrument. It requires a holistic approach which considers the contributions of different factors at different levels of analysis to create food systems that offer the possibilities to meet the availability of qualitatively and quantitatively acceptable food in a given area, accessible (affordable) to all people, with the best and balanced combinations (utilization) to meet the nutritional diets/needs and food preferences of the ever growing population at the regular basis (sustainability/stability) with scarce resources or production factors (land and capital) for an active and healthier life. Considering the growing challenges of climate change and other natural shocks from food production side, an attention should be focused on the trade-offs between the role of some agro-ecological principles like crops diversity on food stuffs diversification as a source of qualitative, sustainable, acceptable and resilient food systems on one hand, and the quantity of agriculture production to meet the food needs and demands of the growing

population irrespective of its quality on the other hand, on either fragmented or consolidated land parcels at the local levels (community, village, household and individual) [11]. The growing tendency is that poor people are choosing to compromise to food quality and quantity aspects for the benefit of food stability in case of shortages of food availability and accessibility as a result of climate change and price fluctuations realities, by creating more sustainable resilient farms through local agroecological farming systems [46,47,156]. The next section establishes the relationship among farmland fragmentation, farmland consolidation and food security concepts.

5. Farmland Fragmentation, Farmland Consolidation and Food Security Nexuses: Relationships, Overlaps, Research Gaps and Future Perspectives

5.1. Relationships, Overlaps and Research Gaps

Farmland fragmentation and farmland consolidation are two interlinked concepts theoretically considered as instruments of agricultural land management for food security purposes [11,33,51]. In this vein, regardless of the fragmentation or consolidation statuses and scenarions, the farmland remains a fundamental asset for food security [33]. However, while there is enough empirical evidence and substantial literature about the relationship amid land fragmentation, land consolidation, land productivity, agricultural production, and farm profitability and efficiency, only few disaggregated studies address the linkages between farmland fragmentation, farmland consolidation and food security. Furthermore, from our critical review, there is a lack of comprehensive studies that have documented the linkages between the two concepts and food security as a multidimensional, multilevel, and multisource concept. Therefore, this section builds on the existing disaggregated studies about these three concepts and adopts the conceptual reasoning approach which follows the rationalist theory to fill this litterature and knowledge gap through the analysis of different related theoretical connotations.

Foremost, a large category of studies shows the physical land fragmentation (internal, location, shape, use) as a defective phenomenon, and a major threat to agriculture production, farm productivity and profitability, by hampering farm efficiency and the economies of scale, thereby positing land consolidation approaches as a panacea to this problem [2,3,6–8,10,12,14,29,52,66,89,90,105,107,118,166–174]. These studies broadly argue that farming on small scattered and irregularly shaped plots increases the travel and supervision costs due to long distances between parcels and the household, which reduces the yield per hectare, farm profitability, and abandonment of farming activities on very distant parcels in some cases. Furthermore, regardless of the distance and adjacency of parcels, land tenure fragmentation leads to small farms with small non-economically viable land units, which in turn hinders the economies of scale, since the mechanization and expansion of market-oriented agriculture is not tenable on such units [4]. This reduces the quantity of agricultural production and food availability or supply in a given area as a pillar of food security. Therefore, the majority of these studies propose land consolidation as the appropriate solution to these issues. They back this position by showing how consolidated and compact big farms with larger farm units and parcels or plots decrease the agriculture production costs and increase the yields per hectare and farm profits as the key characteristics of the economies of scale, which in consequence positively impacts on the supply (availability) and sustainability of enough quantity of food to meet the food demands

of the population for food security in a given area. For Lerman and Cimpoieş [118], big consolidated farms offer higher agriculture production and econimic performance than small fragmented ones, which incresases the food security status and the well-being of the rural population. From the proponents of this view, the quantity of agriculture production of food crops matters most, in order to satisfy the food demands of the growing population following the Malthusian theory of population growth and food availability or supply of 1798 [54] and fill the gap stipulated by the reverse relationship between the population growth and the limited food productive capacity of land resources in this theory. Likewise, this claim is shared by the advocates of other alternative strategies like land banking, cooperative farming, and joint ownership against the tenure or size fragmentation of farmland. They tend to believe that food security of the growing population can be met by producing enough quantity of food crops through agriculture mechanization and the economies of scale, which can only be achieved on consolidated or big farms [21,106,109,125,127,136,175].

Nevertheless, different studies have criticized some farmland consolidation approaches to lead to the establishment of monoculture systems which result in production of single or few types of food stuffs, thereby negatively affecting food diversity and balanced nutritional diets and inducing food insecurity [30,31,37,38,176,177]. This is the case of Land Use Consolidation program in Rwanda, criticised of worsening food insecurity issues by promoting the monoculture system at the expense of multicultural one and its irreplaceable adaptive benefits, through the reduction of agriculture production diversification as a source of food diversity aspect at the household level, despite its major outcomes in terms of boosting the national production of 8 priority crops grown in this program [24,27,32–34,119,121–123,137,178]. These studies posit that the availability of enough quantity of food of some priority crops at the national level through LUC does not necessarily mean that the needs and food preferences of households members are met, while the practical evidence has revealed the increase in households vulnerability to food insecurity since the introduction of this program in 2008 (ibid). Combined with the consequences of climate change (droughts and floods from changes in rainfall patterns) and imperfect food market, this LUC program has been pointed out to worsen the problem of food insecurity at the household and individual levels, by reducing its quality, accessibility, acceptability, and sustainability aspects in some parts of the country [32,33].

Despite these findings, the debates over what to do with farmland fragmentation, farmland consolidation and food security have often been disassociated from those related to climate change and agroecology, and only linked with agriculture production, due to the presumed negative impacts of farmland fragmentation by policy makers. Following the multidimensional nature of food security, the prevalent justification for land consolidation is that it increases the farm size and reduces the producion costs associated with the distance, and thus contributes to food security given higher quantities in food production from food crops. Nonetheless, this logic makes sense when food security is viewed from the lens of quantity, since food security is much more than the quantity of food. It includes the aspects of diversity, quality, access, sustainability, acceptability and utilization of food [64,65,69] along with food sovereignty [46,47,155], which are also achievable under the conditions of land fragmentation scenarios [11,32,33,66].

Therefore, a different category of studies witnesses the evidence of positive relationships between physical farmland fragmentation and food security. These studies argue that physical farmland fragmentation contributes to the improvement of the aspects of food quality through the diversity of nutritional diets, and the regular (sustainable) availability and accessibility of food at the household and individual levels under the conditions of subsistence economy, climate and food prices fluctuations, and vice versa for farmland consolidation [11,30–34,37,38,41,42,50,57,94,122,141,157,176,177,179,180]. These advocates of this standpoint commonly argue that farming on spatially and topographically fragmented and dispersed parcels with irregular shapes offers farmers the possibilities to grow a wide range of diverse crops in areas with different crops suitabilities and growing conditions for the purposes of food stuffs diversity production, farm resiliency, and the management of risks of climate change and food prices fluctuations. This in turn increases food diversity, quality, accessibility, acceptabiliy, and sustainability of subsistence households, thereby inducing the likelihood of meeting food sovereignty and food security at the local levels [11,46], following the economies of scope, resilience, agroecology, and complexity theories. In the same vein, Blarel et al. [31], Alexandri et al. [179], Ciaian et al. [37], Cholo et al. [41], Knippenberg et al. [45], Ntihinyurwa et al. [33], and Ntihinyurwa and de Vries [11] advance that farmland fragmentation leads to the cultivation of diversified food crops and the production of a diversity of food basket for self-sufficiency of subsistence farmers in order to meet their nutritional demands and food security at cheap prices, as the cheapest strategy to achieve the household food security under the circumstances of climate change, land scarcity and food market imperfections. This claim coincides with the advocates of agroecology and food sovereignty, which posit the achievement of food security at the local levels through self-sufficiency and autonomy in food production tailored to the needs of cultural and traditional diets of local subsistence farmers using various local agroecological methods (temporal and spatial crops diversification through polycultures, and the knowledge of local peasants) on more resilient small scale farms [46–48,70,155,165]. The collective of these studies stipulates that, the more the differences and high diversity or heterogeneity in land and soil qualities; the higher the variety of soil-crop suitability classes and production potentials; the higher the crops diversification (agrodiversity), farm resiliency and food stuffs diversity; the higher the self-sufficiency in food production, the higher the nutritional balance; the higher the food quality and sustainability; the higher the food acceptability and sovereignty; the higher the food security [33]. Furthermore, contrary to the principles of the economies of scale theory, the proponents of this view counter argue that land tenure or size fragmentation (small farm sizes) backs the diseconomies of scale theory stipulating the inverse farm size and agriculture production relationships, following the Boserup's theory of population growth and agriculture intensification of 1965, probably due to imperfections in labour market in subsistence economies, and the growth of technology in agriculture [31,49,50,63,181,182]. This implies that the intensification of agriculture leads to better outputs in terms of agricultural production on small farms than on bigger ones, which directly impacts on food availability (quantity and quality). TWN and SOCLA [155] argue that small farms are more productive than large farms, if the total output is considered rather than yields from a single crop. Nevertheless, this Boserup's theory stipulating the proportional relationship between the population growth and agriculture intensification [11,63] has shown its limitation at a certain critical threshold of very high population density, thereby giving a reason to the Malthusian theory in such circumstances [55,56].

However, in case the consolidation practices offer to farmers the options of growing multiple crops on consolidated plots (voluntary land consolidation models), and the provision of agricultural insurance services and resistant crop varieties, there are no more reasons for keeping fragmentation. Such consolidated parcels lead to high agriculture production of diverse crops, which in turn results in the regular and adequate availability and accessibility of food of acceptable quality and quantity, thereby contributing to the improvements in household food security [4,16,30,111,157]. Moreover, comprehensive land consolidation models may integrate some specific programs of food processing, food storage and nutritional education to contribute to the improvement in food quality through more balanced nutritional diets and food accessibility and stability aspects as a support to food availability, to meet the household food security in its multidimensional conceptualization [4,16]. Besides the effects of farmland fragmentation and consolidation strategies on food security, the status of the latter may also determine the kind of decision about the fragmentation management approaches. Since the primary objective of consolidation approaches is to increase the food security status by sustaining food availability (supply) to meet the food demands of the growing population through agriculture production, these approaches may not be necessary in case of the lack of food insecurity problems in a given area (when food security already exist under fragmentation scenarios of big farms) [4,18,21,30,31,37,38,41,50]. This is the case of countries with abundant land and low population densities like the USA, Russia, Canada and many others.

Finally, the critical review has drawn the reciprocal relationship between farmland fragmentation and farmland consolidation concepts. Farmland fragmentation is documented as a precondition and milestone for an establishment of any farmland consolidation program in a given area [4,12,18,19,98], and exists in an area which was previously consolidated according to the Gestalt theory of a whole [53]. Notwithstanding their reverse theoretical meanings, the two concepts share the same practical measurement indicators (see Ntihinyurwa and de Vries [75] for more details). Figure 4 summarizes the theoretical relationships between farmland fragmentation, farmland consolidation and food security. These relational linkages in literature lay a foundation for a theoretical model which could be adapted or used by scholars for building frameworks on the subject (Figure 4).

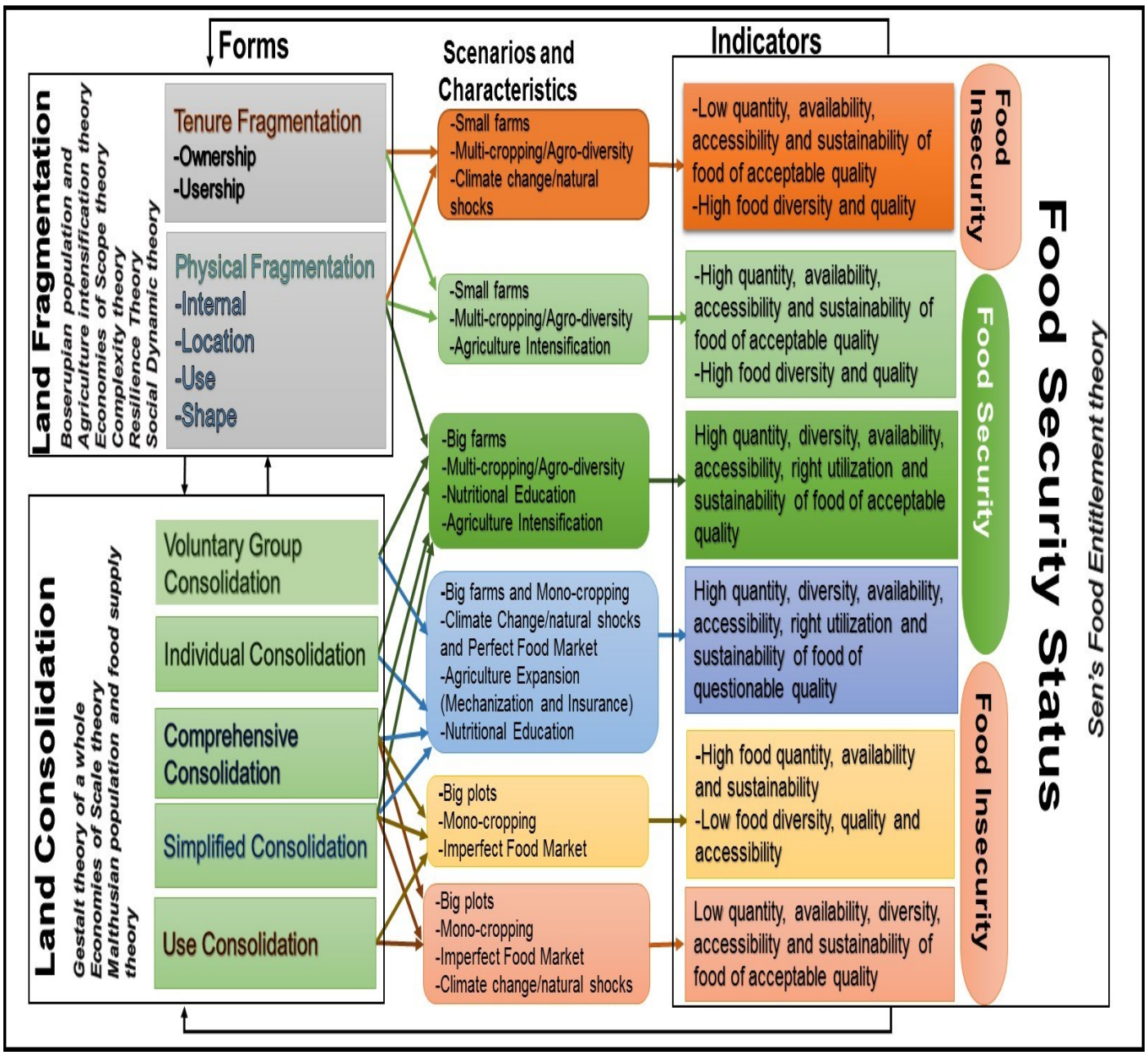

Figure 4A4. Theoretical relationships between farmland fragmentation, farmland consolidation and food security

Source*:* Developed from the reviewed literature

Simply put, Figure 4 shows that any farmland fragmentation and consolidation scenario which engages the multi-cropping system (agroecological approach) and agricultural intensification, food processing and storage, and nutritional education programs may lead to the achievement of food security at the household level, except in cases of lack of those intensification programs on small non-resilient farms. On the other hand, the consolidation programs implying the mono-cropping systems are susceptible to lead to food insecurity status through malnutrition (under and/or over nutrition), especially when combined with external factors like market imperfections, climate change, natural shocks, and the

absence of the above-mentioned supporting programs. In this respect, the concepts of farmland fragmentation, farmland consolidation and food security are interlinked. The type of this interlinkage is determined by external factors like climate change, socio-economic status, agrobiodiversity (agroecology), demographic aspects, and land characteristics. Therefore, for the purpose of achieving the sustainable development goals (SDGs 1,2,12,13 and 15) stipulating the attainment of the multidimensional food security through sustainable (climate resilient) land management strategies (see Paragraph 6 of Section 1 for specific targets), any attempt to achieve food security through agricultural production should consider the importance of all the above-mentioned factors at the local levels for its success.

5.2. Reconceptualization of Farmland Fragmentation Management for Food Security

Recognizing the complexity, polarity and multidimensional nature of farmland fragmentation and food security concepts, there is a need to develop the local context specific and progressive farmland fragmentation management strategies, which consider both its defective and beneficial sides following the dynamic systems theory [84–86] and agro-ecological approaches (elements, principles, and methods) [47,48,155,165], rather than focusing on the blind subjective and irrelevant decisions of either defragmentation through different consolidation programs for food quantity and availability, or fragmentation conservation for food quality, accessibility, sustainability, acceptability and sovereignty purposes. Since our critical review of the literature has shown that both the defective and beneficial fragmentation forms may coexist in the same area, the identification of those forms, their causes and impacts, and assessment of the local social, cultural, economic, political, biophysical, agro-ecological and environmental conditions in a given area along with the benefits-costs analysis prior to any decision, would give an insight on the suitable combinations of strategies. This would further serve as an important guidance to policy makers and research scholars, and the best approach for the optimum management of this phenomenon. This position is theoretically and empirically supported by previous studies of Bentley [30], Van Dijk [18], Van Dijk [21], Asiama et al. [28], Asiama et al. [17], Ntihinyurwa and de Vries [11], and Ntihinyurwa and de Vries [75] in Sub-Saharan Africa and Europe. Being progressive, flexible and fit for specific situations and scenarios, this approach can accommodate different emerging solutions to new problematical situations, under the dynamic climate change realities and changes in local conditions in a given area. Building from this approach, we propose the following conceptual model for farmland fragmentation management in Figure 5 to refresh the existing sporadic and outdated conceptualizations about the management of this phenomenon, considering the major global threats of climate change, natural shocks, population growth, and urbanization. The model implicitly shows when, where, how and why one could opt for defragmentation or fragmentation conservation, through the hypothetical relationship between various farmland fragmentation scenarios [11,75], the proposed suitable management strategies or solutions, and food security and the general livelihoods of the rural (local) farming population. It results from a combination of variance and process models through abstract modelling techniques and the deductive logic conceptual reasoning approach [72–74,77,87]. After being empirically tested in different local areas, the outcomes from this model will be translated into suggestions for farmland fragmentation management strategic options under different specific local conditions.

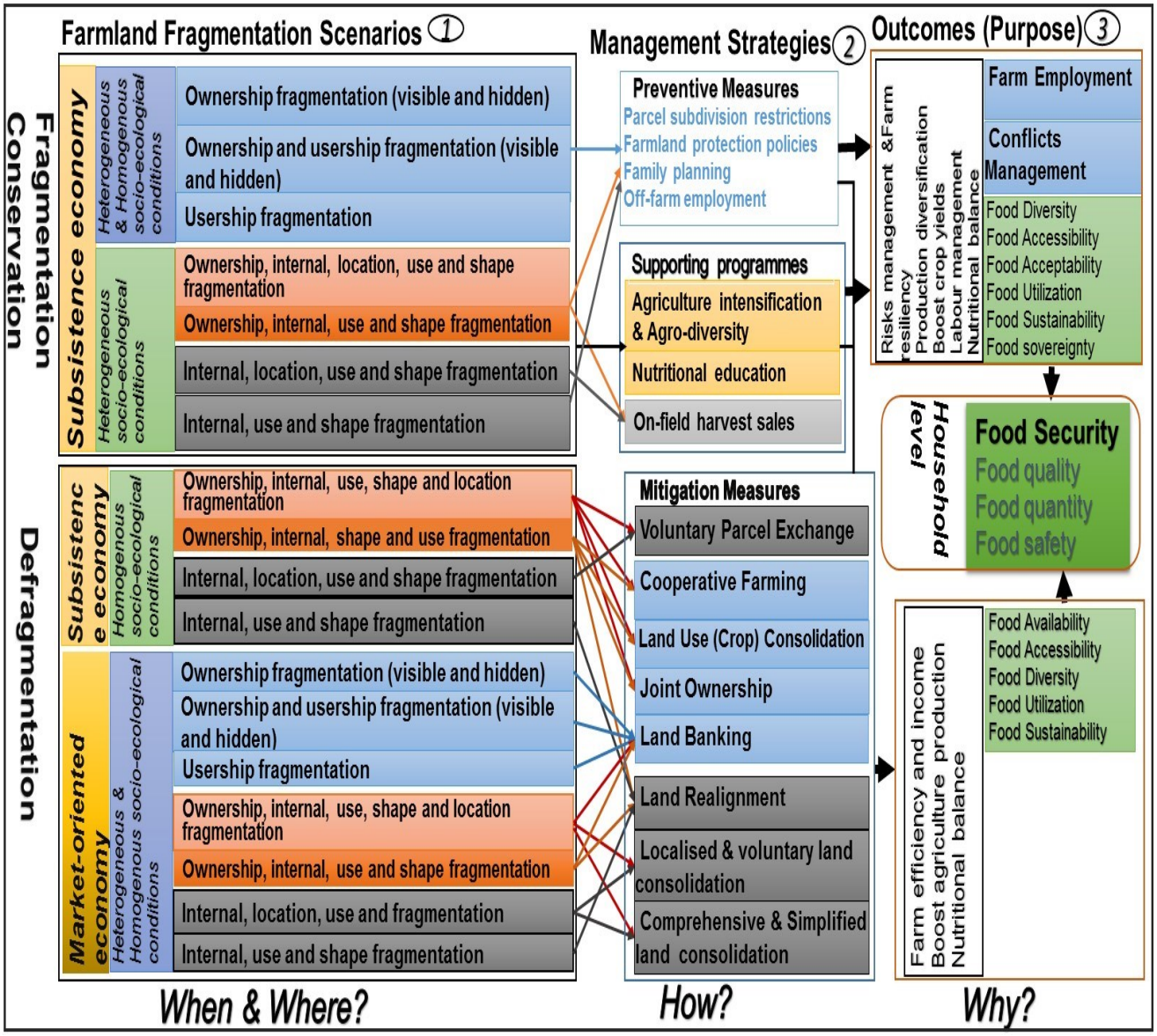

Figure 5A4. Farmland Fragmentation Management Conceptual Model

Source: Developed from the reviewed literature and the logic conceptual reasoning and modelling [11,73–75,77,81,87]

For the sake of optimizing the income from agriculture and meeting food security, both the problematic and rational farmland fragmentation scenarios need a certain level of management. In this regard, as Figure 5 shows, the problems related to *Physical Farmland Fragmentation* (internal, location or distance, shape, use, small parcel and plot sizes, and boundaries) can be minimized by farmland consolidation in case of large heterogeneous farms (under complex strong or market-oriented economies); voluntary parcel exchange and on-field harvest sales in case of small heterogeneous and homogenous farms (under moderate and subsistence economies); land realignment in case of homogenous farms (contiguous plots) to eliminate and reorganize the boundaries; and farmland use consolidation or crop consolidation in case of multiple agricultural uses on small plots and farms. On the

other hand, *Farmland Tenure Fragmentation* problems (ownership, usership, small farm sizes, and boundaries) can be reduced by land banking and off-farm employment in case of small farms under complex strong or market-oriented economies; restrictions about the parcel sizes subdivision and absentee owners, joint ownership, cooperative farming, farmland use (crop) consolidation, and agricultural land protection policies in case of small farms under moderate and subsistence economies. Furthermore, to prevent the worsening of the tenure fragmentation situation, where possible, the combination of these strategies with strong family planning measures that curb the population growth following the Malthusian theory of population and food supply, could generate good results [54–56].

Considering the coexistence of both rational and defective fragmentation in the same area, there is a need to develop strategies that simultaneously minimize the negative effects of fragmentation thereby optimizing or without jeopardizing its potential benefits. To this end, the following specific consolidation models suggested by different researchers would apply in different specific cases after a careful benefits-costs analysis:

❖ *Land consolidation in blocks or localized land consolidation***:** This model is suggested by Bentley [30] and Asiama et al. [17] in areas where only spatially dispersed parcels within the same micro-zone characterized by homogenous soil and ecological conditions are consolidated. This helps to conserve and give farmers access to all types of parcels in different sites with diverse microclimates and growing conditions, for both increase in agricultural production efficiency as well as crops diversification for risks and labour management, and food security purposes. In this case, land consolidation does not necessarily result in a single big parcel, rather in few big and medium size parcels located in different sites to keep the topographical advantages of fragmentation. This would apply to cases of physical (internal) fragmentation under subsistence and developing (middle-income) economies characterized by high heterogeneity of agroecological conditions. This fits with the consolidation model of small topographically dispersed parcels into larger heterogeneous plot clusters proposed by Cholo et al. [41] to enhance food security through the exploitation of synergies between adaptation practices and farmland fragmentation in Ethiopia. The voluntary group, simplified and individual land consolidation models, and voluntary parcel exchange strategies would also apply to this case.

❖ *Multicropping-based land consolidation approach***:** Suggested by Bentley [30] and Ntihinyurwa et al. [33], this model provides farmers with single contiguous farmland parcels which can be cultivated with multiple crops to answer the desire for food diversification, production risks and labour bottlenecks management as farmland fragmentation claims on one hand, and agriculture production efficiency by minimizing the time and travel costs as farmland consolidation claims on the other hand. This applies to the cases of small parcels spatially scattered in the same topography with quite homogenous agroecological conditions, in both subsistence and strong economies for both food quantity and diversity (quality) purposes. The comprehensive, simplified and voluntary land consolidation models, along with land banking programs would also fit for this case, if farmers fully enjoy the use rights over their lands.

The success of these specific models requires a strong objective land capability and suitability classification prior to their development, based on a functional soil information system (SIS), which lacks in many developing and underdeveloped countries. Moreover, drawing from the study of Chigbu et al.

[32] on tenure and food security responsive land use consolidation in Rwanda, the consolidation of land for agriculture expansion through market-oriented and monoculture based systems in more homogenous areas with less variability in agro-ecological, physical (soil, slope, water, etc), socio-economic, cultural, and climatic conditions for food quantity and availability; and the conservation of multiculture based systems on either consolidated or fragmented land in more heterogeneous conditions through various agroecological approaches as a risk management strategy, climate change resilience and adaptation strategy, and food crops diversification for food diversity and quality, accessibility and sustainability, cultural acceptability and sovereignty, could offer optimal solutions to farmland fragmentation and food insecurity problems.

In developed countries characterized by complex strong economies with market-oriented agriculture and perfect food, land and labour market, the fundamental reasons for internal fragmentation conservation (use of multiple zones for production diversification, production risks management, and labour management strategies) are always removed and compensated by the introduction of insurance systems and mechanization programs in agriculture [18,30,98]. In this case, keeping fragmentation would be useless. In contrast, different agriculture intensification and agroecological programs including the combined use of soil mineral and organic fertilizers and amendments, pests control measures, labour use efficiency and intensity, crops diversity, and high yielding and resistant crop varieties could be the most suitable strategies to maximize the income from agriculture on fragmented plots under the circumstances of beneficial fragmentation in subsistence and moderate economies characterized by high population densities and market imperfections. This can offer the benefits of risks management, labour schedule, agriculture production diversification, and control of land ownership and use related conflicts, thereby by increasing food sovereignty and the local (household and individual) food security, following the Boserup's theory of 1965 on population growth and agriculture intensification [63] below a certain critical threshold. This has empirically been evidenced by various studies in different countries [30,31,33,37,41,50,55,56,94,155]. Furthermore, in some particular cases like mountainous areas under subsistence economies where the costs of alleviating farmland fragmentation outweigh its benefits, keeping fragmentation would be more beneficial than its alleviation [11,30].

6. Conclusions

In the context of contrasting advocacies for farmland fragmentation, farmland consolidation, farmland use consolidation and food security nexuses, this study extends the discourse by explicitly and comprehensively displaying different conditions under which and how one could choose between farmland fragmentation conservation and defragmentation (consolidation) policies or both, as responsible farmland management tools to achieve food security. With logical reasoning, the study critically analysed different documented farmland fragmentation scenarios, their problematical (defective) and rational (beneficial) situations under different circumstances, and proposed their suitable specific management models to achieve the multidimensional food security at the micro levels (household and individual) as a new contribution to the knowledge in the field of farmland management.

In contrast to the dominant standpoint of the current literature, this study reveals that both farmland fragmentation and farmland consolidation impact on food security in different ways at different levels.

Therefore, for the purposes of achieving food availability, accessibility and sustainability for food security at all levels, the defragmentation process to minimize the problems related to physical farmland fragmentation (internal, location or distance, shape, use, small plot sizes and boundaries) can take the form of farmland consolidation for large heterogeneous farms under complex strong or market-oriented economies with high land availability; voluntary parcel exchange and on-field harvest sales for small heterogeneous farms under moderate and subsistence economies with land scarcity; land realignment for homogenous farms with contiguous plots to eliminate and reorganize the boundaries; and farmland use consolidation or crop consolidation for multiple uses on small plots and farms. Similarly, farmland tenure fragmentation problems (ownership and usership, small farm sizes and boundaries) can be prevented and minimized by land banking for small farms under complex strong economies; restrictions about the parcel sizes subdivision and absentee owners, joint ownership, cooperative farming, farmland use (crop) consolidation, agricultural land protection policies, and family planning measures (to curb the population growth) in the case of small farms under moderate and subsistence economies. This hypothetical stance is backed by the Malthusian theory of population and food supply, economies of scale and Gestalt theories, which commonly advocate in favour of agriculture expansion on bigger consolidated farms than on fragmented ones. On the other hand, for the purposes of food diversity, quality, accessibility, independency, acceptability, sovereignty, and sustainability for food security, different agriculture intensification and agroecological programs, and other land saving technologies could be the most suitable strategies to maximize the income from agriculture on fragmented plots under the circumstances of beneficial fragmentation in subsistence and moderate economies characterized by high population densities, market imperfections and land scarcity. These include the combined use of soil mineral and organic fertilizers and amendments, crops diversification, pests control measures, labour use efficiency and intensity, and resistant and high yielding crop varieties. This position is supported by the Boserup's theory on population growth and agriculture intensification below a certain critical threshold. In case of the coexistence of both rational and defective fragmentation scenarios in an area, various specific strategies which could simultaneously minimize the defective effects of fragmentation thereby optimizing or without jeopardizing its potential benefits can give better and more balanced or optimal solutions. These include land consolidation in blocks or localized land consolidation models for internally fragmented subsistence farms with plots spatially scattered in different heterogeneous topographies, and multicropping-based land consolidation approaches for fragmented farms with parcels spatially dispersed in homogenous topography, in combination with or without agriculture intensification programs.

In order to empirically test and evaluate how farmland fragmentation can be best managed for food security motives, prior to the design of any policy and strategy in favour of either farmland fragmentation conservation or defragmentation (consolidation) or both as land management tools, this study recommends the identification of all the possible farmland fragmentation scenarios (forms, causes, and their positive and negative impacts) in a given area, and the conditions dictating their problematic and beneficial status quos. In this line, for the sake of assessing the problematic and rational farmland fragmentation forms and scenarios under distinctive local circumstances, a rigorous feasibility study should be conducted, before the development of their suitable, flexible (dynamic), desirable, climate

resilient, sustainable, feasible and multidimensional food security responsive coping strategies, policies and interventions at the household and individual levels. Instead of the existing focus on food productivity at the community, regional and national levels, the efforts should be oriented towards the improvement of food security status at the household and individual levels and the consideration of agro-ecological approaches in local food production on either fragmented or consolidated land. Therefore, further research should focus on the scrutiny and the development of more detailed and comprehensive indicators which can facilitate the trade-offs between farmland fragmentation conservation and defragmentation policies and interventions for food security motives under various particular local contexts.

The novel insights of this study can inform and guide policy makers, research scholars and the general scientific community for the devise of the suitable policies, interventions, tools and strategies for the best management of local farmland fragmentation scenarios. Moreover, contrary to the existing popular and global logic favouring the market-oriented agriculture often combined with agriculture expansion on big consolidated farms to achieve food security, this novel knowledge about the necessity of the variety of farmland management instruments to address particular farmland fragmentation scenarios contributes to the achievement of the sustainable development goals (SDGs 1.4; 2.1,2,3,4 and 5; 12.2; 13.1; and 15.3,4,5 and 9) of ending hunger, malnutrition, and poverty in the framework of the agenda 2030. As stipulated by these SDGs specific targets, this can be possible through the diversification of crops in diverse fragmented and scattered areas with various crop-growing conditions; equal distribution, ownership, access and control, sustainable management and efficient use of land resources; and agrobiodiversity and ecosystems conservation on land as an adaptive strategy to the global climate change realities and challenges (through climate smart or resilient agriculture), often combined with agriculture intensification programs to increase the agriculture production of small farms (see Paragraph 6 of Section 1 for these specific SDGs targets), for food sovereignty and the household food security motives.

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