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Economic approaches to sustainable land use in Ecuador:

Compensation payments and diversification on areas of profitable intensive farming

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"Earth provides enough to satisfy every man's needs, but not every man's greed"

Mahatma Gandhi

Abstract

Decision making constitutes one of the most important topics concerning land-use planning and resource allocation. Nevertheless, people often make choices without having enough information about the future. Analysis and consideration of uncertainty applied to land-use issues turns out to be a valuable tool to predict how the variation of parameters might affect the performance of a system. At the farm level, it enables to test the effect of alternative technologies and policies before its implementation. It is also a useful tool to include land owners' preferences. This aspect is of great importance considering the encroaching of farming land at the expense of forest and other natural ecosystems. The high profitability of cash crops has exacerbated the adverse effects of land-use change; however, landowners should be cautious about making investments based solely on the expected revenues. Risk analysis, for instance, offers interesting insights for long term planning. Bearing in mind this aspect, the present work investigates whether the application of appropriate economic approaches may lead to modified patterns of land allocation, provided that farmers' preferences and uncertainty of land-use options have adequately been addressed in land-use models.

In a first paper, decision making under uncertainty was applied to calculate compensation payments for farmers growing environmentally desirable shade coffee to prevent conversion towards maize, the most profitable alternative in southwest Ecuador. Two approaches were selected for this analysis: Stochastic Dominance which makes only few assumptions about farmers´ preferences and Mean-Variance which assumes risk aversion. The inclusion of all or at least many of the investor´s utility functions, as an important feature of stochastic dominance led to very high compensations, at least twice the amount calculated by the alternative method which maximizes a concave utility function. It is important to note that the comparison considered both options as mutually exclusive in a first step. However, seeing alternatives as mutually exclusive was not the best approach to address farmers´ issues, given that they are risk averse. To find more cost-efficient compensation payments, the effects of land-use diversification were tested by allowing for shade coffee on part of a landholding, and maize on what remains. For calculating the optimal share of shade coffee and maize, land use portfolios were calculated considering two types of aversion towards risk- moderate and strong risk aversion. Based on a concave utility function, the optimal portfolio for moderately risk-averse farmers consisted of 27% of shade coffee and 73% of maize. A larger share of shade coffee was the best option for strongly risk-averse farmers, because this option holds less risk - 51% and 49% maize. An implicit conservation of biodiversity rich shade coffee areas was a result of economic diversification, which is used as a hedge against risks. As a consequence, policy should

only carefully subsidize farmers to not push the need for diversification aside. Given that optimal portfolios were to a large extent dominated by maize, compensation was required to increase the share of shade coffee. The amount of compensation needed to achieve 75% of shade coffee was always lower than for that derived under the assumption of mutually exclusive land uses. Thus, stimulating diversification may help to significantly reduce compensation payments necessary to preserve less profitable agroforestry options.

In a second paper, organic farming as a more environmentally friendly form of land use than conventional agriculture was assessed as part of optimal land-use portfolios in the lowlands of Ecuador, an area dominated by highly profitable conventional farming. The main issue was assessing whether or not organic banana could be part of economic land-use portfolios. The results demonstrated that acceptance of organic banana is strongly driven by its economic uncertainty. Two levels of risk for organic banana were modelled, the first one using the same price volatility as for conventional banana and second one based on more realistic, lower price volatility for organic products. As a result, organic banana was included in land-use portfolios for almost every level of accepted risk with proportions from 1% to maximally 32%, despite a very high simulated risk. A lower simulated uncertainty of organic banana's economic returns increased their proportion substantially to up to 57% and increased annual economic returns. An assumed integration of conventional and organic markets, simulated by an increased coefficient of correlation of revenues (ρ up to= +0.7) demonstrated that the proportion of banana is significant dependent on price volatility, only if price risks is low organic banana is included, in land-use portfolios. As historic data support a low price risk for organic banana, landowners should consider this land-use option in their land-use portfolios as a strategy to buffer risks.

Based on the experiences with two bio-economic land-use models, a third paper addresses the advantages and shortcomings of bio-economic models applied to land-use issues in a literature review, by analyzing the inclusion of four important aspects such as uncertainty, time, system dynamics and multiple objective functions from a list of relevant papers. The progress of mathematical programming has made it possible to improve the performance of land-use models; however, none of the models analyzed throughout this research included the four aspects simultaneously. Uncertainty was seldom integrated to modelling, in those cases where it was incorporated; stochastic approaches were more frequent than non-stochastic robust methods. Despite multiple objectives have recently been integrated into land-use optimization, it is evident that a solid combination between multiple-objective approaches and uncertainty consideration is often lacking. Similarly, static approaches are more frequently applied than truly dynamic models.

Straightforwardness seems to be the clue for selecting land-use modelling approaches, because increasing complexity may not necessarily lead to better outcomes. Sophisticated models turn out to be very specific, which limits their transferability to other contexts. Simpler models, even of static nature, showing plausible results are therefore more often recommendable to address land-use issues.

Throughout this research, it was possible to prove that modelling under uncertainty provides new insights to promote sustainable land-use practices even when high profitable farming is the business as usual strategy for land owners. Even though sustainable farming was slightly less profitable than conventional farming, in every case the options involved less risk than the conventional practices. This feature makes sustainable farming an efficient risk coping strategy with great impact for risk-averse farmers. However, it is clear that in order to be embraced by conventional farmers, incentives must be developed and implemented in the field. Suitable policies, financial inducements and technology transfer will facilitate the transition from intensive agriculture to biodiversity-friendly farming while reducing concerns about food security.

Keywords: land use, organic farming, portfolio optimization, compensation, uncertainty

Zusammenfassung

Die Entscheidungsfindung stellt eines der wichtigsten Themen in den Bereichen der Landnutzung und Ressourcenverteilung dar. Trotzdem werden Entscheidungen oft ohne ausreichende Informationen über die Zukunft getroffen. Die Analyse und das Einbeziehen der Unsicherheiten bei der Landnutzung sind wertvolle Werkzeuge um vorherzusagen, wie die Veränderung von Parametern die Leistung des Gesamtsystems beeinflussen kann. Damit können alternative Techniken und Gesetze vor ihrer Einführung auf der Ebene von landwirtschaftlichen Betrieben getestet werden. Es ist auch ein nützliches Mittel um die Präferenzen der Landbesitzer herauszuarbeiten. Dieser Aspekt ist besonders wichtig, wenn man die Zunahme landwirtschaftlicher Nutzflächen auf Kosten von Wäldern und anderen natürlichen Ökosystemen betrachtet. Die hohe Rentabilität mancher marktfähiger Agrarprodukte hat die negativen Auswirkungen des Landnutzungswandels verstärkt, dennoch sollten Landbesitzer vorsichtig damit sein, Investitionen nur aufgrund der zu erwartenden Einnahmen zu tätigen. Beispielsweise bietet die Risikoanalyse interessante Erkenntnisse zur Planung für lange Zeiträume. Vor diesem Hintergrund untersucht diese Arbeit, ob die Anwendung geeigneter ökonomischer Ansätze zu veränderten Landverteilungsmustern führen kann, wenn in den Landnutzungsmodellen die Präferenzen der Farmer und die Unsicherheiten der Landnutzungsmöglichkeiten adäquat einbezogen werden.

In der ersten Veröffentlichung wurden Ansätze der Entscheidungsfindung unter Unsicherheit dazu benutzt, die Kompensationszahlungen für Landwirte zu berechnen, welche unter Schatten spendenden Bäumen Kaffee anbauen und damit einen Beitrag zum Erhalt der Artenvielfalt leisten und gleichzeitig auf die Pflanzung von Mais verzichten, der die lukrativste Kulturpflanze im Südwesten Ecuadors darstellt. Zwei Ansätze wurden für diese Analyse ausgewählt: Die Stochastische Dominanz, welche nur wenige Annahmen über die Präferenzen der Landwirte macht und die Mittelwert-Varianz-Analyse, welche auf der Annahme einer Risikoaversion basiert. Da bei der Stochastischen Dominanz alle oder zumindest viele Nutzenfunktionen des Investors einbezogen werden, führte das zu sehr hohen Kompensationsbeträgen. Diese waren doppelt so hoch wie die Beträge, die durch die alternative Methode errechnet wurden, welche eine bestimmte konkave Nutzenfunktion maximiert. Hierbei ist es wichtig zu erwähnen, dass für den Vergleich zunächst in einem ersten Schritt beide Optionen als gegenseitig ausschließend betrachtet wurden. Vor dem Hintergrund risikoscheuer Landwirte erscheint es jedoch keine empfehlenswerte Herangehensweise, die Alternativen als sich gegenseitig ausschließend zu betrachten. Um kosteneffizientere Kompensationszahlungen zu identifizieren, wurden die Auswirkungen von Diversifikation bei der Landnutzung getestet, indem auf einer Teilfläche der Anbau von

beschattetem Kaffee ermöglicht wurde, während auf dem verbleibenden Land Mais gepflanzt wurde. Um das optimale Verhältnis zwischen beschattetem Kaffee und Mais zu berechnen, wurden unter der Annahme einer moderaten und einer starken Risikoaversion Landnutzungsportfolios erstellt. Basierend auf einer konkaven Nutzenfunktion lag das optimale Portfolio für Landwirte mit moderater Risikoaversion bei 27% beschattetem Kaffee und 73% Mais. Ein höherer Anteil beschatteter Kaffee war die beste Option für Landwirte mit starker Risikoaversion, weil sie weniger Risiken mit sich bringt – 51% und 49% Mais. Der Erhalt von artenreichen Kaffee-Anbaugebieten war das Ergebnis von ökonomischer Diversifizierung, die als Absicherung gegen Risiken genutzt wird. Folglich sollte die Politik die Farmer nur mäßig mit Subventionen unterstützen, so dass sie die Möglichkeit einer Diversifizierung nicht ganz beiseite lassen. Da die optimalen Portfolios immer noch vom Maisanbau dominiert werden, waren Kompensationszahlungen nötig um den Anteil von beschattetem Kaffee zu erhöhen. Die nötigen Kompensationszahlungen, um 75% Anbau von Schattenwald Kaffee zu erzielen, waren immer niedriger als die Kompensationen, die unter der Annahme von sich gegenseitig ausschließenden Landnutzungsoptionen ermittelt wurden. Daraus folgt, dass die Anregung zur Diversifikation dazu beitragen könnte, die Höhe von Kompensationszahlungen zu reduzieren, die zum Erhalt von weniger profitablen agroforstwirtschaftlichen Optionen nötig sind.

In einer zweiten Veröffentlichung wurde die ökologische Landwirtschaft als umweltfreundlichere Form der Landnutzung im Vergleich zur konventionellen Landwirtschaft als Teil eines optimalen Landnutzungsportfolios in den von sehr profitabler konventioneller Bewirtschaftung dominierten Tieflagen Ecuadors bewertet. Die grundsätzliche Fragestellung war dabei, ob ökologisch angebaute Bananen als Teil eines ökonomischen Landnutzungsportfolios in Frage kommen oder nicht. Die Ergebnisse haben gezeigt, dass die Aufnahme ökologisch angebauter Bananen in das Landnutzungs-Portfolio stark von deren finanzieller Unsicherheit beeinflusst wird. Es wurden zwei Szenarien der Preisfluktuation für ökologisch angebaute Bananen simuliert: Beim ersten wurde dieselbe Volatilität der Preise wie bei konventionell produzierten Bananen zugrunde gelegt, beim zweiten wurde dagegen mit einer realistischeren, niedrigeren Preisvolatilität für ökologische Erzeugnisse gearbeitet. Selbst für das Szenario einer hohen Preisfluktuation wurden Biobananen für fast alle akzeptierten Risikostufen mit einem Anteil von 1% bis maximal 32% in die Landnutzungsportfolios aufgenommen. Für das Szenario einer geringeren Unsicherheit der finanziellen Erträge von Biobananen erhöhte sich deren Anteil deutlich bis auf 57% sowie insgesamt die jährlichen finanziellen Erträge. Unter der Annahme, dass beide Märkte (konventionell und ökologisch angebaute Bananen) zu einem Markt verschmelzen (Integration) – dies wurde mit einem

erhöhten Korrelationskoeffizienten der Einnahmen aus ökologisch und konventionell angebauten Bananen (ρ bis zu$= +0.7$) simuliert – haben Biobananen nur dann einen bedeutenden Anteil der Landnutzungsportfolios, wenn eine geringere Unsicherheit ihrer finanziellen Erträge bestehen bleibt.

Auf Grundlage der Erfahrungen mit zwei bioökonomischen Landnutzungsmodellen geht eine dritte Veröffentlichung in einem Literaturüberblick auf die Vor- und Nachteile von Anwendungen bioökonomischer Modelle auf Landnutzungsthemen ein, indem in der relevanten Literatur die Berücksichtigung bzw. Vernachlässigung vier wichtiger Aspekte wie Berücksichtigung von Unsicherheit, zeitlichem Eingang der Deckungsbeiträge, Systemdynamik und Zielfunktionen analysiert werden. Integrierte Modelle zu konstruieren stellt eine Herausforderung dar, da eine Vielzahl von Variablen und Prozessen berücksichtigt werden muss. Die Fortschritte in der mathematischen Programmierung ermöglichen eine simultane Berücksichtigung verschiedener Aspekte, dennoch müssen einige Methoden noch weiter angepasst werden. Obwohl in jüngster Zeit Mehrfachziele und nicht nur reine Profitmaximierung in die Landnutzungsoptimierung aufgenommen worden sind, zeigt sich, dass eine solide Kombination von Mehrfachzielansätzen und Unsicherheitserwägungen oft noch fehlt. Sehr ausgefeilte Modelle erweisen sich dann oft als zu spezifisch und haben den Nachteil einer reduzierten Allgemeingültigkeit. Dadurch ist ihre Übertragbarkeit auf andere Zusammenhänge begrenzt. Demnach erbringen einfachere Modelle, selbst die statischen, oft plausiblere Ergebnisse als die hochkomplexen. Um sie noch leistungsfähiger zu machen, können sie mit neu verfügbaren Informationen aktualisiert werden.

Im Rahmen dieser Dissertation konnte gezeigt werden, dass die Modellierung mit Berücksichtigung von Unsicherheit interessante Einsichten für die Förderung nachhaltiger Landnutzungspraktiken liefert, auch wenn eine am Profit orientierte Landwirtschaft das gewöhnliche Verfahren für die Landeigentümer darstellt. Obwohl die nachhaltige Landwirtschaft etwas weniger profitabel war als die konventionelle, ergaben diese Optionen in allen Fällen ein geringeres Risiko als die konventionelle Praxis. Dieses Merkmal macht die nachhaltige Landwirtschaft zu einer effizienten Risikomanagementstrategie mit Vorteilen für risikoscheue Landwirte. Es ist jedoch klar, dass Anreize geschaffen und im umgesetzt werden müssen, damit die konventionellen Landwirte zu einer nachhaltigeren Landwirtschaft übergehen. Eine angepasste Förderpolitik, finanzielle Anreize und Technologietransfer werden den Übergang von intensiver Landwirtschaft zu artenfreundlicher Landwirtschaft erleichtern und gleichzeitig die Sorgen um die Lebensmittelsicherheit verringern.

Schlüsselwörter: Landnutzung, biologische Landwirtschaft, Portfolio-Optimierung, Ausgleichszahlungen, Unsicherheit

Resumen

El proceso de toma de decisiones constituye un tema de gran importancia en cuanto a uso del suelo y distribución de recursos. Sin embargo, es común que las personas decidan sin suficiente información sobre la ocurrencia de eventos futuros. El análisis de la incertidumbre aplicada a temas de uso del suelo es una herramienta valiosa para predecir como los cambios en los parámetros pueden afectar el desempeño de un sistema. A nivel de finca, permite evaluar los efectos de la aplicación de tecnologías alternativas y políticas previas a su implementación. Además permite integrar las preferencias de los propietarios de la tierra, siendo este aspecto fundamental considerando el incremento de tierra agrícola a expensas del bosque y otros ecosistemas naturales. A esto debe sumarse la alta rentabilidad de ciertos cultivos que ha exacerbado el cambio de uso, sin embargo, tomar decisiones únicamente en base a la rentabilidad puede ser engañoso. El análisis de riesgos por ejemplo, ofrece interesantes aspectos a considerar para la planificación a largo plazo. Teniendo en cuenta estos antecedentes, el presente trabajo investiga si la aplicación de enfoques económicos puede modificar patrones actuales de uso de recursos, considerando que las preferencias de los agricultores y la incertidumbre han sido apropiadamente integradas en modelos de uso del suelo.

En un primer artículo, la toma de decisiones bajo incertidumbre fue aplicada para calcular compensaciones para productores de café de sombra para evitar la conversión hacia maíz que es la opción más rentable en el sur del Ecuador. Dos enfoques fueron empleados para este análisis: Dominancia estocástica cuyas consideraciones sobre preferencias son muy amplias y Promedio-Varianza que asume explícitamente aversión al riesgo. La inclusión de muchas funciones de utilidad aplicando dominancia estocástica llevo dio como resultado compensaciones muy altas, el doble del valor calculado con el método alternativo que maximiza una función de utilidad cóncava. Es importante mencionar que en un primer paso se calcularon compensaciones considerando ambas alternativas como excluyentes. Sin embargo, este escenario no es el más adecuado, si se tiene en cuenta que los agricultores tienen aversión al riesgo como se ha demostrado en estudios previos. Por este motivo se consideró los efectos de la diversificación sobre las compensaciones. Los portafolios de uso del suelo se calcularon usando dos tipos de aversión al riesgo, moderada y extrema. El portafolio óptimo considerando aversión moderada al riesgo fue 27% de café sombra y 73% de maíz. Para los agricultores con mayor aversión al riesgo un porcentaje mayor de café fue preferible 51%, y 49% de maíz. La diversificación tiene como consecuencias una menor exposición a riesgos, mejor balance de ingresos y una implícita protección de la biodiversidad. Como

consecuencia, las compensaciones deben realizarse cuidadosamente para no tener efectos contraproducentes sobre las opciones de diversificación. Para incrementar el porcentaje de café es necesario pagar una compensación, sin embargo para incrementar el porcentaje a 75% por ejemplo considerando un escenario de diversificación resultó mucho mayor que bajo un escenario de usos excluyentes. Así, la diversificación es una alternativa para disminuir las compensaciones requeridas para preservar usos de suelo deseables desde el punto de vista ambiental pero con menor rentabilidad.

En un segundo artículo, la agricultura orgánica fue evaluada como parte de portafolios de uso del suelo en la costa ecuatoriana donde domina la agricultura comercial. El objetivo fue evaluar si la banana orgánica puede ser parte de portafolios óptimos de uso del suelo. Los resultados demostraron que la aceptación depende en gran medida de su incertidumbre económica. Dos niveles de incertidumbre fueron evaluados, el primero usando la misma volatilidad de precios que la banana convencional y la segunda basada en la volatilidad de precios registrada para productos orgánicos. Como resultado, la banana orgánica fue incluida en portafolios en casi todos los niveles, en proporciones desde el 1% hasta el 32% a pesar del alto riesgo simulado. En el escenario donde se consideró una volatilidad menor el porcentaje de banana subió hasta el 57%. Ante la posibilidad de que ambos mercados se integren simulado con un incremento en la correlación de ambos productos (ρ hasta= +0.7), la producción orgánica alcanza porciones significativas solamente si se considera una baja incertidumbre en sus precios, de lo contrario se excluye de los portafolios óptimos. Dado que información histórica de precios de banana orgánica confirma su menor volatilidad, esta opción es recomendable para los productores como una estrategia para reducir riesgos.

En base a la experiencia con dos modelos bioeconómicos, un tercer artículo analiza las ventajas y limitaciones del uso de modelos en la planificación del uso del suelo, y cómo se han integrado importantes aspectos como la incertidumbre, tiempo, dinámica de los sistemas y funciones objetivo múltiples. Es importante resaltar que la inclusión de varios aspectos es muy compleja por la gran cantidad de información y procesos que se integran simultáneamente. A pesar de un progreso evidente en el campo de la programación matemática algunas metodologías requieren perfeccionarse. El uso de funciones objetivo múltiples va ganando terreno en el campo de planificación de uso del suelo, sin embargo se evidencia que frecuentemente no se aplica este tipo de funciones en combinación con análisis de incertidumbre. Además, modelos muy específicos y complejos tienen la desventaja de ser difícilmente transferibles a otros contextos. Por tanto, el uso de modelos sencillos, incluso estáticos, demuestra ser todavía una opción válida frente a modelos

complejos y para mejorar su desempeño pueden actualizarse cuando nueva información esté disponible.

A través de esta investigación fue posible demostrar que la modelación bajo incertidumbre ofrece interesantes alternativas para promover usos de suelo más sostenibles incluso cuando la agricultura comercial es la estrategia usual de los agricultores. Incluso si las opciones que se consideran tienen menor ingreso que la agricultura convencional, generalmente involucran menor riesgo. Esta característica hace que la agricultura sostenible sea una excelente estrategia para reducir riesgos. Sin embrago es claro que para convencer a los agricultores convencionales es necesario compensarles por las ganancias que no percibirán al optar por formas de agricultura menos intensivas. Políticas adecuadas, incentivos financieros y transferencia de tecnología facilitaran la transición reduciendo la preocupación sobre la biodiversidad y la seguridad alimentaria.

Palabras clave: uso del suelo, agricultura orgánica, optimización de portafolios, compensaciones, incertidumbre

Table of contents

List of figures

List of tables

1. Introduction

Producing food subject to sustainable standards is one of the most challenging scenarios nowadays. The accelerated growth of population has triggered the demand of food worldwide with dramatic effects on ecosystems' diversity and functionality (Lalani et al. 2016). Land-use schemes have habitually been designed to meet the needs of societies with little consideration about their impacts of the environment (FAO 2016). Sustainability issues have positioned now in the public debate because consequences of unsustainable land-use are affecting human populations directly (e.g. biodiversity loss and climate change) (Blasi et al. 2016). Thus, efforts must be devoted to develop approaches able to meet the population demand for natural resources without compromising ecosystems functions necessary to maintain a balance between production and use.

Even though unsustainable land use is a matter of concern around the globe, it is particularly important for developing countries because the following conditions create a vulnerable situation. First, their economies depend to a large extent on raw materials and primary sectors like agriculture; second, population growth and demand of land for food production is a permanent threat for natural ecosystems; third, tropical countries hold priority areas for conservation (FAO 2016). Ecuador, for instance, is among the most biodiverse countries in the world despite its small size (Lizcano et al. 2016). In this country agriculture represents approximately 8% of the Gross Domestic Product (INEC 2014); it is also among the major contributors to carbon emissions caused by land-use change and land degradation (World Bank 2009, Bertzky et al. 2010, FAO 2016). Thus, actions towards sustainable land-use are urgent and should be a main concern for policy makers.

Research institutions and development agencies have allocated enormous amount of resources to address land use related topics. In the 60´s the main problem was food availability, to deal with this issue efforts focused on increasing the productivity of farming systems by means of intensification (Garnett et al. 2013). Global aggregate food production grew significantly as consequence of the application of technologies to improve soil fertility, irrigation, mechanization and the use of high yielding crop varieties (Firbank et al. 2008, Nin-Pratt and McBride 2014). Nowadays, most concerns are related to the unsustainable methods applied to increase food production and their consequences on ecosystems (Hazell and Wood 2008, FAO 2010, Power 2010, Baudron and Giller 2014). Intensive use of soil leads to nutrient depletion and degradation (Stoate et al. 2009). Water is often used inefficiently for irrigation causing water logging and salinization and approximately 30-80% of nitrogen leakages to contaminate water systems (Pretty 2008). Intensive farming is also a

critical source of greenhouse gases due to increased use of fertilizers and energy (Baudron and Giller 2014).

Detrimental impacts of intensive farming on the environment make clear the urgency to adopt more sustainable methods to produce food (FAO 2016). Ponisio et al. (2014) point out that sustainability may only be achieved if food is produced in a way that allows protection, use and regeneration of ecosystem services, but still allows efficiency in terms of productivity (Tscharntke et al. 2012). Approaches embracing the sustainability philosophy are wildlife-friendly, community-based, organic and permaculture to mention some of them, which in practice refer to a reduction of external inputs (Pretty 2008) and from here onwards will be referred in this text as sustainable farming. Common practices under these schemes are integrated control of pests and diseases, crop diversification, agro-ecology, precision farming and restoration of abandoned lands (Tscharntke et al. 2012, Knoke et al. 2009a, Knoke et al. 2012).

Ecological benefits of sustainable farming schemes are evident (Sherwood and Uphoff 2000, Liu 2008, Power 2010, FAO 2010). Unfortunately, sustainable farming is often perceived as less profitable than conventional farming (Adl et al. 2011, Ponti et al. 2012, Patil et al. 2012). If comparisons are made solely based on a classical accounting frame, in which externalities (either positive or negative) are neglected, sustainable farming might result less attractive, due for instance to increased labor costs (Grieg-Gran et al. 2005, Bryan 2013). This perverse accounting system neither forces conventional farmers to assume their negative externalities, nor rewards farmers involved in sustainable schemes for delivering important ecosystem services (Wunder and Albán 2008). Similarly, if avoided environmental costs of reducing external inputs were included in the accounting systems, benefits could be more plausible for farmers (Gordon et al. 2007, Beckman et al. 2013). In order to implement appropriate incentives to sustainable farming, approaches must understand the complex economics of farming systems (Rădulescu et al. 2014). Moreover, states must provide legal and institutional frameworks in order to create conditions to engage land users with sustainable alternatives (FAO 2016). Offering inducements and compensations could be a feasible alternative (see Möhring and Rüping 2008 for a forestry example).

Considering this background, expectations about large scale shifts towards sustainable farming must be cautious because a transition from conventional farming represents a challenge to land owners due to economic concerns, lack of expertise and uncertainties (Tscharntke et al. 2012, Ponisio et al. 2014). As farming is very sensitive to natural and financial risks, addressing uncertainty is pivotal to guide farmers' decision making. By including uncertainty in land-use models,

farmers have the opportunity to consider multiple scenarios and select those that better fit their preferences. Interesting shifts in resource allocation have been reported when perceptions about risks and profitability are considered simultaneously (Castro et al. 2013, Castro et al. 2015). Unfortunately, economic assessment of land-use options often disregards uncertainty (Castro et al. submitted).

Nevertheless, farmers do not need to select between mutually exclusive land-use options, a combination of assets can also be an alternative to facilitate transitional stages. Despite diversification has been considered in land-use modelling in the past (for examples in forestry see Clasen et al. 2011, Härtl et al. 2015), it has hardly been analysed in a portfolio-theoretic framework, if at all, and if, how much land should be allocated to sustainable farming. The impact that diversification might have on the amount calculated as compensation has never been evaluated so far either. Thus, this thesis is among the early applications of optimal land-use diversification to foster sustainable farming considering land owner´s preferences. Bringing these theoretical analyses to the conditions of the farming sector of a tropical county like Ecuador provides a perfect case scenario to analyze the consequences of economic approaches to guide landowners' decisions. In this country climate scenarios have suggested that corn, rice, soybeans, cocoa and banana are vulnerable to climate change, thus projects should be implemented to reduce the vulnerability of the sector (World Bank 2009). Consequently, land-use diversification is applied to the case of Ecuadorian farms producing by means of profitable monocultures, in areas where sustainable farming need to be adopted to reduce negative impacts of conventional farming.

The hypotheses tested in this research are the following:

1. *Mean-variance decision rules address farmers' risk aversion more proficiently than stochastic dominance and allow calculating more cost-effective compensations.*
2. *Land-use diversification reduces the amount required to compensate farmers for switching to environmentally friendly land uses such as agroforestry.*
3. *The inclusion of sustainable land uses into efficient land-use portfolios is driven by the uncertainty of their economic return.*
4. *Basic bio-economic models are more recommendable than complex models to support decision making.*

Three papers form the backbone of this thesis, they contribute to understanding the impact of economic approaches to promote sustainable land use by analysing the effects of uncertainty on decision making at the farm level (Table 1).

Table 1. Overview of the publications on which the dissertation is based

List of publications	Summary	Division of labor
Castro, L.M., Calvas, B., Hildebrandt, P., Knoke T., (2013). Avoiding the loss of shade coffee plantations: how to derive conservation payments for risk-averse land-users. In: *Agroforestry Systems* 87, 331-347	The publication analyzes two methods (stochastic dominance and mean-variance) to derive compensation payment for risk-averse farmers growing shade coffee, in areas where maize is the most profitable option.	Concept and design: LMC, TK Data collection: LMC, BC Data analysis: LMC, PH, BC Writing the article: LMC, BC, PH, TK
Castro L.M., Calvas B., Knoke T., (2015). Ecuadorian Banana Farms Should Consider Organic Banana with Low Price Risks in Their Land-Use Portfolios. In: PLoS ONE 10(3) doi:10.1371/journal.pone.0120384	In this publication organic farming is assessed as part of land-use portfolios in combination with conventional and highly profitable options, considering different levels of risk. As organic banana holds lower price risk than conventional banana, it becomes a good component of land-use portfolios for Ecuadorian farmers.	Concept and design: LMC, TK Data collection: LMC, BC Data analysis: LMC, TK Writing the article: LMC, BC, TK
Castro L. M., Härtl, F., Ochoa, S., Calvas, B., Knoke T. (Submitted). Potentials and limitations of integrated bio-economic models as tools to support land-use decision making: Submitted to Journal of Bioeconomics	The publication describes advances related to integrated bio-economic modelling. Through an analysis of the application of uncertainty, systems and time dynamics and multiple objective functions, we analyze whether complexity may improve overall performance of land use models.	Concept and design: LMC, TK Data collection: LMC, BC Data analysis: LMC, FH Writing the article: LMC, FH, SO, TK

LMC: Luz María Castro; TK: Thomas Knoke; BC: Baltazar Calvas; PH: Patrick Hildebrandt; FH: Fabian Härtl, SO: Santiago Ochoa

2. State of the art

2.1. Approaches to sustainable land use

Economic growth has affected the relation of humans and the environment, resulting in substantial degradation of ecosystems and natural resources due to increased demand of goods (FAO 2016). Economic growth together with population growth has an enormous impact on the demand of natural resources. Thus, food security is one of the main concerns and for many years scientists considered that agricultural intensification was the only way to produce enough food (Schut et al. 2016). Nowadays, there is consensus that increments in food supply should not compromise ecosystem integrity (Tilman et al. 2002, Poppy et al. 2014). To achieve sustainability, farming systems must embrace economic, social and environmental aspects (Pretty 2008). However bringing these aspects together results complicated in practice due to a series of trade-offs between conservation and economic goals (Nguyen et al. 2015).

Scientific debate concerning sustainable farming was for several years focussed on two mutually exclusive approaches: land sharing and land sparing. Land sharing is an approach to sustainable farming in which biodiversity conservation and food production are integrated on the same land (Phalan et al. 2011). Even though this form of agriculture is able to host more biodiversity than conventional farming, it received criticism due to likely lower yields, which in the long run could lead to deforestation to increase farming land in order to produce similar yields than those achieved in conventional farming (Green et al. 2005).

In land sparing, farming and conservation occur in separated land. Thus, agricultural areas are used intensively to achieve high yields from a relatively small area. These agricultural systems are typically industrial in style and strive for maximum economic efficiency. Biodiversity is confined to nature reserves often on government-managed land, because farmers lack short-term economic incentive to manage land for conservation (Green et al. 2005, Fischer et al. 2008). A shortcoming of land sparing is the difficulty to deal with the negative externalities of (conventional) intensive farming.

An alternative to achieve similar yields than under conventional farming is sustainable intensification, which is less dependent on harmful technologies (Pretty et al. 2008). Poppy et al. (2014) suggest that practices and technologies following this approach require strong innovation to guarantee sustainability. Even though sustainable intensification may reduce negative externalities compared to conventional intensive farming; a meaningful increment of biodiversity is not

necessarily expected to happen following this type of approach. Thus, a radical rethinking of farming is required to respond to context and location issues (Garnett et al. 2013, FAO 2016). Phalan et al. (2011) suggest that intensive farming and wild-life friendly farming should no longer be regarded as opposite approaches and should rather be combined to achieve sustainable land-use.

Comprehensive land-use concepts have been proposed by Odum (1969) in the "Compartment approach" and more recently by Gardner et al. (2009). Authors coincide that landscapes should be regarded as contiguous land-use mosaics of well-connected habitats to support biodiversity and deliver multiple services simultaneously (Bennet et al. 2006). With this background Knoke et al. (2012) proposed an approach to integrate intensive sustainable farming with agroforestry and forest plantations. Even though methodologies based on optimization routines are available, only few studies have applied land allocation in agricultural studies at the farm level (for examples in forestry see Clasen et al. 2011, Härtl et al. 2014). Hence, it is imperative to assess how different land-use types can be integrated following economic and biological processes in combination with farmers´ preferences.

This section introduces a description of the most widely spread farming schemes fitting sustainability considerations, which have an improved performance in terms of ecosystem functionality compared to conventional farming. A brief description of contributions and shortcomings of each type of farming is also included in an attempt to extend the analysis about the effectiveness of mutually exclusive land-use options –even the biodiversity-friendly ones- compared to more diversified schemes.

2.1.1. Wildlife-friendly farming

In wildlife-friendly farming a close integration of low-input farming and conservation takes place (Pywell et al. 2012). Typical characteristics of wildlife-friendly farming include high level of spatial heterogeneity attained by combining several layers of vegetation (trees, shrubs and crops) with patches of native vegetation (Fischer et al. 2008). The most widespread form of wildlife-friendly farming is agroforestry; due to their diverse composition agroforestry systems are able to deliver food, fibre and firewood to local dwellers (Ribaudo et al. 2010, Buechley et al. 2015). A relevant feature of agroforestry areas is their ability to deliver important ecosystem services in human-intervened landscapes (Pollini 2009). Scientific reports have indicated their potential to remove and store atmospheric carbon dioxide through enhanced growth of trees and shrubs (Goodall et al. 2015). They also provide shelter for flora and fauna and connect isolated patches allowing the flow of species (Pandey 2002; Perfecto et al. 2005). Additionally, agroforestry systems play an essential

role as transitional areas surrounding protected areas (Perfecto and Vandermer 2010, Greenler and Ebersole 2015).

Despite the benefits provided by agroforestry systems, large areas are converted into industrial farming (Olschewski et al. 2006). Should this trend continue, agroforestry areas that provide food security to rural dwellers might be significantly reduced due to the high demand for cash crops (Benítez et al. 2006, Fischer et al. 2008). Trade-offs among biodiversity conservation and productivity are at the core of the debate about agroforestry, as more biodiversity occur in areas of high structural complexity under extensive use (Valkila 2009, Goodall et al. 2015). Pollini (2009) points out the economic performance of agroforestry systems as the main cause for its low adoption, despite having better ecological outcome than conventional systems. Productive activities consisting of forest management or agroforestry are often not attractive at the farm level because they constitute long term investments; small scale farmers have preference towards short term options with earlier payback periods (Benítez et al. 2006).

Shade coffee is the most widely spread form of agroforestry and the most important tropical commodity (Buechley et al. 2015). The importance of the coffee sector is acknowledged globally despite market shocks caused by the entry of new producers or loses due to disease, which permanently affect the stability of coffee prices (Capa et al. 2015). The instability of the coffee market has led to land abandonment and conversion to more profitable crops. In order to halt this trend, mechanisms such as price premiums and renovation of plants have been implemented (Leigh 2005). Price premiums have a large range of targets, being grain quality the most important (Buechley et al. 2015). Other schemes also recognize labour rights and biodiversity hosting, but several ecosystem services are still neglected (Goodall et al. 2015). Wildlife-friendly farming schemes are not likely to thrive, if an adequate compensation is not paid to farmers. Thus, it is important to determine the best methods to derive cost-effective compensation payments considering farmer´s preferences to prevent further conversion process.

2.1.2. Organic farming

Organic agriculture is an environmentally friendly approach to agriculture, which largely excludes the use of synthetic fertilizers, pesticides, growth regulators, and livestock feed additives (Yadav et al. 2013). A strong effort is placed to maintain soil fertility by careful mechanical intervention and effective recycling of organic materials produced within the farm (Yadav et al. 2013). The terms 'organic' and 'sustainable' are not equivalent though; organic farming may or may not practice the full suite of techniques characterizing sustainable agriculture (Ponisio et al. 2014).

Organic farming represents only 1% of total agricultural land (Willer et al. 2009, Crowder and Reganold 2015). In order to promote organic farming to a larger extent, two assumptions must be refuted: a) reduction in yield due to decreased germination and loss to disease, and b) increased costs of production (Badgley et al. 2007, Adl et al. 2011, Seufert et al. 2012). A recent study conducted by Crowder and Reganold (2015) conclude that in spite of lower yields, organic agriculture was significantly more profitable than conventional agriculture after analyzing 55 crops grown in five continents. Despite that organic systems require 35% more labor than conventional, reduced costs of fertilizers and pesticides represent an important advantage (Pimentel et al. 2005, Liu 2016). Accordingly, the extra costs generated by adopting organic standards are supposed to be more than offset by the price premium that consumers pay when purchasing products with a sustainable label (Liu 2008).

2.1.3. Afforestation on abandoned land

The on-going intensive use of land for agriculture and cattle ranching is the main cause for degradation, and abandonment, which increases the risk to erosion and fire (Sherwood and Uphoff 2000, Stoate et al. 2009, Power 2010). Abandoned areas can undergo natural succession or be subject to active restoration through afforestation (Nadal-Romero et al. 2016). Even though reclaiming abandoned areas to resume production is rarely considered an advisable alternative, afforestation with native species represents an opportunity to increase the natural capital and enhance ecosystem services provision (carbon sequestration, soil amelioration, biodiversity shelter etc.) (Knoke et al. 2009a, Phalan et al. 2011, Singh et al. 2012).

Singh et al. (2012) indicate that afforestation with multiple tree species improves soil fertility and restores site conditions improving soil properties. Besides accumulation of biomass, it also stimulates the autogenic succession and alters the structure and stability of communities. The accumulation of litter by different tree species promotes the enrichment of soil fauna and activates processes of nutrient cycling (Wang et al. 2011). A comprehensive study by Knoke et al. (2014) indicates that afforestation with native species and restoration of agricultural potential must be part of land-use planning. This aspect is essential, as re-utilization could not only mitigate the increasing pressures on natural forest, but also alleviate poverty by improving food security. Restoration might not be attractive for landowners as individual alternative; nevertheless, it could be combined with other land-uses to deliver financial and ecological benefits (Singh et al 2012).

According to Crăciunescu et al. (2014) many afforestation projects have achieved success, with degraded lands reinstated into the productive circuit. Some problems related to afforestation

23

projects constitute the high upfront investments from establishment to tree consolidation. Uncertainties limit private interest for afforestation on degraded lands because restoration lacks financial attractiveness. Several countries have implemented programs to promote forestry initiatives. In Ecuador the Ministry of Agriculture, Livestock and Fisheries developed a strategy which has the goal to promote afforestation with commercial purposes and restoration (MAGAP 2015). This program includes incentives such as devolution of 75% -100% of the investment after the plantation has been implemented and the survival of the trees has been assured. The program includes species such as Andean alder (*Alnus accuminata*), balsa (*Ochroma piramidale*), laurel (*Cordia alliodora*) among other, which due to their fast growth and production of litter are able to facilitate restoration on degraded lands and produce commercial timber within short time periods (Knoke et al. 2014, Castro et al. 2015)

2.2. Mechanisms to promote sustainable land uses: Compensation payments

Sustainable land use is a main concern for decision makers. In order to promote sustainable alternatives several strategies have been developed and tested in the field (Kemkes et al. 2010). Command and control seek to prevent overuse of inputs by implementing bans and taxes on conventional farming, however, shifts towards desirable levels of sustainability were only modest. Thus, a second generation of policies focused on rewarding land owners´ best practices by means of financial incentives such as compensation payments (Bureau, 2005). Knoke (et al. 2008a) point out that the amount paid to farmers must be determined using appropriate methodologies in order to use public and private funding for conservation in efficient ways. Most compensations payments are determined based on old fashioned methodologies reduced to simple accounting models, which systematically neglect externalities and simply quantify resource budgets in terms of inputs and outputs (Kragt 2012). In order to analyze the performance of land-use systems in a comprehensive way, methodologies must be updated to amend market failures.

Pretty et al. (2008) conducted an interesting study in which they analyze how prices for agricultural products do not reflect the full costs of farming. When negative externalities are neglected, an underestimation of actual costs of producing food takes place which affects prices of commodities. This situation causes a distortion on markets encouraging activities that are costly to society even if the private benefits are substantial. Positive externalities of sustainable farming are also neglected by the market. Olschewski et al. (2006) analyzed the impact of reduced pollination services caused by destruction of forest adjacent to shade coffee areas on net revenues in Ecuador and Indonesia.

They found that a decrease in pollination services affects profits by reducing yields, which leads to lower gross revenues even if market prices remain constant.

Bryan (2013) points out that the failure of markets to internalize environmental costs associated with land-use and management decisions is a primary reason for degradation. To address this issue market-based policy instruments have slowly percolated to redress market failures. Instruments such as direct payments, tax incentives, voluntary markets, and certification programs are part of agri-environmental schemes (Wendland 2008). The main aspects about incentives is that they may change the relative profitability of land uses and provide a price signal for landholders to change land use, provided they are appropriately supported.

Even though profitability is known to be a major driver of land use change and adoption of conservation technologies, other less-well-known factors such as uncertainty and option values are also important. Predicting the response to incentives is extremely challenging due to the large number of determinants involved in the process (Bryan 2013). Incentives in the form of compensation payments may have the desired effect only if they reach the land users in ways that influence their decisions to allocate resources in sustainable ways. This implies that compensation must cover forgone profits and costs associated with adopting and maintaining sound practices (Larsen 2009). In theory participants in a compensation program must also decide how many hectares will be devoted to the program and how many hectares that will be kept in conventional production. Under the very simplifying assumption that a farmer maximizes profits and is risk-neutral, he/she will choose to participate only if the profit is equal to or larger than the land opportunity costs. Nevertheless, strong risk aversive farmers have demonstrated to be willing to accept less compensation if the sustainable option is less risky than the conventional one (Knoke et al. 2008a).Thus, understanding the economics of the farming system is imperative to determine the appropriate amount and form of payment.

2.3. Decision making under uncertainty applied to land-use problems

The management of various uncertainties is one of the main challenges in land-use management. Landowners have to cope with natural and financial risks which affect their income (e.g. weather risks, pest risks, disease risks, market risks, etc.) (Rădulescu et al. 2014). Understanding how farmers make their decisions is crucial to design strategies to foster sustainable land-use. Profitability of land-uses influences farmers´ decisions; nevertheless, motivations are more complex than simply profit maximization (Ribaudo et al. 2010). Uncertainty represents the limited knowledge about future decision consequences (Hirshleifer and Riley 2002).The effects of uncertainty have

been analyzed in many fields of decision analysis (Bawa 1975, Machina 1987, Götze et al. 2008). Nevertheless, this type of analysis is relatively novel in natural resource management (Kangas and Kangas 2004, Benítez et al. 2006, Knoke et al. 2008a, Hildebrandt and Knoke 2011, Clasen et al. 2011).

Landowners allocate scarce resources to meet their objectives. Their objectives include aspects such as ensuring family welfare, maximizing returns or minimizing risks. Available technology, assets, land tenure, market conditions and other factors constrain the choices that farmers have available (Angelsen et al. 2001). Identifying the objective function of farmers enables to attain results that are more reliable at the moment of modelling land-use decisions at the farm level. The objective function states which goals the farmer wants to achieve. Depending on the objective function, farmer´s decision making can be modeled in different ways: profit maximization, profit maximization minus some risk penalty, maximization of expected utility and objective functions based on different various objectives (Janssen and van Ittersum 2007).

The expected utility theory is one appropriate opportunity to adequately address farmers' preferences. This theory states that the decision maker chooses between uncertain prospects by comparing their expected utility values. Utility functions provide a method to measure the landowners' preferences for wealth, and the amount of risk they are willing to bear in the hope of attaining greater wealth (Hildebrandt and Knoke 2011). Different types of utility functions are used to describe the attitude of the decision maker towards risk: linear increasing utility functions for risk neutral decision makers ($U(x)´>0$; $U(x)´´=0$), convex increasing functions for risk seeking ($U(x)´>0$; $U(x)´´>0$), concave increasing functions for risk avoiding decision makers ($U(x)´>0$; $U(x)´´<0$) and combinations of them (Hildebrandt and Knoke 2011). Risk aversion is assumed to be a common behavior of farmers; consequently, most studies use concave utility functions (Baumgärtner and Quaas 2010). Nevertheless, assumptions regarding risk preferences must be selected carefully and should consider that preferences are not always constant over the entire planning horizon, but rather depending on temporal circumstances (e.g. Post and van Vliet 2006).

Risk management strategies

In general, it is reasonable to expect that farmers will choose productive activities that maximize their well-being, given the resources and opportunities available to them. However, as typically farmers are regarded as risk-averse, strategies to reduce the uncertainties inherent to agricultural production provide beneficial effects (Ogurtsov et al. 2008, Knoke et al. 2011). Farmers hedge risks by mixing two or more land-use options whose financial returns fluctuate independently from one

another (low correlations) (Anderson 2003). The relationship between risk levels and diversification is explained by the overall reduction of risks when additional assets are added to a single product portfolio. In periods when one asset generates unexpectedly great returns, other options might have a rather poor performance, and thus the combination of several assets may compensate for the unexpected losses keeping the overall returns stabile. These financial risk interdependences must be considered for optimized land-use diversification to reflect the risk-reducing effects that can be achieved (Knoke et al. 2011).

A well-recognized method for finding the optimal diversification strategy is the Portfolio Theory developed by Markowitz (1952). This theory has been used, for instance, to further develop von Thünen's economic land-use theory (von Thünen 1842) using a portfolio-theoretic reformulation (Knoke et al. 2013). In a more recent analysis Markowitz (2010) indicates that his famous portfolio theory was proposed in a normative sense to suggest the best scenario and in a positive sense, too, as a hypothesis about investor behavior. Even though normative models may hardly be tested empirically (see Roll 1977), they still can help forming comprehensible land-use scenarios and delivering valuable hints for efficient land-use strategies (Knoke et al. 2013). These kinds of models have been applied in the past in order to model decisions on land allocation to various land-use practices from an economic perspective and to derive cost-effective conservation strategies (Clasen et al. 2011, Knoke et al. 2013).

2.4. Bio-economic modelling at the farm level

Application of bio-economic modelling is a trend nowadays to promote optimal resource allocation and management. Its application has been reported in fisheries, forestry and agriculture (Kragt 2012). Bio-economic models are simplified representation of real world problems, as all models are; its particular feature is the combination of biological and economics aspects (Brown 2002). Most bio-economic models are built following normative and mechanistic approaches in order to make recommendations for managers about the best scenarios available to them (Delmotte et al. 2013).

In order to achieve optimal resource allocation, bio-economic models are solved by applied optimization routines, which depend to a large extent on the type of objective function (Herrero et al. 1999, Kragt 2012). Objective functions can be modeled in different ways: profit maximization, profit maximization minus some risk factor, maximization of expected utility and multiple objective functions (Janssen and van Ittersum 2007). For instance, linear programming is widely applied to problems which consider only an objective function aimed to be either maximized or minimized. In linear programming, each possible solution is represented as a linear combination of activities and a

set of constraints which represent the minimum or maximum amount of a certain inputs available for the system (Ten Berge et al. 2000, Janssen and van Ittersum 2007). An advantage of linear programming is its versatility; it can be used to integrate uncertainty in stochastic (Acs et al. 2009) and robust applications (Knoke et al. 2015). Some problems, however, demand a nonlinear programming solution (Bradley et al. 1977). Thus, activities must be defined in such a way that all nonlinearities are embedded in the values of the input-output coefficients (Ten Berge et al. 2000). Nonlinear programming is applied to the portfolio-theoretic framework offering a feasible solution by combining expected return and risk in one objective function; making it possible to reach two aspects at the time to maximize the expected economic return and to minimize risks (Clasen et al 2012, Castro et al. 2015). In situations when researchers expect to reach multiple objectives, techniques based on goal programming are recommended (Charnes et al. 1955, Charnes 1977). This technique establishes a target for each goal and seeks to minimize the deviations between the actual goals and their target levels (Hazell and Norton 1986).

In order to resemble real systems, scientists have attempted to integrate several aspects to bio-economic models (e.g. uncertainty, time dynamics, biophysical interactions and multiple objectives (Castro et al. submitted). Models include uncertainty in order to address natural variability of input factors; it can be incorporated by applying stochastic and non-stochastic robust programming (Birge and Louveaux 1997, Beyer and Sendhoff 2007, Bertsimas et al. 2011). In stochastic programming uncertainty is represented by probability functions of real system parameters, it thus depend to a large extent on the availability of precise information about the occurrence of a specific future event and the randomness of the events occurring in nature (Yu and Jin 2012). As information can be scarce, probabilities can be derived using historical data using Monte-Carlo simulation (Knoke and Wurm 2006). This method enables integrating various sources of risk that affect the dispersion of return, which makes it particularly convenient to land-use management problems (Griess and Knoke 2013). Approaches for modelling decision making within a probabilistic framework are stochastic dominance, downside risk and mean-variance (Benítez et al. 2006, Hildebrandt and Knoke 2011).

A method to include uncertainty in bio-economic models demanding less amount of information is non-stochastic robust optimization. This method, however, needs at least some specification of possible input data variations (see Knoke et al. 2015). It gives all considered data perturbations an equal weight and does not assign various probabilities to specific events (Ben-Tal et al. 2006, Bertsimas et al. 2011).. Thus, parameter variation is integrated using pre-defined uncertainty sets over which optimization is carried out resulting in robust solutions (Knoke et al. 2015). The difference between robust optimization and sensitive analysis is how the fluctuating parameters are

integrated in the optimization process; in sensitive analysis is a post optimization process to test how changes in parameters may affect the results (Yu and Jin 2012).

The influence of time on decision making has been captured by means of dynamic modelling (Bertsimas et al. 2011). The field of time dynamics has made it possible to integrate feedbacks and interactions between time periods. The term "dynamic" involve that decisions in one period depend on events in a previous period. Thus, agents know that one period later more information would be available, and they can revise their decisions for the next period (Samuelson 1969). The possibility of analyzing the effect of different mechanisms before, during and after their implementation makes dynamic modelling a great tool for decision making. Nevertheless, routines to incorporate such interactions demand sophisticated software and are thus more expensive (Castro et al. submitted). Static models lack the ability to incorporate such interactions; nevertheless, they can model what happens over time, but time itself is not embodied in the model (Bertsimas et al. 2011). Despite this limitation, static models are still widely applied to land-use problems. An alternative to enhance its performance is to run the models when new information is available (Castro et al. submitted).

Another important step towards integrative bio-economic modelling has been the integration of biophysical interactions and feedbacks occurring at the ecosystem level and how they influence agents facing a sort of decision variables (Brown 2000). This particular field has experienced an important growth in terms of the number of studies addressing the topic and its importance to understand how systems operate (Griess et al. 2012, Larkin et al. 2008). Nevertheless, when a scientist studies profoundly a system in particular and models its behavior, the model becomes quite specific, which reduces the possibility of replication and escalation to other contexts (Castro et al. submitted).

In general, bio-economic models provide interesting insights to address land-use issues due to the variability of methodologies available to fit each decision problem. Regardless the type of model selected by the researcher or the objective function, bio-economic models can assist decision making proficiently and guide agents to make better choices from a portfolio of modelled scenarios. Additionally, they constitute a great tool when only scarce information is available. If models integrate aspects such as uncertainty and multiple objectives simultaneously, their predictive capacity is enhanced allowing more plausible results. Nevertheless, tradeoffs among accuracy and simplicity must always be pondered by the researcher while designing a proposal in order to avoid creating overly complex models.

3. Material and Methods

3.1. Methodological approach

In order to investigate the influence of uncertainty on land-use modelling, approaches based on the expected utility approach are applied to the Ecuadorian context considering conventional and sustainable land uses. First, a short theoretical description of stochastic dominance and mean variance is presented and their suitability to derive cost-efficient compensation payment (Castro et al. 2013). This is followed by a description of the theoretical basis for Markowitz´ portfolio optimization applying nonlinear programming as a tool for diversification purposes (Castro et al. 2013, Castro et al. 2015). Afterwards, the process to evaluate how bio-economic models have evolved to integrate multiple objectives, uncertainty and system dynamics following various programming techniques is presented and analyzed, as reviewed in Castro et al. (Submitted). Finally, this section includes the description of the two case study regions on which the suitability of the economic approaches to improve decision making at the farm level was tested.

3.1.1. Generation of probability distributions to model uncertainty

Following the expected utility framework, an important step for risk analysis is the generation of probability distributions of possible investment outcomes - for the purposes of this research net present value (NPV) and its annualized value[1]. The application of Monte Carlo Simulation has made it possible to increase the number of studies based on the stochastic programming framework (Castro et al. submitted). Nowadays, Monte-Carlo simulation is the most broadly tool used for risk assessment as it is able to incorporate different uncertain inputs.

Nevertheless, applying this technique also poses some challenges, as indicated by Hildebrandt and Knoke (2011). When input distributions are unknown, this situation may lead to considerable effects on the tails of the simulated probability distribution functions. Additionally, correlations between input factors should allow for any interdependency. In this thesis the correlation between prices and productivities from one year to the next year for the same option was not considered, but rather the correlation between prices and productivities between all land-use options. For the purpose of this study, input coefficients were price volatility and yield variation drawn from the database of the division of statistics, FAOSTAT (FAO 2015). The cumulative distribution functions (CDF) of annualized returns for each option consisted of 1000 simulated samples.

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[1] The calculation of net present values and the annualized net income from different land use is described in detail by Castro et al. (2013) and Castro et al. (2015).

### 3.1.2. Approaches to determine compensation payments

Compensation payments play an essential role in ensuring the maintenance of socially desirable levels of agrobiodiversity (Larsen 2009, Krishna et al. 2013). Most schemes, however, derive compensations solely based on land opportunity costs, without taking into account the uncertainty related to the different types of land-use options (Kragt 2012). In this research, stochastic dominance and mean-variance are evaluated as tools to derive cost-effective compensation payments when financial and productive risks are integrated during the modelling process. Consequently, compensation payments do not address solely the expected return of individual land uses, but also risks and uncertainties.

Stochastic dominance is an approach with loose assumptions about risk aversion; thus, it includes a rather large set of risk attitudes and does not require a full parametric specification of decision-maker preferences (Hadar and Russell 1971, Levy and Levy 2001). Here, expected utility is a function of all moments of the probability distribution for economic return. To assess mutually exclusive options following the criterion of stochastic dominance there are two prominent decision rules, named first stochastic dominance (FSD) and second stochastic dominance (SSD). To meet the dominance criterion according to FSD, the CDFs of possible NPVs of the options must not intersect. When the CDFs intersect, FSD cannot discriminate between the alternatives (Knoke 2008b). Castro et al. (2013) introduced an example comparing the CDFs of expected NPVs for an environmentally-friendly option A(x) and a conventional option M(x) to explain stochastic dominance rules. Thus, an alternative A dominates alternative M by FSD provided that,

$M(x) − A(x) \geq 0, \forall\ x \in Z$ (1)

with at least one strict inequality.

Following FSD rules, when there is dominance of one investment over another, (see Figure 1, productive alternative's CDF is at the right of the conservation alternative's CDF), every non-satiated individual with a non-decreasing utility function would prefer that option in theory. This means that in order to convince a farmer to choose the less profitable option, a compensation payment able to shift the whole CDF of that option to the right of the more profitable choice is required (Figure 1).
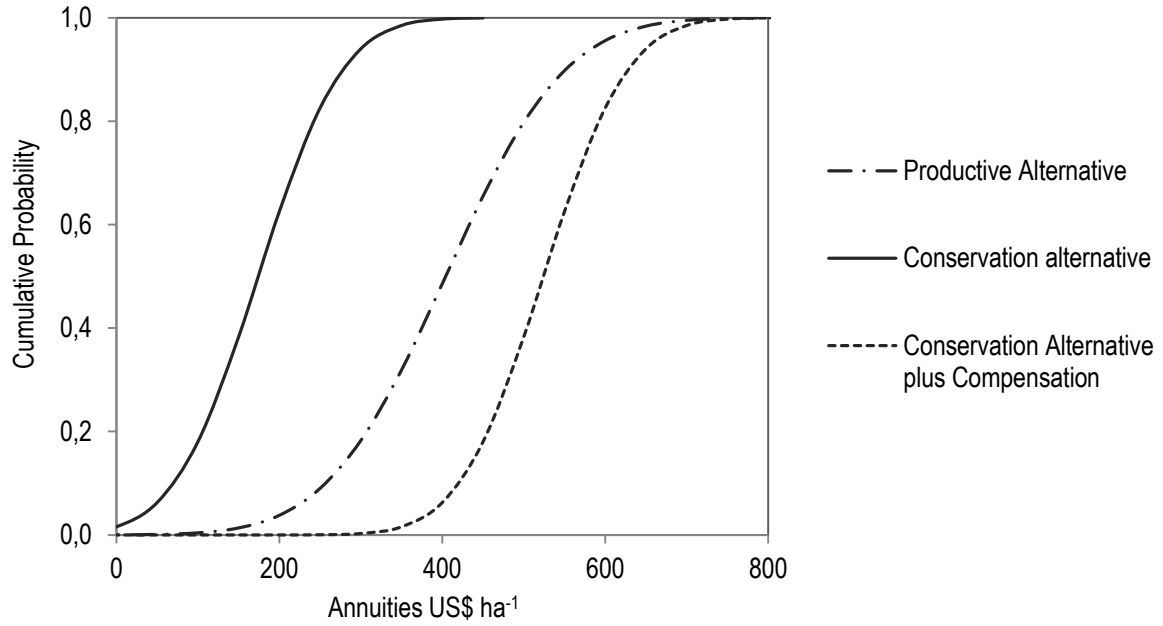
Figure 1. Compensation to shift the CDF of annuities of the conservation option so that it finally dominates the alternative (adapted from Castro et al. 2013)

Even though SSD considers risk aversion, decision makers with extremely small risk aversion (who may even be almost risk neutral) may also be included. To achieve SSD requires the area under the CDF for option *A* must be equal or smaller than the area under the CDF for option *M* for every *x*.

In this case, option *A* dominates option *M* by SSD if

$$\int_{-\infty}^{x} \big(M(z) - A(z) \big) dz \geq 0 \ \forall x \in R \qquad (2)$$

with at least one strict inequality.

Following SSD, the compensation required must at least be equal to the average land opportunity cost, provided that the environmentally-friendly option is less risky than the more profitable alternative; otherwise a risk premium must be paid on top of the land opportunity costs to convince all risk-averse farmers about the environmentally-friendly option.

Mean-Variance like Stochastic Dominance is a decision criterion based on the expected utility approach. The difference is that this approach considers only one specific utility function with well-defined risk aversion. Bearing in mind risk avoidance, various combinations of NPV and risk may generate an identical utility, because a reduced risk may compensate for a lower NPV and vice versa (Hildebrandt and Knoke 2011). An approximation to maximize the utility of a risk-averse person is the maximization of the estimated certainty equivalent, which represents the equivalent

risk-free value (NPV or annuity) that makes the risk-averse decision maker indifferent between receiving either this riskless value or choosing the risky prospect, with higher expected value (Adhikari et al. 2017). Compensation payments following mean-variance rules consist of the difference between the certainty equivalents of the two options. The certainty equivalent (Equation 3) reduces the maximization of expected utility to only two moments of the NPV (or annuity) distribution - expected value of NPV and its variance.

$$CE = E(NPV) - \frac{\alpha}{2} * \sigma^2{}_{NPV} \qquad\qquad (3)$$

With *CE* representing the certainty equivalent; *E (NPV)* the expected NPV; *α* the constant quantifying the degree of absolute risk aversion and *σ² NPV* the variance of the NPV. The constant for quantifying the absolute degree of risk aversion α can be estimated by *α =a/I*, with *a* representing the degree of relative risk aversion (e.g. a value of 1 for the moderate relative risk aversion and 2 for strong risk aversion) and *I,* being the initial investment or wellbeing[2].

3.1.3. Portfolio optimization applied for land diversification

The Portfolio Theory developed by Markowitz (1952) showed that investing in a combination of different financial assets (i.e. a portfolio) may reduce the risk when compared to an individual investment of the same profitability. Diversification has been widely suggested as a risk management tool to reduce the impact of fluctuating farm incomes (Libbin et al. 2004). Diversification applying optimization routines enables to identify different combinations of investments if the variability of their financial return is not perfectly positive correlated (k≠1). Thus, as suggested by Hildebrandt and Knoke (2011) diversification effects are helpful when investors are risk aversive. Risk neutral investors would prefer the asset with the highest expected financial return without regarding risk. In conclusion, the higher the risk aversion, the greater is the potential to gain expected utility by diversification.

In Castro et al. (2013) and Castro et al. (2015), Markowitz' theory is applied in combination with the von Thünen approach in a normative sense. Thus, models only constitute a recommendation for portfolio selection, in which farmers decide how land should be allocated to achieve the highest economic return for an accepted level of risk in a consistent way. Castro et al. (2013) applied these theories for an analysis of the effects that land-use diversification might have on the amount calculated as compensation payment. Here, considering an optimal land-use portfolio consisting of

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[2] The detailed explanation to estimate the initial wellbeing is given in Castro et al. (2013)

the two options under analysis, compensations to increase the share of the environmentally-friendly option were calculated.

Notice that for portfolio analysis the covariance and the correlation coefficient are very important elements to understand the tendency of returns to move together and describes whether the returns of two stocks tend to rise and fall together and how large those movements are. The correlation coefficient standardizes the covariance to create a relative and comparable scale of measurement between -1,0 and +1,0 (Libbin et al. 2004). This aspect has special relevance in Castro et al (2015) where the implications of the correlation of conventional and organic have been tested to assess the integration of both markets.

The expected financial yield of a portfolio with two or more assets V_p is obtained by adding the proportional expected financial yields of the single options through weighting with the area percentage fractions.

$$V_P = \sum_{i=1}^{n} f_i v_i \qquad (4)$$

with, v_i being the expected financial yield of a single asset i; f_i the weight of the single asset (the area based fraction of a specific land-use in our case), and, n the number of assets.

The SD of financial returns for the portfolio σ_p is quantified as follows,

$$\sigma_p = \sqrt{\sum_{i \in N} f_i^2 \sigma_i^2 + \sum_{i \in N} \sum_{\substack{j \in N \\ j \neq i}} f_i f_j cov_{i,j}} \qquad (5)$$

$$\sum_{i \in N} f_i = 1; \ cov_{i,j} = k_i \sigma_i \sigma_j; \quad f_i, f_j \geq 0$$

with i, j being the indices for the specific assets; N the set of available assets; f_i the weight (proportion) of a specific asset in the portfolio; σ_i the SD of returns for asset i; $k_{i,j}$ the coefficient of correlation between the returns for asset i and asset j; and $cov_{i,j}$ the covariance between the financial yields for asset i and asset j.

The portfolio was optimized using MS EXCEL © -solver, based on non-linear programming. The constraint of the maximum acceptable standard deviation of the portfolios was gradually relaxed by increasing the permissible risk. As a result, it was possible to calculate efficient portfolios that achieved the maximum financial return for each tested acceptable level of risk.

3.2. Case studies

Two case studies have been conducted to test the hypothesis raised in this research. The first one analyzes how intensive production of maize threatens shade coffee grown in agroforestry systems in south Ecuador (Castro et al. 2013) (Figure 2). In order to avoid further loss of shade coffee, the amount that in theory would compensate farmers for the forgone profits of producing maize was assessed. Here, the role of financial incentives such as compensation payments to revert land-use change patterns was assessed, taking into consideration different levels of aversion toward risks.

Figure 2. Land uses in South Ecuador: shade coffee (left), maize (right) (adapted from Castro et al. 2013)

An aspect that has rarely been considered for calculating compensations is the impact of risk on farmers' decisions. Thus, two probabilistic based-approaches, Stochastic Dominance and Mean Variance optimization, were evaluated first for mutually exclusive land uses, and later for portfolios containing shade coffee only in part.

The second case study explores the feasibility of introducing organic banana subject to various levels of uncertainty into land-use portfolios in a highly productive area of Ecuador –the Babahoyo sub-basin- where the most important cash crops are produced (cacao, soybean, maize and rice) (Castro et al. 2015). Banana -the main export-oriented agricultural commodity in Ecuador- is generally produced under very intensive agricultural practices (Baquero et al. 2004). Due to the importance of banana to the local economy, the extent of the area currently under production and the impacts caused by the use of synthetic inputs, it is important to assess whether at least partial conversion to organic production might be economically attractive for local farmers (Figure 3). This conversion is meaningful in terms of ecological improvement and perhaps because of risk reduction, as prices for conventional and organic products are subject to different market conditions (Kilian

2006, Su et al. 2013). Two forestry options were selected as a complement to agriculture, balsa (*Ochroma Pyramidale*) and laurel (*Cordia alliodora*). Both species are able to thrive in lands formerly dedicated to agriculture, which make them ideal for reforestation in land undergoing degradation processes.

In an initial scenario, the coefficients of variation of prices (65%) and productivity (22%) for conventional banana were used as proxies to model uncertainty for organic banana. However, the correlation of prices for conventional and organic banana is probably more important than price volatility itself. The finding by Kleemann (2014), who points out that price for organic products are largely independent from prices for conventional products, suggests a coefficient of correlation of zero between the economic returns of both variants of banana. In this study, the coefficient of correlation between prices for organic and conventional banana ($\rho_{conv,org}$) was derived from price changes of documented wholesaler prices (International Institute for Sustainable Development 2014, Intergovernmental Group on Bananas and Tropical Fruits 2014). To be on the safe side, the effect of increasing correlation between economic returns of conventional and organic banana was also tested, possibly due to growing integration of both markets, by assuming $\rho_{conv,org}$ of up to +0.7.

As the modelling led to a very high SD and coefficient of variation of the economic return for organic banana (81%), the impact of a lower uncertainty of the economic returns of organic banana on the optimal land allocation in the portfolios was also tested. Assuming lower uncertainty is well justified and may be even more realistic compared to the initial scenario, where the price uncertainty of conventional banana dominated the large uncertainty of the economic returns. By setting the uncertainty of the crop productivity equal to zero a standard deviation of 95% compared to the combined standard deviation from crop and price volatility was observed. Thus, a scenario with reduced uncertainty of economic return for organic banana to US$ ±30 per Mg resulted in a coefficient of variation of organic banana's economic return of ±50%.
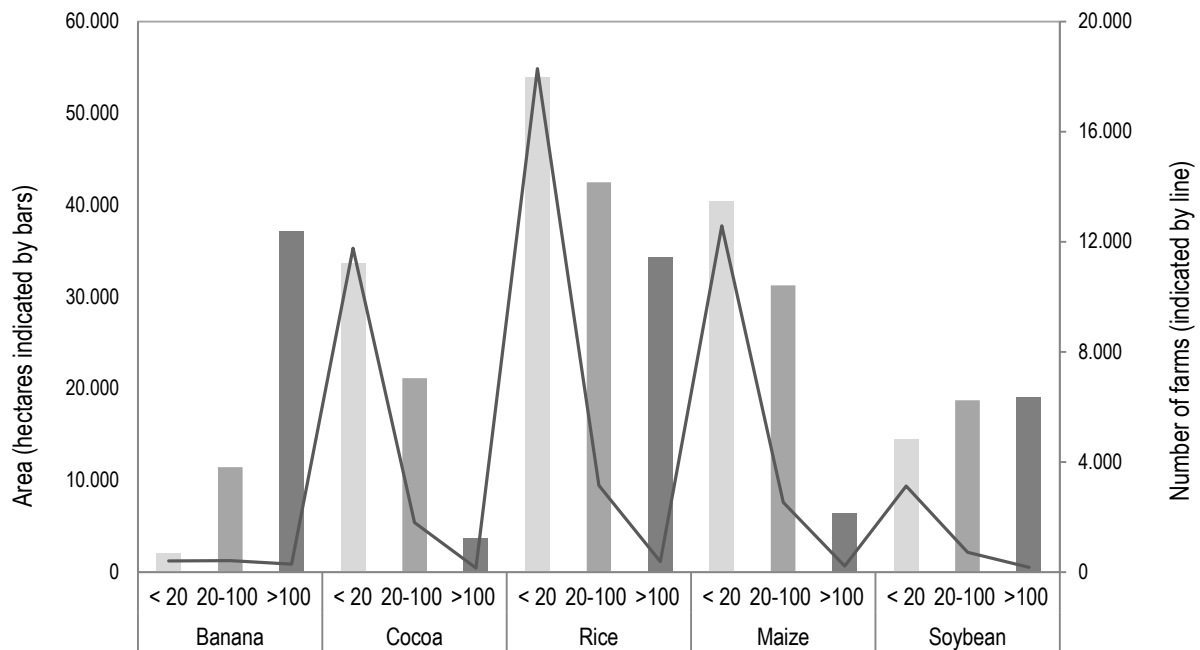
Figure 3. Crops in the Babahoyo sub-basin sorted by area of production, size and number of farms (SINAGAP 2013) (adapted from Castro et al. 2015)

3. 3. Review of bio-economic models applied to land-use problems

Bio-economic modelling has become a useful tool for anticipating the outcomes of policies and technologies before they are implemented (Delmotte et al 2013). There exists a large variation among bio-economic models as they aim to embrace biological and economic processes with various degrees of success (Brown 2000). Integrating both components requires the collaboration of multiple disciplines to understand and resemble the dynamic interrelationships between natural and socio-economic systems (Castro et al. Submitted).

Advances in mathematical programming have made it possible to improve modelling techniques and include multiple factors to build more plausible models, even when only limited data is available. The most commonly applied techniques for optimization are linear programming (Acs et al. 2007), non-linear programming (Clasen et al. 2012, Härtl et al 2013) and multiple objective programming (Knoke et al. 2016).

With the aim of analyzing the progress in bio-economic modelling applied to land-use issues a review of studies was conducted in Castro et al (submitted). The analysis identifies how aspects such as uncertainty, system dynamics, interactions and multiple objective programming have been incorporated in models aiming to support land-use decision making and resource allocation (Figure 4). Even though this topic has been explored in previous studies (Janssen and van Ittersum 2007,

Delmotte et al. 2013), these reviews did not analyze in detail the treatment of uncertainty in multiple-objective modelling and the use of non-stochastic optimization methods.
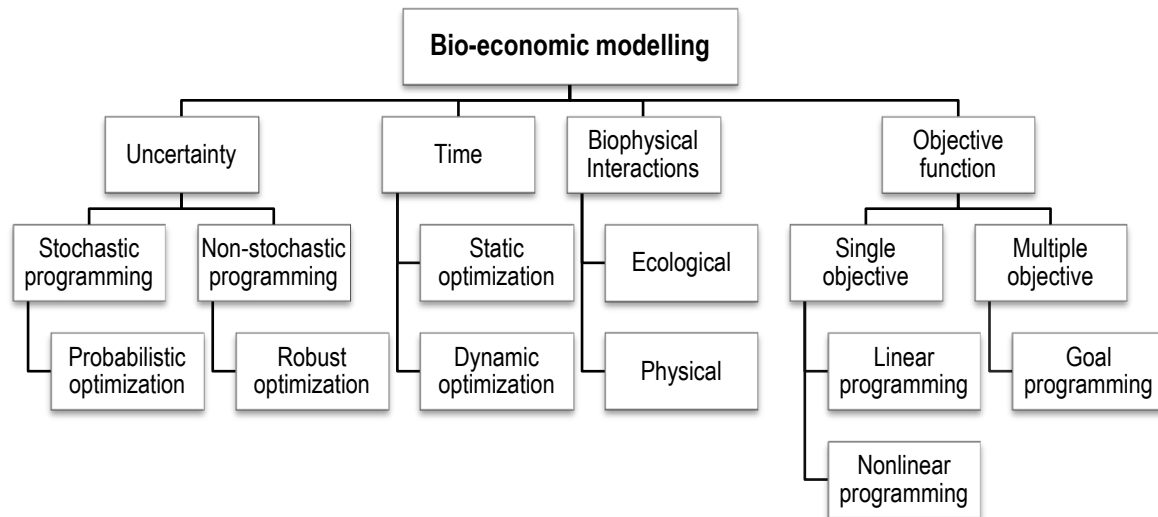
Figure 4. Description of components recommended for achieving integrated bio-economic modelling applied to land-use management (adapted from Castro et al. submitted)

The literature search included scientific platforms such as ISI Web of Knowledge, Scopus and Google Scholar. The search was focused on bio-economic models applying mechanistic and normative approaches in the field of land-use management at the farm level. With the set of articles fitting this required frame, the next step consisted in analyzing the way the authors treated the aspects concerning this study as shown in Figure 4 and the mathematical programming techniques employed to solve the problem of resource allocation. This step allowed to evaluate whether the complexity with which models are formulated and developed enhance the overall performance of land-use models to guide decision making at the farm level.

4. Results and discussion

This chapter summarizes the findings obtained with the three papers that form part of this dissertation thesis, in which decision making under uncertainty have been applied to promote sustainable alternatives in areas currently dominated by conventional farming. The results constitute a basis to analyze the advantages and limitations of applying uncertainty to calculate compensations and optimal land use portfolios following diversification approaches. The scenarios simulated serve as recommendations for farmers to use their resources in farming systems able to deliver ecosystems services with the least impact on revenues.

4.1. Compensation payments for agroforestry systems (Castro et al. 2013)

Annual returns simulated for shade coffee and maize are illustrated in Figure 5. Annuities of maize fluctuate from US\$ 6 to 584 (mean value of US\$ 294 ± 111 ha^{-1}year^{-1}), showing a greater dispersion than coffee which ranges from US\$ -14 to 279 (mean value of US\$ 128 ± 62 ha^{-1}year^{-1}). Since the CDF of maize was always to the right of that of coffee, maize dominated shade coffee by FSD. As a consequence, every non-satiated decision maker with a non-decreasing utility function would always prefer maize over coffee. In order to convince all landowners -even the risk seeking ones- about shade coffee, the required compensation to move the CDF of coffee to the right of the one of maize is as high as US\$ 294 ha^{-1}year^{-1} (difference between the maximum annuities of both options). Given FSD of maize over shade coffee, maize also dominates shade coffee by SSD (Figure 6). Thus, US\$ 166 ha^{-1}year^{-1} -the land opportunity costs- would be an acceptable compensation for risk aversive landowners following SSD rules. In our case, no risk premium is needed since shade coffee holds less risk than maize.

The application of MV resulted in smaller compensations because it assumes a higher degree of risk aversion than SSD, provided that compensation is secure. According to this method an amount of US\$ 86 ha^{-1}year^{-1} -difference between the certainty equivalent of maize and shade coffee- would be in theory capable of convincing moderate risk-averse landowners. Farmers with strong risk aversion would demand only US\$1 ha^{-1}year^{-1}, which basically means that they would not convert coffee plantations into maize. These findings confirm the first hypothesis of this study

H1: Mean-variance decision rules address farmers' risk aversion more proficiently than stochastic dominance and allow calculating more cost-effective compensations.
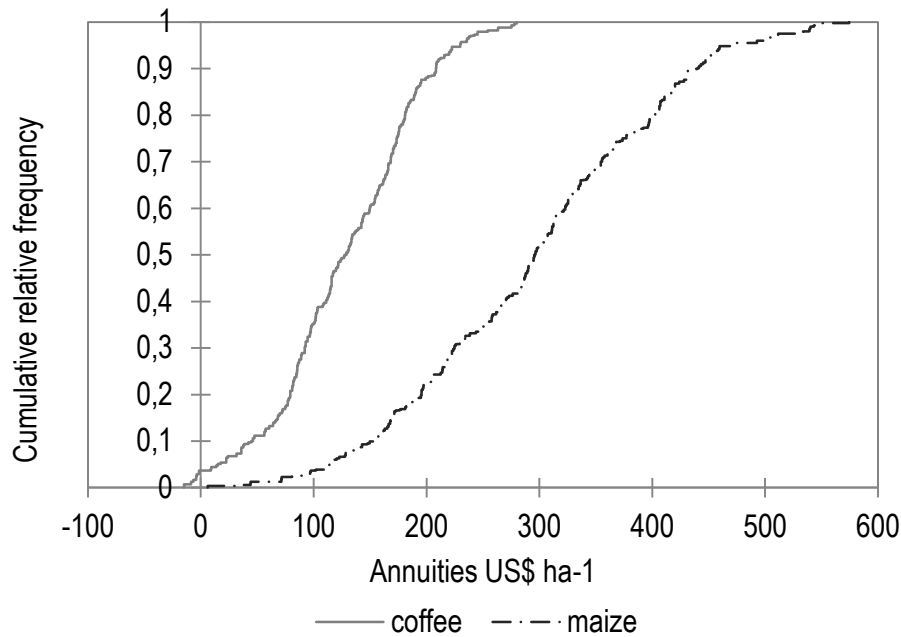
Figure 5. Simulated distributions of annuities for shade coffee and maize arranged in cumulative distribution functions (adapted from Castro et al. 2013)
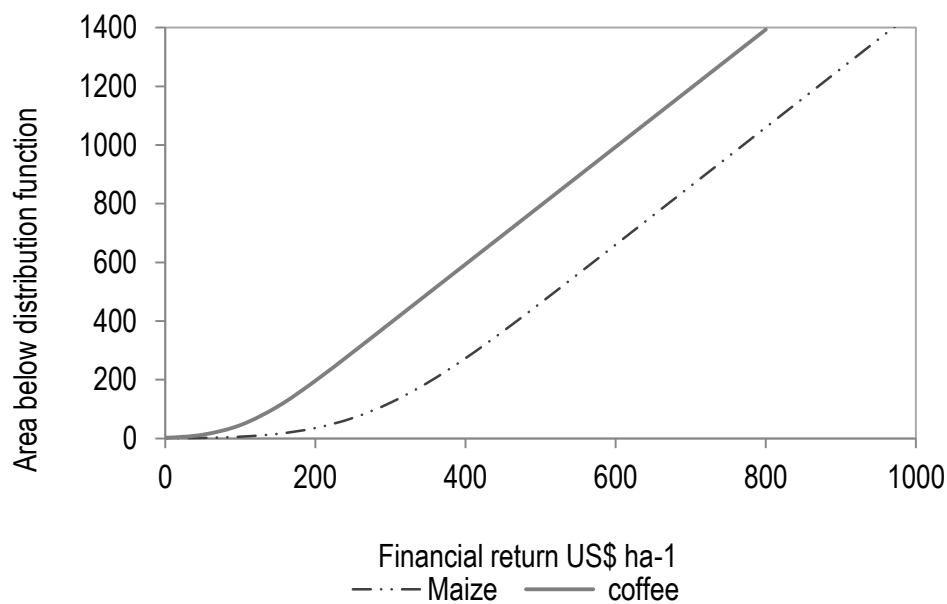
Figure 6. Second Order Stochastic Dominance of maize over shade coffee (adapted from Castro et al. 2013)

Note, however, that this holds only under the artificial situation of considering shaded coffee and maize as mutually exclusive land-use options. When combinations of shade coffee and maize were evaluated, and its impacts on the compensation payments, the situation changed significantly. The shares of several land-use portfolios are shown in Figure 7 considering two levels of risk aversion.

When strong risk aversion is assumed, the share of shade coffee is 51% and 49% for maize. This land-use portfolio had a mean expected value of US$ 218 $\pm$ 71 ha^{-1}year^{-1} having a better performance than shade coffee with regards to revenues which could make it very attractive for landowners. Those with moderate risk aversion would achieve the maximal certainty equivalent at shares of 73% maize and 27% shade coffee with expected return of US$ 261 $\pm$ 87 ha^{-1}year^{-1}. This portfolio has two outstanding outcomes compared to the mutually exclusive land uses. On the one hand, it doubles returns obtained by growing shade coffee alone; while in the other hand it achieves a lower standard deviation compared to maize. In other words, it is less risky and provides a slightly higher level of biodiversity by allowing for 27% of the area as shade coffee.
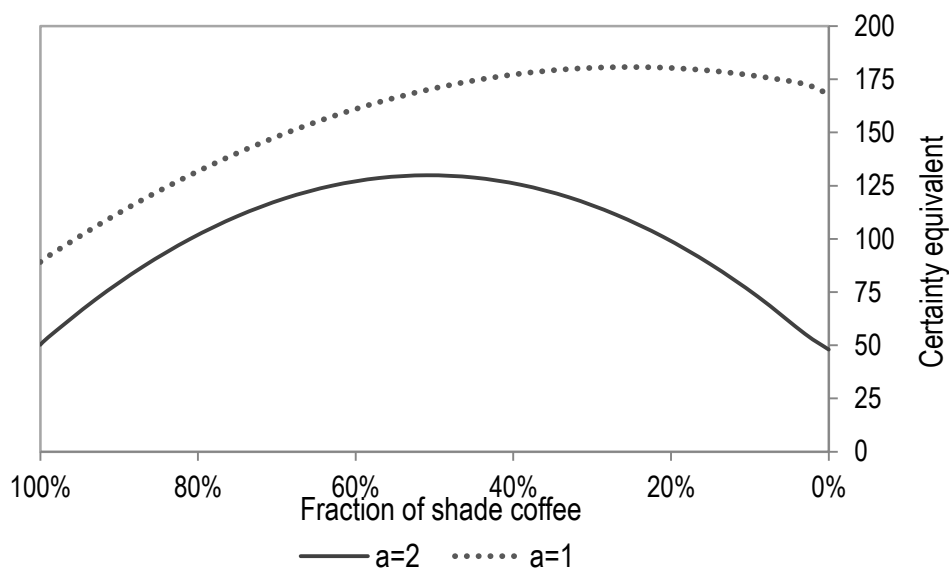
Figure 7. Optimal portfolio of assets combining shade coffee and maize based on the certainty equivalent (adapted from Castro et al. 2013)

As the optimal portfolio given moderate risk aversion is dominated by maize, a question that rose was: How much compensation would be needed to increase the fraction of coffee? The set of compensations capable to shift the optimal share of maize is presented in Table 2. For instance, to increase the fraction of coffee to 63%, a farmer with moderate risk aversion would demand US$23 while US$5 would be sufficient for a strongly risk aversive peer. Similarly, a rise in the share of coffee to 75% would require a payment of US$40 for moderately risk aversive land-users compared to US$19 for strongly risk aversive peers. This means that to achieve beneficial shifts in the land-use distribution from maize towards shade coffee for comparatively small compensations is sufficient, if some areas of maize are accepted, this analysis confirms the second hypothesis:

H2: Land-use diversification reduces the amount required to compensate farmers for switching to environmentally friendly land uses such as agroforestry.

Table 2. Compensations required to obtain a specific share of shade coffee in portfolios calculated for moderately and strongly risk-averse farmers in Pindal (US$ ha^{-1} year $^{-1}$) (adapted from Castro et al. 2013)

Portfolio share		Moderate risk aversion	Strong risk aversion
Coffee %	*Maize %*		
27	73	0	0
39	61	3	0
51	49	11	0
63	37	23	5
75	25	40	19
87	13	62	43
99	1	89	76
100	0	92	80

Note: A value of zero has been assigned when the estimated payment was negative

Both optimized portfolios broke FSD since their CDFs intersect that of maize (Figure 8). This means that the performance of the land-use portfolios was better than single shade coffee and not necessarily worse than maize resulting in more economically and ecologically desirable options.

Note that considerably higher compensation payments were required to achieve the optimal portfolio of 100% shade coffee (see Table 2) in comparison to the amount derived for mutually exclusive alternatives (moderate risk aversion: US$ 86; strong risk aversion: US$ 1). Therefore, it is not recommended from a methodological point of view to consider only mutually exclusive alternatives for deriving compensation.
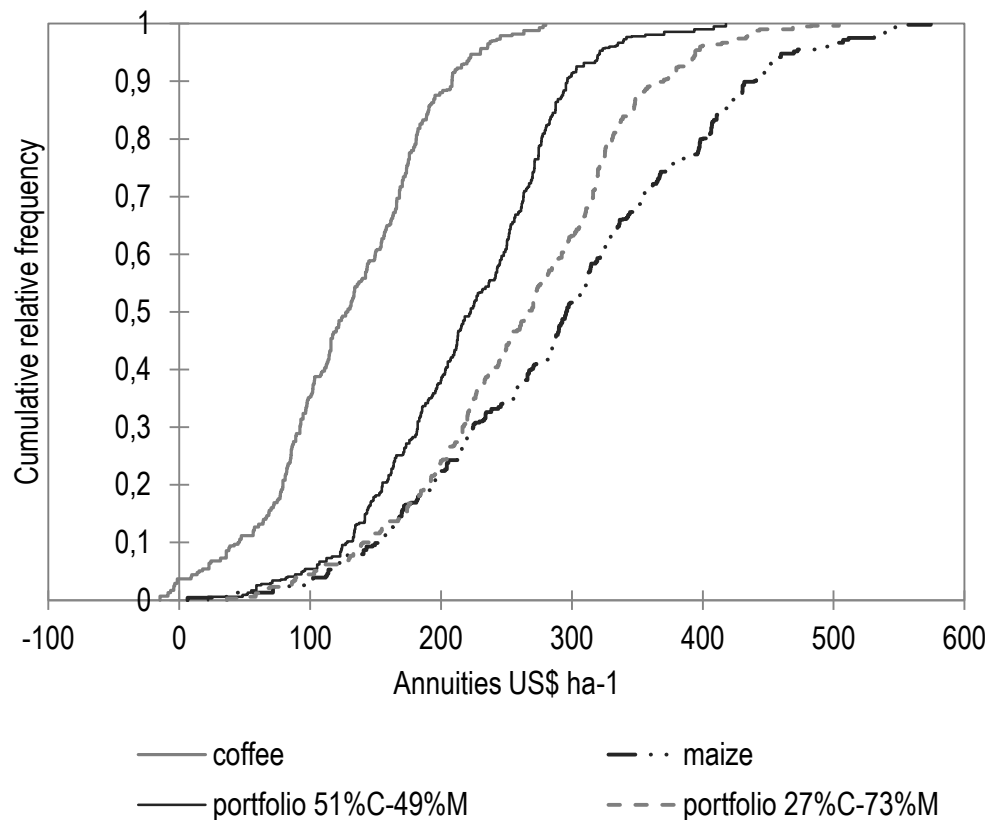
Figure 8. Cumulative distribution functions of exclusive land uses and two portfolios in southwestern Ecuador (adapted from Castro et al. 2013)

Main contribution: The incorporation of uncertainty is an essential step to support decision making at the farm level and to minimize the impact of risks by effective economic measures. Like other financial decisions, the calculation of effective compensation payments is directly affected by the attitude of the investor towards risk. By applying uncertainty analysis, compensations can be tailored following land owners´ preferences (Torkamani and Haji-Rahimi 2001). The results have shown that risk seeking investors –included under FSD- might demand a higher compensation than previous studies suggested (Benítez et al. 2006) to preserve a sustainable farming scheme such as shade coffee. Gloy and Baker (2001) have pointed out that stochastic dominance lacks discriminatory power, which explains why compensations tend to be so large, even under SSD. If one considers real risk-averse landowners, mean variance is more suitable than stochastic dominance, because it explicitly addresses risk aversion through a specific concave utility function, which results in a reduction of the compensation. Under this approach farmers might accept a lower compensation renouncing part of the financial return and accept a guaranteed compensation, as long as shade coffee is the less risky option. Only if the compensation is uncertain, a higher average payment could be necessary to address the risk-avoiding attitude of farmers regarding mean

variance rules (Knoke et al. 2008a; Knoke et al. 2009b). This kind of decision making is not applicable under SSD, where the dominant option must have an expected NPV at least as great as that of the alternative option.

The discussed study has shown that considering mutually exclusive land-use options and applying stochastic dominance may lead to excessive compensations. In real world decision-making, it may be quite sufficient to achieve considerable shifts in current conversion practices leading to greater fractions of the environmentally desirable land-use options. Optimization of land-use portfolios opens a new range of possibilities to calculate compensations for diversified landscapes. So far, most studies have compared only mutually exclusive land uses, the alternative of considering various land-use types simultaneously has been seldom addressed. If compensation schemes would consider diversified landscapes in which conservation alternatives are combined with productive options, land owners would enormously benefit (Knoke et al. 2009b). Diversification is a practice that indicates pronounced risk-aversion. Thus, it is likely that risk-averse farmers may opt for diversified systems in the face of uncertainty as a form of natural insurance (Baumgärtner and Quaas 2010). Land-use diversification led to reduced amounts of compensation to avoid land-use conversion towards more profitable options such as maize, as the results presented in this research have confirmed. The application of this method appears very useful in engaging farmers, because it identifies the best shares of assets providing ecological benefits but also including options which deliver high returns.

4.2. Diversification with high yielding crops: land-use portfolios with organic banana (Castro et al. 2015)

4.2.1. Economic return and risk for single land-use options

In this first part the economic return of individual land uses simulated by means of Monte Carlo simulation is presented. From the set of land-use options selected both forms of banana delivered exceptionally higher returns and risk (given by the standard deviation), compared to the other crops and forestry options (Figure 9). Annual returns for conventional banana were on average US$1786 ha^{-1} ± 945 and for organic banana US$ 1040 ±843 ha^{-1}. The great volatility is caused by the large fluctuations of prices and yields of conventional banana, which in this first approach were used as a proxy for the risk of organic banana. Organic banana achieved lower returns compared to conventional banana due to a reduced productivity of 35% and the increase of costs due to higher labor requirements. When market correlation of both types of banana is assumed, the worst case

scenario is more disadvantageous for organic banana (US$-1897) than conventional banana (US$-1557).

The economic returns for both conventional and organic banana were very high in comparison with the other crops. Nevertheless, high computed annual economic returns for banana seem quite realistic. For example, a study by Mukul and Rahman (2013) reported high annual economic return for banana between ~US$ 1200 to 2000 per ha for India. For the Ecuadorian case, banana also achieved higher gross incomes than other high profit crops such as sugar cane, potatoes, or African palm (Wunder 2001). However, the estimates for economic return of bananas reported in the literature are extremely variable, with annual economic returns up to ~US$ 3800 per ha in Bangladesh (Parvin et al 2013), while the maximum included in our Monte Carlo simulations was US$ 4808 per ha for conventional banana.
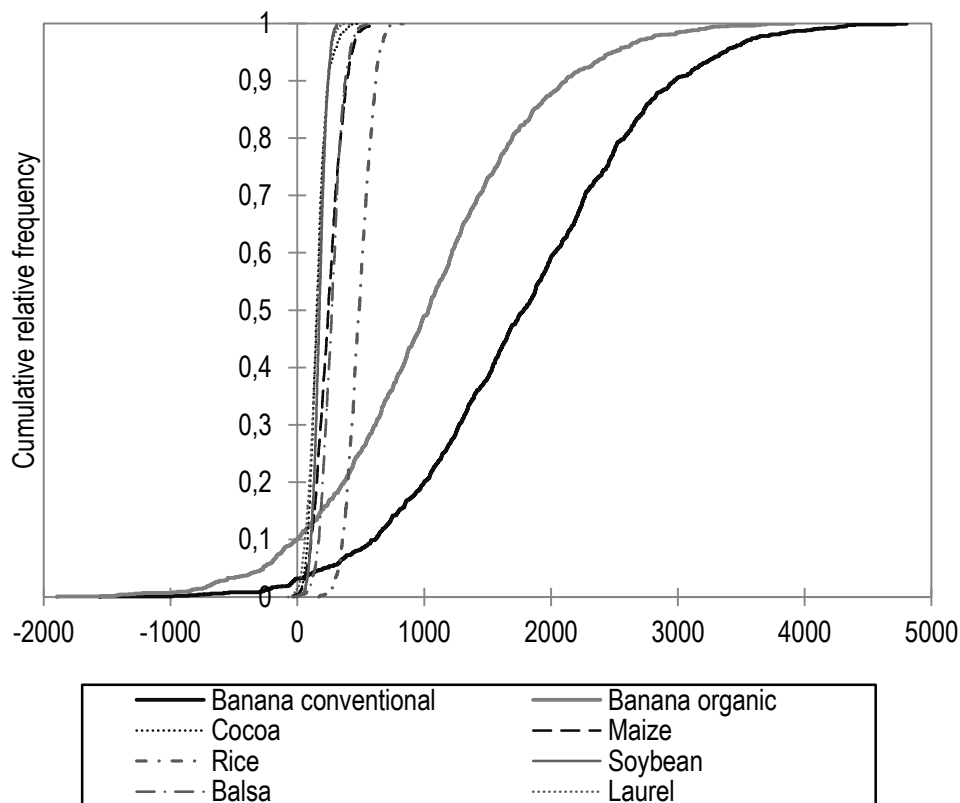
Figure 9. Simulated annuities for land-use options produced in the Babahoyo sub-basin (adapted from Castro et al. 2015)

The annual returns for all of the non-banana options were below US$500 ha^{-1}. An economic advantage of rice found by our modelling was that, even in the worst case, it was the sole option

45

which yielded positive annual returns (US$ 170). Among annual crops, the crop with the largest SD was maize, while soybean had the lowest. Permanent crops - forestry and cocoa were part of the group with low SD. In general, the distribution of the revenues derived from time data series was largely not significantly different from an expected normal distribution (Figure 10). Only maize $p(\chi^2)$ was below the required threshold of 0.10. Thus, the requirement for the analysis of economic returns to be normally distributed was regarded in general as largely fulfilled.
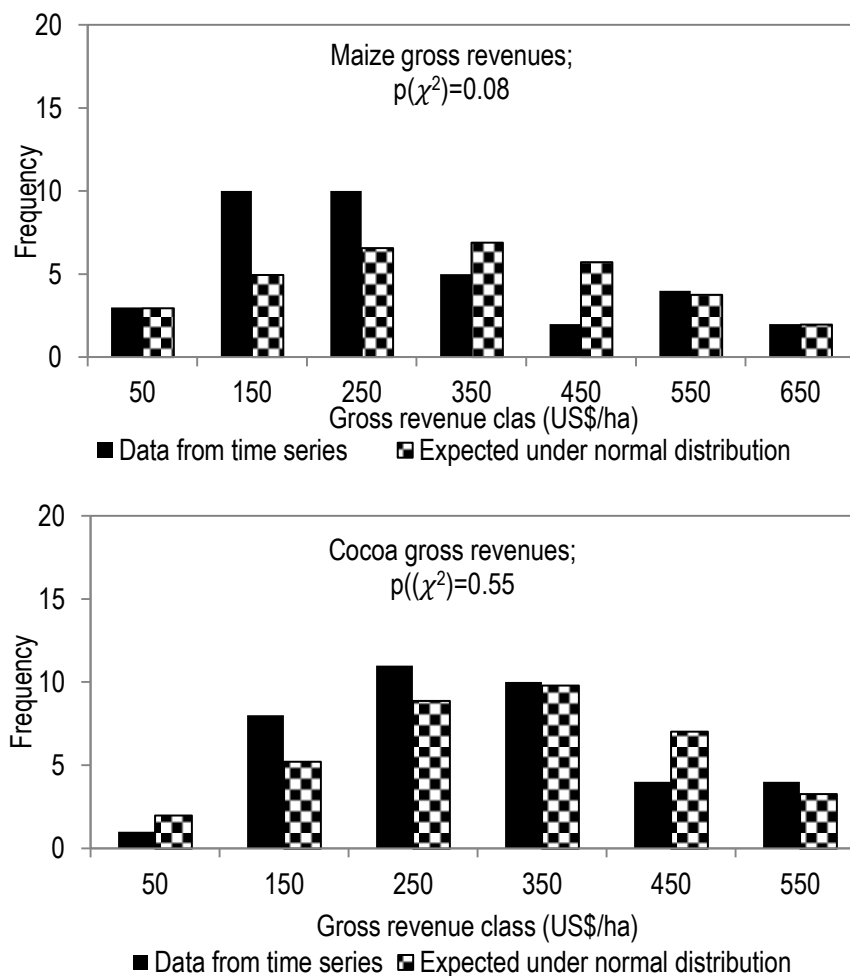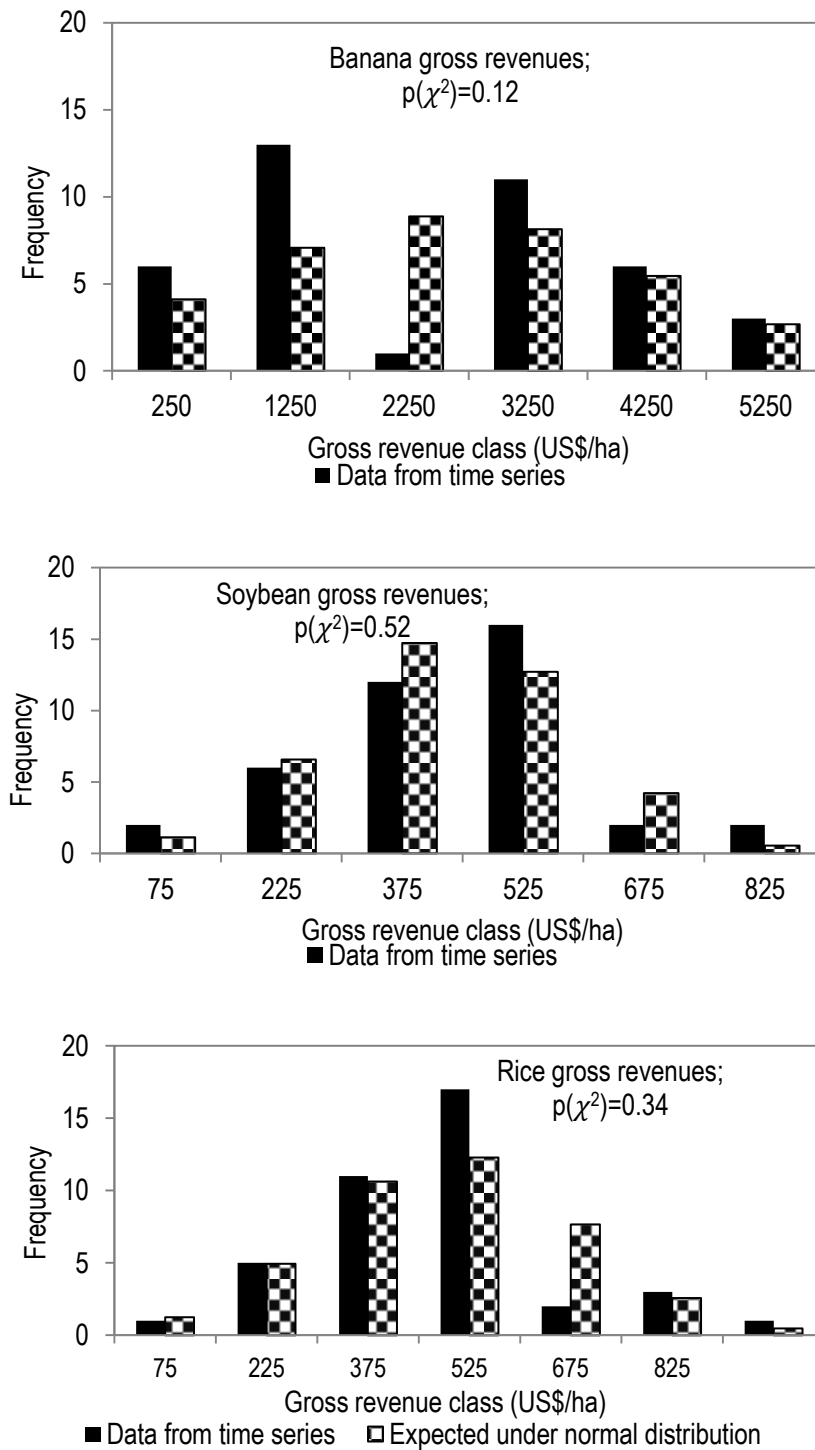
Figure 10. Distributions of gross revenues from time series data used for bootstrapping and expected distribution under the normality assumption. Organic bananas as well as forestry options were modelled by means of assumed normal distributions (adapted from Castro et al. 2015)

4.2.2. Correlation between prices for conventional and organic banana

Any portfolio-theoretic analysis demands a plausible idea about the correlation between economic returns. As data for organic banana was not available in FAOSTAT, time series were documented on wholesaler prices (International Institute for Sustainable Development 2014, Intergovernmental Group on Bananas and Tropical Fruits 2014). In general, the volatility of economic return for banana is driven by price uncertainty; consequently, the correlation between prices for organic and conventional banana is a good indicator for the correlation between economic returns (Table 3).

Table 3. Correlation coefficients of land-use options (adapted from Castro et al. 2015)

	Banana conventional	Banana organic	Cocoa	Maize	Rice	Soybean	Balsa	Laurel
Conventional banana	1.00							
Organic banana	0.02	1.00						
Cocoa	-0.01	-0.03	1.00					
Maize	-0.06	-0.01	-0.02	1.00				
Rice	0.02	-0.03	0.43	0.02	1.00			
Soybean	0.03	-0.01	0.36	0.01	0.59	1.00		
Balsa	0.04	0.02	-0.02	0.02	-0.02	0.00	1.00	
Laurel	0.01	0.02	0.03	-0.01	-0.02	-0.02	0.08	1.00

Organic banana seems to be an ideal complement for conventional banana, as price shifts for organic banana are independent or even slightly negatively correlated with price decline of conventional banana ($\rho_{conv,org}$= -0.1, see Figure 11). Moreover, when prices for conventional banana increase, also the prices for organic banana show a tendency to increase ($\rho_{conv,org}$ = +0.6).

4.2.3. Forming land-use portfolios

Several scenarios were modeled to test optimal combinations subject to restriction about risk tolerance. A reference scenario which exclude organic banana consisted of 14% cocoa, 10% maize, 37% soybean, 15% balsa, and 23% laurel obtained a return of US$ 191 ha^{-1} yr^{-1} $\pm$34 (Figure 12). A land-use portfolio of 2% conventional banana, 15% maize, 38% rice, 27% balsa, and 18% laurel would yield an expected return of US$ 352 ha^{-1} year^{-1} ±52. This portfolio has the same level of risk as soybean but the returns are considerably higher. Highly diversified land-use portfolios containing forestry options are more appealing for farmers with low risk tolerance, the proportion of high-return conventional banana increases with increasing risk tolerance (Figure 12). However, rice is also included over a large range of possible risk tolerances, while only those farmers who would totally disregard risks should work with conventional banana as a stand-alone option.
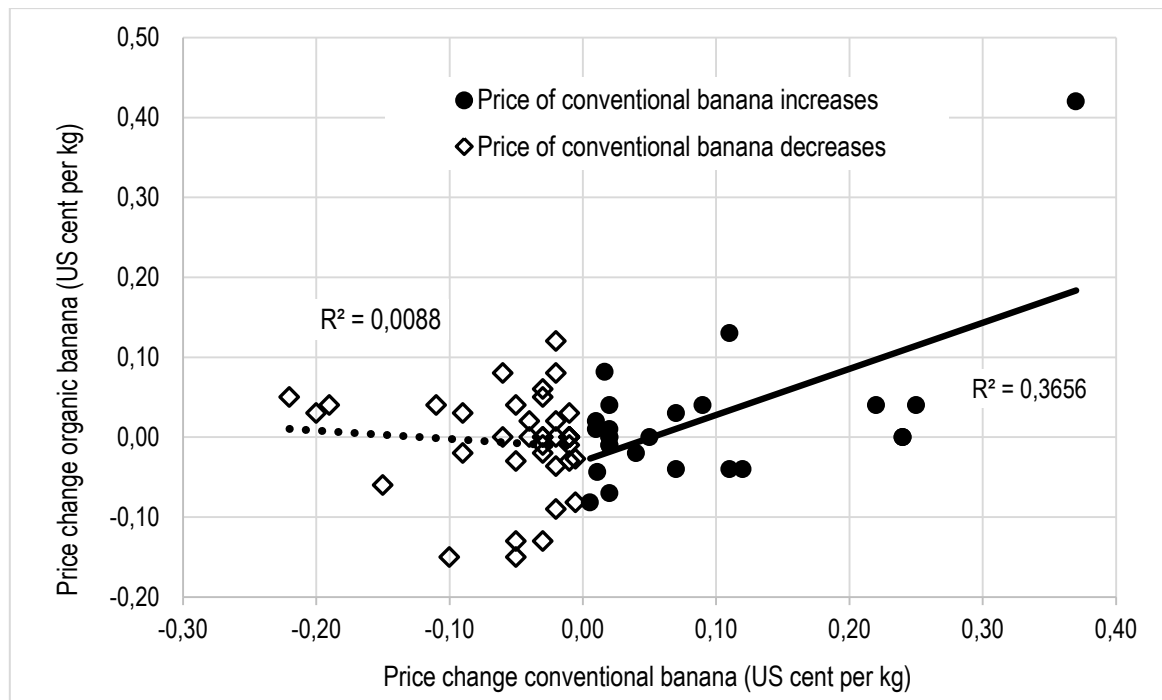
Figure 11. Correlation of price changes for conventional and organic banana (International Institute for Sustainable Development 2014, Intergovernmental Group on Bananas and Tropical Fruits 2014)

An interesting finding concerning organic banana to land-use portfolios was that this option was included in portfolios under a large range of tolerated risks, despite its large risk as a single option. Proportions for organic banana ranged between 1%, for a low tolerated risk (i.e. standard deviation, SD) of ±50, and 32%, for a tolerated risk of ±650. The proportion of organic banana only sinks to 5% when a very high tolerated risk level of ±900 is assumed (Figure 13a). To hedge uncertainties of organic banana as a single option, an excellent alternative was rice. A portfolio structured by 35% conventional banana, 19% organic banana, and 46% rice would achieve US\$ 1040 ha^{-1} year^{-1} ±369.
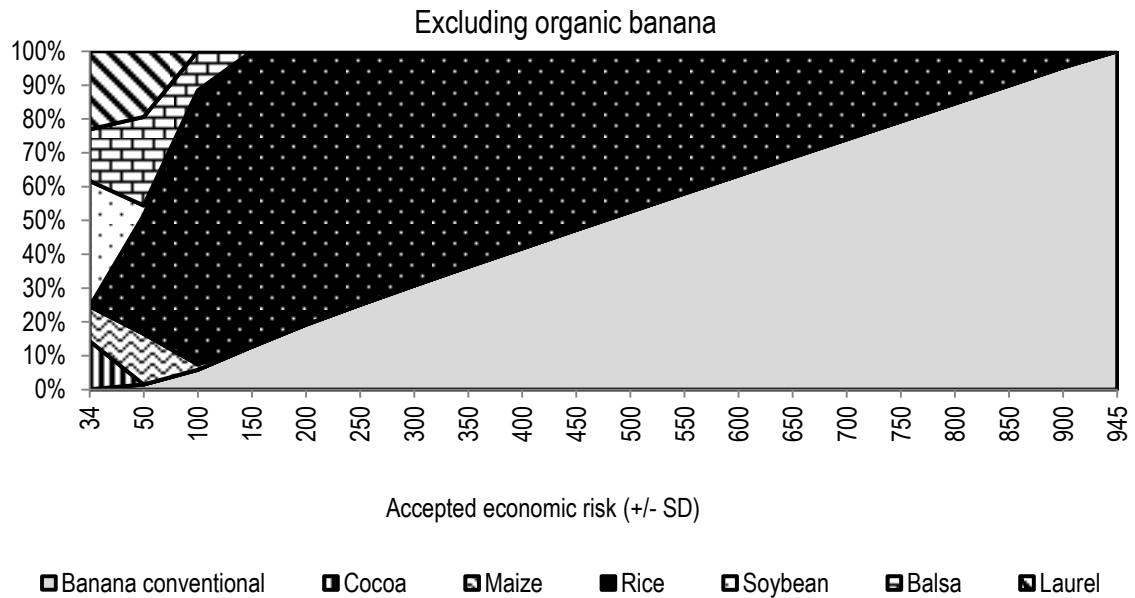
Figure 12. Structural composition of various land-use portfolios without organic banana for increasing levels of accepted economic risk

If, however, simulated risk of organic banana is modelled based on the volatility of retailer prices (resulting in ±506), the portfolio's structure would change significantly. Under the assumption of a lower uncertainty, the proportion of organic banana is greatly increased, up to 57%, and this on the cost of rice (Figure 13b). If an increased coefficient of correlation between organic and conventional banana is assumed ($\rho_{conv,org}$ of +0.5 or +0.7), the sensitivity of the results largely depends on the risk of producing organic banana. When simulated risk of organic banana followed the basic initial scenario, the increased correlation reduced the proportion of organic banana to a maximum of only 1% ($\rho_{conv,org}$ of +0.5). Organic banana is replaced by rice. Under a reduced risk scenario for organic banana, which appears to be a quite realistic assumption, the proportions of organic banana remain relatively stable, even if the correlation, $\rho_{conv,org}$, of the returns is quite high ($\rho_{conv,org}$ of +0.5 or +0.7). In summary, although organic banana appears less attractive as a single option, this option may, when embedded in land-use portfolios together with other crops, improve the economic return of Ecuadorian banana farms. This confirms the third hypothesis of this thesis

 H3: *The inclusion of sustainable land uses into efficient land-use portfolios is driven by the uncertainty of their economic return*

a)

Considering organic banana with high return volatility

b)

Considering organic banana with low return volatility
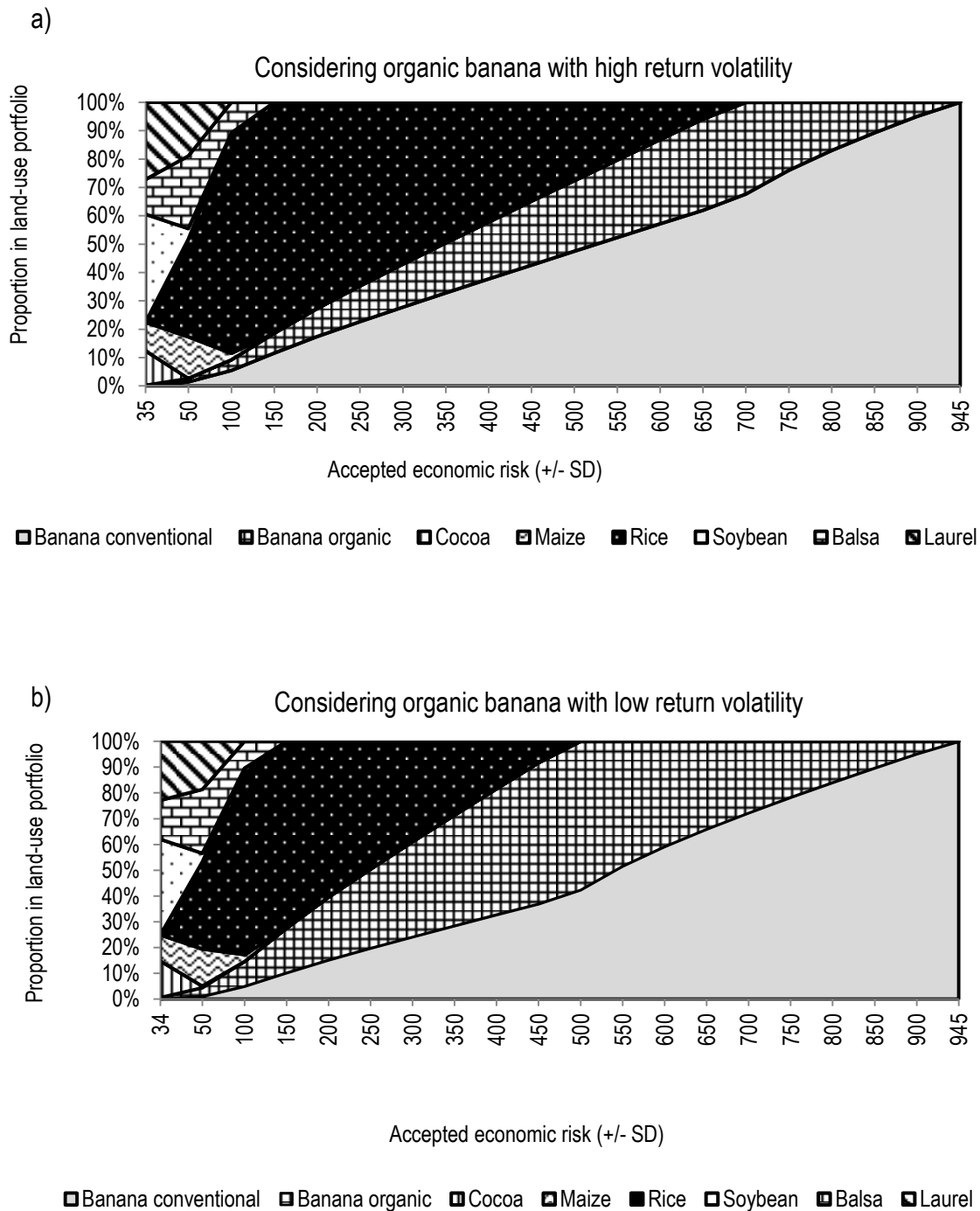
Figure 13. Structural composition of various land-use portfolios for increasing levels of accepted economic risk when organic banana is included and has high (a) or low (b) risks (Adapted from Castro et al 2015)

Main contribution: This study has proved that in areas of intensive and very high yielding agriculture shifts towards more sustainable land-use systems is challenging because farmers have at hand multiple mechanisms to cope with risks. Nevertheless, even under these conditions, land-use diversification provides benefits to farmers, but the level of diversification achieved was strongly

linked to the risks associated to the options as well as the comparatively high profitability of conventional banana with respect to the other options. While the forestry options diversified the land-use portfolios effectively rather for very cautious risk-avoiding farmers, organic (and also conventional) banana enters the land-use portfolios only, if higher risks are tolerated. The degree of diversification however is limited when high-yielding crops are included in the portfolios. For this case, including high-yield banana lowered the resulting degree of land-use diversification, limiting the portfolio to only a few land-use options. But still, every portfolio generated included at least two crops (except the maximum risk portfolio), so that no single-crop turned out to be optimal.

The alternative explored in this research was the introduction of organic farming on part of the farms, as a strategy to enhance ecosystem services provision while also reducing health hazards caused by the application of agrochemicals and reduce the dependency of farmers on rising fossil fuel prices (Liu 2008). Producing organic crops provides an opportunity for farmers in developing countries to participate in new markets (FAO 2016). Nevertheless, a shift towards organic production is tricky, and also risky, due to the changes and uncertainties which occur during the transition. Yield decline might be only the first obstacle for farmers who are used to producing high-yielding crops like banana. However, for such a situation this study proved the great advantages of embedding the organic banana parcels in a more diversified portfolio together with other land-use practices. So given that the price premium for organic products is likely to remain stable and that the market is still growing without a strong integration between the markets for organic and conventional products (Kleemann 2014), the allocation of significant proportions of land to organic banana appears advantageous for farmers.

4.3. Analysis of bio-economic models (Castro et al. submitted)

Given the experience gained with own bio-economic modelling, this section introduces an assessment of approaches to bio-economic modelling applied to land-use issues as a result of analyzing 30 studies related to this subject (see Publication 3 in Appendix). By identifying advances and shortcomings in bio-economic modelling it was possible to identify research gaps related to this field and to assess whether increasing the complexity enhances the overall performance of land-use models. The introduction of aspects such as uncertainty, time dynamics, biophysical interactions and objective functions and their contribution to achieve integrative models were assessed. The full description of studies can be found in the Castro et al. (submitted), the main findings are described in the next section.

4.3.1. Approaches to deal with uncertainty

According to the review, uncertainty was a topic occasionally addressed in bio-economic models. Fifteen studies applied the expected utility framework based on various objective functions (Figure 14). Among approaches to uncertainty, stochastic optimization was the most frequently applied method, with applications including downside risk analysis (Holden et al. 2004; Komarek et al. 2015) and mean-variance decision rules in agriculture (Rădulescu et al. 2014, Castro et al. 2015) and forestry (Clasen et al. 2011, Härtl et al. 2013). Studies applying non-stochastic robust optimization were less frequent, despite demanding less information (Knoke et al. 2015, 2016). Uncertainty has been rather neglected in multiple-objective models (del Prado et al. 2011, Koschke et al. 2012, Estrella et al. 2014, Paracchini et al. 2015, Cortez-Arriola et al. 2016), only two studies included risk analysis to situations where land allocation was optimized to improve the provision of multiple and uncertain ecosystem services (Rădulescu et al. 2014, Knoke et al. 2016).
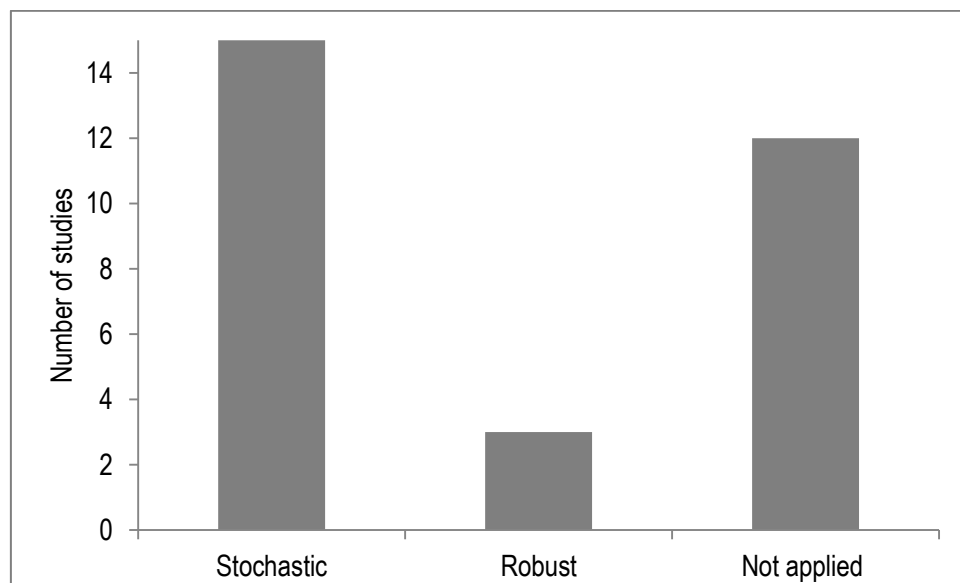
Figure 14. Approaches to include uncertainty in bio-economic models applied to land-use management (adapted from Castro et al., submitted)

4.3.2. Static versus dynamic modelling

Static modelling was more frequently applied among the studies under review; however, dynamic models are gaining room because of the advantages for adaptive decision making (Figure 15). There was not a noticeable pattern of preference related to the objective function or the optimization routine used by authors with the static or dynamic structure of the model. Static models have been applied for single objective functions solved by linear programming (Pacini et al. 2004,

Kanellopoulos et al. 2014) as well as by nonlinear programming in models where risk has also been incorporated as a restriction (Clasen et al. 2011, Doole et al. 2013, Schönhart et al. 2016). Models aiming to optimize multiple-objectives have also been addressed statically (del Prado et al. 2011, Cortez-Arriola et al. 2016, Townsend et al. 2016).

The improvements in dynamic approaches have made it possible to increase the number of studies where time is modeled dynamically (Holden et al. 2004, Pfister et al. 2005, Acs et al. 2007, Liu et al. 2016). Dynamic modelling has been applied by Barbier and Bergeron (1999), Acs et al. (2007) and Härtl et al. (2013). Interestingly, dynamic modelling has rarely been applied in combination with multiple-objective modelling. Thus, methodologies allowing both approaches simultaneously deserve more attention in the future.
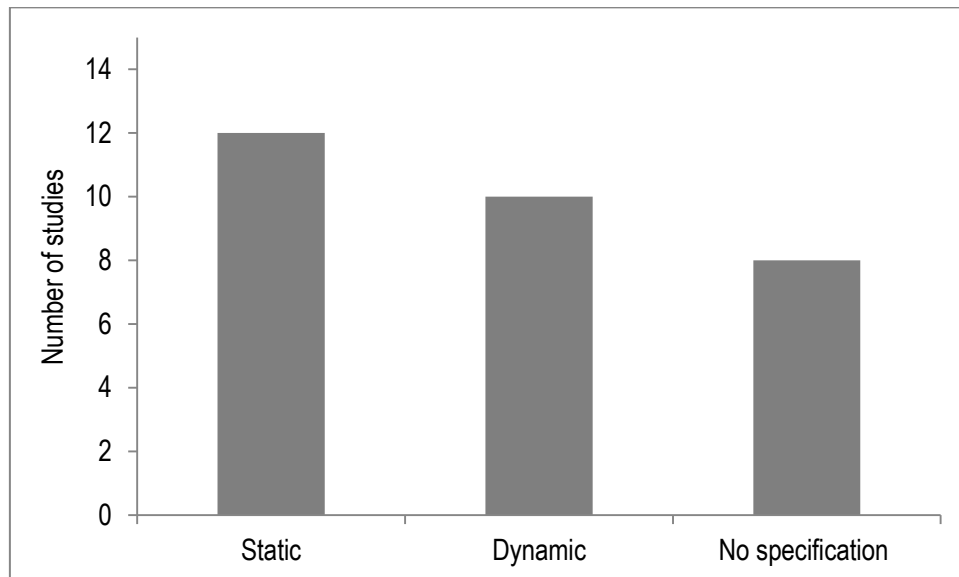
Figure 15. Approaches to address time in bio-economic models applied to land-use management

4.3.3. Biophysical interactions

The application of systems analysis and dynamics has been a precondition to include more variables and feedbacks to land-use models, which helps to explain interrelations in land use systems. The relation between inputs and crop yields have been analyzed in detail by Pacini et al. (2004), Acs et al. (2007), Ghebremichael et al. (2013) and Paracchini et al. (2015). These studies have analyzed the response of farming systems to improved technological change. Other studies addressed the impact of nutrient flows, climate change, water availability and soil management on cropping systems and profitability of farms (del Prado et al. 2011, Kanellopoulos et al. 2014). Biotic relations (competition for nutrients between individuals) are described in the literature using crop

growth (Pfister et al 2005, Semaan et al. 2007) and animal growth models (Ghebremichael et al. 2013, Doole et al. 2013).

Land degradation has also been incorporated into few models. In Barbier and Bergeon (1999) the biophysical component of the model includes soil erosion equations, and interactions among livestock, crops and forest. Holden et al. (2004) developed a model to assess the impact of improved access to non-farm income on household welfare, agricultural production, conservation investments and land degradation in form of soil erosion. Studies have also tested the effects of agro-environmental policies on farmers' income (Barbier and Bergeron 1999, Semaan et al. 2007, Doole et al. 2015) and willingness to accept payments (Kolinjivadi et al. 2015).

Even though the inclusion of system dynamics improves the understanding of a system in particular, it supposes a tradeoff between accuracy and simplicity. Models aiming to integrate relations and feedbacks among variables turn out to be more complex, expensive and time demanding. The disadvantage of overly complex models is the low generality, which limits extrapolation beyond the boundaries of the context where the models are created.

4.3.4. Single objective versus multiple-objective models

Despite that single-objective functions continue to be more frequently used, the application of multiple-objective models are raising, thanks in part to the development of new programming routines (Figure 16). Studies which consider multiple-objective functions are Paracchini et al. (2015), Rădulescu et al. (2014), Eyvindson and Kangas (2014), Estrella et al. (2014) and Koschke et al. (2012), Knoke et al (2016) and Cortez-Arriola et al. (2016). .

Most multiple objective models have largely excluded uncertainty and time interactions. Knoke et al (2016) is one of the few examples in which a model has included uncertainty by robust methods. Future applications should definitely include both aspects to support decision making.

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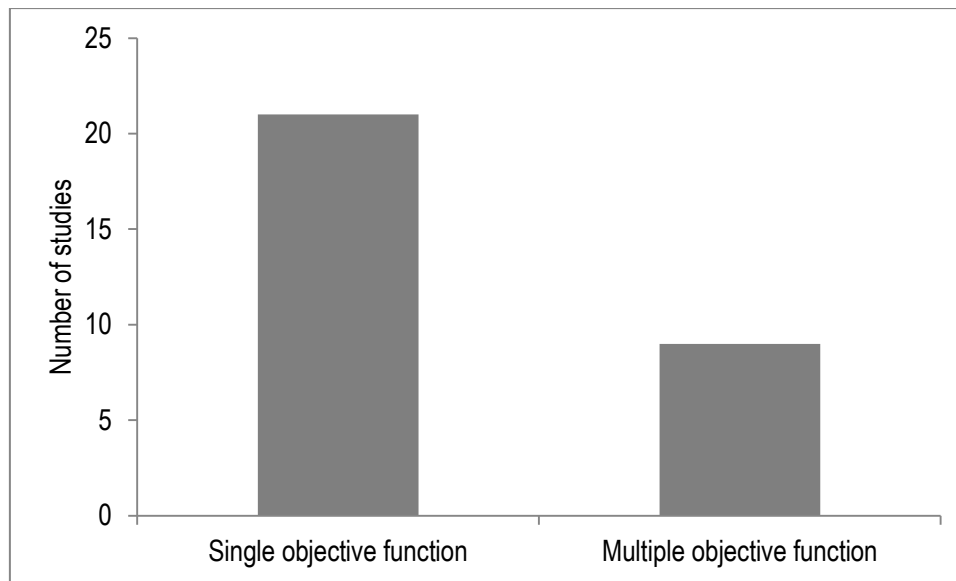
Figure 16. Bio-economic models applying single or multiple objective functions to land-use management (adapted from Castro et al. forthcoming)

It is important to highlight that due to the availability of improved programming techniques models tend to be in general more complex. Nevertheless, this situation involves an unavoidable trade-off between simplicity and accuracy. Increasing complexity makes models quite specific which reduces its range of applicability. A recommendation is to avoid the temptation to create overly complex models as simpler models still show plausible results. For instance, static models like the ones developed in this research are much easier to solve and can result in quite stable solutions and could easily be re-run from time to time to include new information, as recommended by Clark (2006) and Larkin (2011). This analysis confirms the fourth hypothesis of this research:

H4: Basic bio-economic models are more recommendable than complex models to support decision making

Main contribution: Even though bio-economic models are used as a tool to support decision making, there are still many aspects that should be improved in order to provide better information about the social, environmental and economic systems as well as their interaction. While none of the studies included all factors simultaneously, all of them included at least one aspect. Stochastic approaches seem to be increasing due to the availability of simulation techniques such as Monte-Carlo simulation. The non-stochastic approaches such as robust optimization deserve more attention for situations when only little information is available, but currently its application is limited to only a few cases. Expanding the uncertainty approach, especially to multiple-objective modelling would signify great progress in the field of land use modelling.

In general, bio-economic modelling has progressed in the last years due to accessibility to improved programming techniques, which has made it possible to create more comprehensive models embracing complex interactions and feedbacks. Nevertheless, researchers should be very cautious in adding variables because complexity might lead to black boxes. Overly complex models have the disadvantages of low generality which limits extrapolation beyond the boundaries of the context where the model was created. A general recommendation would be to avoid the temptation to create overly complex models as simpler models still show plausible results. To date, simple models seem be the most suitable option to model land-use issues in light of this research.

5. Conclusions and outlook

Based on the findings accomplished in this research, it was possible to draw the following conclusions:

The inclusion of uncertainty enables the calculation of cost-efficient compensations; the amounts calculated under risk aversion are lower than those solely based on opportunity costs. This factor must be analyzed by compensation programs currently running to use the funding in ways that can reach a larger number of farmers using the same amount of money available for the program.

Moreover, considering a diversified portfolio of land-uses instead of mutually exclusive options reduces the revenue gap among conventional and sustainable farming, as farmers can maintain both options in their farms. This aspect may have an enormous effect in enabling the transition from conventional towards more sustainable farming alternatives, as farmers can adapt to new technologies and knowledge required by agroforestry, organic farming or forestry. To increase the share of the sustainable land use beyond the optimal land use combination, the amount required as compensation is considerably lower than those meant for mutually exclusive options.

Sustainable farming options are attractive options to farmers as long as uncertainty of revenues is kept low; otherwise they cannot compete with intensive farming. If the coefficient of correlation of sustainable and conventional land-use option is low, they can complement each other proficiently, keeping risk to a minimum while achieving a noteworthy income.

Even though diversification can be compromised in the faith of extremely profitable crops, every portfolio generated in this research showed that no single-crop depicted an optimal economic performance –because they turned out to be highly risky. Thus, the role of uncertainty on decision making deserves more attention in order to design better policies to promote sustainable land uses, because farmers could accept slightly lower revenues provided that they involve less risk.

Despite that the models developed in this research are basically static; the approach can provide some interesting insights to elaborate recommendations about transition towards sustainable land-use. This type of analysis is more revealing than studies considering sustainable and conventional farming as mutually exclusive and less speculative than the option value approach, being particularly useful for new farmlands.

In order to achieve a better understanding of land-use decision making future research should incorporate uncertainty and multiple goals into the modelling framework. It is clear that a model that considers simultaneously two or more objectives can produce solutions with a higher level of equity than one that considers variables independently.

Finally, even though complex models are being enthusiastically applied to land-use issues recently, basic models have the advantage of being easier to solve and demand less information, time and funding. Interestingly, basic models can still provide plausible results and contribute to elaborating on instruments to improve land use allocation problems.

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9. Appendix

9.1. Publication 1

Castro, L.M., Calvas, B., Hildebrandt, P., Knoke T. (2013) Avoiding the loss of shade coffee plantations: how to derive conservation payments for risk-averse land-users[3]. Agrofororestry Systems 87: 331-347.

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Publication 1

Avoiding the loss of shade coffee plantations: how to derive conservation payments for risk-averse land-users

Luz Maria Castro · Baltazar Calvas · Patrick Hildebrandt · Thomas Knoke

Abstract We usually have only limited knowledge about the economic consequences of land-use decisions, thus they are uncertain. We analyze the implications of this uncertainty on conservation payments (CP) to preserve wildlife-friendly shade coffee production in southwest Ecuador, when conversion to maize is the most profitable alternative. Our objective is twofold: First, we analyze the consequences of applying Stochastic Dominance (SD) to derive CP, an approach making only minimal assumptions about the preferences of farmers. Second, we investigate the effects of land-use diversification to reduce CP by allowing for shade coffee on part of a landholding, and maize production on what remains. CP derived by SD turned out to be at least twice the amount calculated by an alternative method which maximizes a concave utility function—US\$ 166 to US\$ 294 ha^{-1} year^{-1} instead of US\$ 86 ha^{-1} year^{-1}. Given this result, we doubt that the assumptions underlying SD are reasonable for farmers, who are known to be risk-averse. Allowing for land-use diversification has a significant impact on CP. The optimal portfolio share of shade coffee is 27 % and for maize 73 % for moderately risk-averse farmers—without any CP. A larger share of shade coffee is preferable for strongly risk-averse farmers—51 and 49 % maize. The amount of CP necessary to encourage the expansion of shade coffee to 75 % is US\$ 40 ha^{-1} year^{-1} (for moderately risk-averse) and US\$ 19 ha^{-1} year^{-1} (for strongly risk-averse farmers). Stimulating diversification may thus help to significantly reduce CP necessary to preserve less profitable agroforestry options.

Keywords Biodiversity conservation · Agroforestry · Conservation payments · Uncertainty · Diversification · Mean–variance · Stochastic dominance

Introduction

Agroforestry systems are the most widespread wildlife-friendly farming practices in the tropics. Approximately 1.2 billion people depend directly on agroforestry products and services in developing countries. The practitioners are often poor people living in rural areas (Pandey 2002). Due to their diverse composition (trees and crops), these areas are able to deliver food, fiber and firewood to local dwellers (Ribaudo et al. 2010).

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Publication 1

Besides allowing the production of a wider range of goods that contribute to attain food security and to alleviate poverty, agroforestry systems provide additional socio-economic benefits to local dwellers (Pandey 2002; Baumgärtner and Quaas 2010). These benefits include diversification of assets, a buffer against natural calamities (e.g. pest outbreaks, drought, hail, etc.) and financial risks (price volatility, changes in demand and supply, etc.).

Agroforestry systems may also be cost-effective options for the mitigation of climate change in developing countries. These systems have the potential to remove and store atmospheric carbon dioxide through enhanced growth of trees and shrubs. They also provide shelter for local flora and fauna and connect isolated patches allowing the flow of species (Pandey 2002; Perfecto et al. 2005). Agroforestry systems are thus indispensible as buffer ecosystems surrounding areas with high conservation value (Koh et al. 2009; Perfecto and Vandermeer 2010).

Despite the benefits provided by agroforestry systems, they have not escaped the threat of conversion into more intensive land uses. The main reason for this is the rising demand for food and non-traditional energies (for example ethanol and biodiesel) that has encouraged farmers to opt for more intensive agriculture in order to obtain higher yields per unit of area (Green et al. 2005; Fischer et al. 2008). Negative externalities attributed to intensive agriculture such as the loss of spatial heterogeneity, and the degradation of water, soil and biota caused by the unsustainable use of fertilizers and pesticides have not been adequately considered (Sherwood and Uphoff 2000; Lichtenberg 2002; Parry et al. 2007; Hazell and Wood 2008; FAO 2010b; Power 2010).

Shade coffee is an important example of an agroforestry system which is widely applied by farmers in the lower montane regions of the Coast and the Andean valleys in Ecuador (Junovich 2002). Perfecto et al. (2005) consider traditional coffee plantations among the few remaining forested areas, especially in the mid-to high elevation ranges in many Latin American countries. In traditional plantations, coffee is grown under a structurally and floristically diverse canopy of shade trees, which provide habitat for a high diversity of associated flora and fauna (Perfecto et al. 2005).

Coffee is also a highly valuable commodity—one of the ten most important products for international trade in Ecuador, according to Junovich (2002). During the period from 1962 to 1984, the area cultivated with coffee increased from 152 to 345 thousand hectares. However, in 2000, the area under coffee production dropped to 286 thousand hectares, a decrease of around 17 %, in addition the existing coffee fields are old, poorly managed and the rate of renewal of the plantations is low, 80 % of the fields are older than 10 years, 12 % are between 5 and 10 years, and only 8 % are younger than 5 years, according to the III CNA[1] (Junovich 2002). This indicates that investments in proper shade coffee production are low; without any intervention it is thus likely that the area of shade coffee will further decline.

There are several factors behind the actual situation. A global crisis in the coffee market was triggered by a drop in the international price of coffee resulting from the disintegration of the International Coffee Agreement, market liberalization, the entry of new producers from South East Asia such as Vietnam into the market, as well as a substantial increase in production in traditional producing countries in Latin American like Brazil (Kilian et al. 2006; Ponte 2002). The resulting abrupt drop in the price paid to coffee producers during the 90s pushed many farmers to replace coffee with more profitable options such as maize.

The local and international demand for maize for ethanol and livestock feed increased substantially in recent decades (Alston and Beach 1996; Kosareck et al. 2001). According to the FAO (2010a), in Latin America and the Caribbean region maize is currently planted on over 29 million ha. In Ecuador alone, the area cultivated with maize increased by 20 % during the 1990s. Not only has the area under cultivation increased, but investments expanded by US$ 20.3 million during the period 2007–2009 alone (MAGAP 2011).

Local and international maize prices continue to trend upwards. In 2007, the price paid to producers increased by 20 % in comparison to prices in 2006, and in 2008, maize prices increase by 24 %—the greatest increase in 8 years, according to MAGAP (2011). Increases in the demand and price for maize were not an isolated event taking place only in Ecuador. These increases coincided with the "Tortilla crisis" in Mexico, where maize and its products

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[1] III Censo Nacional Agropecuario (Third National Census for Agriculture and Livestock).

Publication 1

experienced a sharp rise in prices in 2007. This led to a deep-seated economic crisis in the country due to its citizens' significant dependence on maize—a staple food in Mexico (Murphy and Paasch 2009).

Given this background, a continuing pressure to convert shade coffee plantations into agriculturally intensified alternative land-use options is evident. Mechanisms must thus be found to preserve this important wildlife-friendly land-use option. The following chapter outlines how economic factors may influence farmers' land-use decisions. It will conclude with two specific objectives of our study. Subsequently, we present our methods, results, discussion and conclusions.

State of the art: Impacts of economic factors on land-use decisions

Understanding how farmers make land management decisions is critical to designing strategies to enhance the provision of ecosystem services delivered by areas under wildlife-friendly farming regimes, such as agroforestry systems. Profitability of a particular land use obviously encourages farmers to allocate land to it, nevertheless, motivations behind decisions are often more complex than simple profit maximization (Ribaudo et al. 2010).

First of all, through prices, well-functioning commodity markets influence what farmers produce with their land, and how resources can be most efficiently allocated in order to maximize profits. In contrast, markets for most ecosystem services are generally not well developed. As a result, market signals tend to lead producers to opt for agricultural commodities (Ribaudo et al. 2010).

A second key factor to consider is farmers' time preferences (Amade et al. 1990). If farmers place little value on the future, conventional intensive agriculture is favored, even if land degradation and pollution of the environment is associated. Farmers prefer to exploit their land for quick profits instead of thinking in the long run, because positive net revenues from land uses that include forest and agroforestry often lie far in the future (Benítez et al. 2006; Hildebrandt and Knoke 2011, Knoke et al. 2012). This situation might apply especially to farmers with insecure land tenure and limited access to funding.

Profitability of the asset is another factor to consider, because an investor's decision to enter in business will be influenced by this aspect. However, the ability of agroforestry systems to deliver yields that are comparable to more intensive land uses has not yet been proven, and authors still have differing opinions about this matter (Green et al. 2005; Perfecto et al. 2005). The emphasis on biophysical rather than socioeconomic research on agroforestry systems contributes to the uncertainty of farmers, because predictions about future prices, yields, political developments and risks of crop failure are as yet not really possible (Mercer and Miller 1998; Pollini 2009). This situation makes it difficult to categorically affirm that agroforestry can compete with more intensive land uses in terms of profitability.

In arriving at an investment decision, it is wise to weigh the uncertainties of the investment against its profitability. Agriculture is a business exposed to multiple natural (e.g. crop failure by drought or fire) and financial uncertainties (e.g. fluctuations of market prices), and farmers are generally considered to be risk-averse (Knoke et al. 2008a, 2011). The risk involved with the possible options can be an essential factor in assessing preferences, because risk-averse farmers tend to choose the option with the lowest uncertainty, despite the fact that the potential reward may be lower as well (Aimin 2010; Ogurtsov et al. 2008; Knoke et al. 2011).

Finally, due to market failures associated with externalities and the provision of public goods, the economic value of ecosystem services is seldom a factor in land-use decisions (Grieg-Gran et al. 2005). Offering inducements and compensations to farmers for the potential profits they must forego by maintaining wildlife- friendly systems is a possible option to internalize those services that are neglected by the market, and channel them to natural resource managers who generate these services (Pagiola et al. 2005; Grieg-Gran et al. 2005; Möhring and Rüping 2008; Engel et al. 2008; Kemkes et al. 2010).

However, CP must be calculated wisely in order to be effective. According to Knoke et al. (2008a) CP must fulfill two demands: they must be high enough to convince landowners, but not unnecessarily large as to render them unfeasible. Determining the optimal amount to be paid to landowners will depend on their risk preferences (Benítez et al. 2006; Knoke et al. 2008a). Effective CP can be calculated by applying the decision making under uncertainty approach, thus

Publication 1

incorporating the attitude of farmers against risks. However, CP schemes should also be combined with economic improvement of land use, as farmers need productive land-use options to satisfy the ever increasing food demand (Knoke et al. 2008b, 2012).

Given this methodological background, we have two objectives:

First, we want to assess the relevance of two economic approaches in deriving CP—stochastic dominance (SD) and mean variance (MD) (explanation below)—for the case of small-scale land-users in southern Ecuador having two alternative livelihood strategies—shade coffee and maize. Our goal here is to determine which of the above methods is the most appropriate in order to arrive to the most effective and efficient level of CP for farmers.

Second, we will address the fact that in heterogeneous landscapes, agroforestry and more intensive agricultural uses can coexist. For this situation, we apply Modern Portfolio Theory in order to calculate the optimal shares that each option should have, depending mainly on their performance in terms of economic return and uncertainties and allowing for a mixture of both land-use options.

Methods

Decision making under uncertainty

The effects of uncertainty on decision making have been analyzed in many fields of decision analysis (Bawa 1975; Machina 1987; Götze et al. 2008), though analysis of this aspect is relatively novel in natural resource management (Kangas and Kangas 2004; Benítez et al. 2006; Knoke et al. 2008a; Hildebrandt and Knoke 2011, Clasen et al. 2011).

Some economic studies use the terms 'risk' and 'uncertainty' interchangeably (Levy 2006; Hirshleifer and Riley 2002). Knight (1921) however, makes a distinction between uncertainty and risk: Risk is applied for situations where the decision maker can assign mathematical probabilities to the randomness which he faces, while uncertainty is used for situations where randomness cannot be expressed in terms of specific mathematical probabilities. However, we will follow the notion of Hirshleifer and Riley (2002) and use both terms to represent our limited knowledge about future decision consequences.

Probabilistic, risk-based approaches are useful conceptual tools for dealing with well-understood systems and for addressing highly repetitive events. A frequent constraint to modeling decision making is the unavailability of precise information about the occurrence of a specific future event and the randomness of the events occurring in nature. Nevertheless, it is possible to derive the probabilities of the outcomes using existing, mostly historical data. The estimation of probability distributions for economic outcomes is an important step for risk analysis. The quality and quantity of available information are important elements in determining the reliability of results, however (Hildebrandt and Knoke 2011). Estimates of the probability distributions of economic returns can be obtained with techniques such as bootstrapping or Monte Carlo simulation (Benítez et al. 2006, Hildebrandt and Knoke 2011). Economic return may either be expressed by the sum of discounted net revenues—known as net present value (NPV)—by annuitized NPV, or by internal rate of return. The frequency distribution of simulated results can be arranged in cumulative distribution functions to be used as empirical surrogates for the required probability distribution.

Since its introduction by Bernoulli (1738), most analyses of investment decision rules rely on the expected utility paradigm (Hildebrandt and Knoke 2011). The expected utility theory does not analyze risk and return separately; but rather considers the whole distribution of returns simultaneously (Levy 2006). This theory states that the decision maker chooses between uncertain prospects by comparing their expected utility values, i.e., the weighted sums obtained by adding the utility values of outcomes multiplied by their respective probabilities.

Utility functions provide us a method to measure the farmers' preferences for wealth, and the amount of risk they are willing to carry in the hope of attaining greater wealth. Several types of utility functions have been used to describe the attitude of the farmer towards risk (Kirkwood 2004). Someone who prefers to receive a safe economic return rather than risk a possibly lower return because a potential exists for a higher average return, is known as risk-averse. In contrast, someone who has no preference for safe or uncertain returns, as long as the expected average is equal, is known as risk-neutral. Finally, someone who prefers to risk the uncertain alternative rather than settle for the lesser, but more certain economic return is known as risk-seeking.

Publication 1

A farmer's attitude toward risk-taking determines the shape of his or her utility function: Thus, it is possible to use linear increasing utility functions for risk neutral farmers ($U'(x) > 0$; $U''(x) = 0$), convex increasing functions for risk seeking farmers ($U'(x) > 0$; $U''(x) > 0$), concave increasing functions for risk-averse farmers ($U'(x) > 0$; $U''(x) < 0$) and combinations of them.

Most studies use concave utility functions, as risk aversion is assumed to be a common among farmers (Levy 2006). According to Baumgärtner and Quaas (2010) farmers are assumed to be non-satiated and risk-averse, and thus a concave increasing utility function holds.

Selected approaches to calculate conservation payments (CP)

SD and MV are both methods that have been used for calculating CP (Benítez et al. 2006; Knoke et al. 2008a; Clasen et al. 2011). Given the assumption that farmers are risk-averse, our goal here is to assess which method provides the more cost-effective CP. To promote a better understanding of the methods used for calculating CP for risk-averse farmers, we provide the theoretical basis in the next section as well as its application to our case study.

Stochastic dominance

SD as proposed by Hadar and Russell (1971) provides a criterion for decision making under uncertain circumstances. The attractiveness of SD lies in its nonparametric orientation: SD criteria do not require a full parametric specification of decision maker preferences, but rather rely on general preference assumptions and do not make strong predictions about the statistical distribution (Levy and Levy 2001). Following the criterion of SD, expected utility is a function of all moments of the probability distribution for economic return. Application of SD rules is recommended for comparison between mutually exclusive assets (e.g. land uses); nevertheless joint distribution functions can also be simulated, as done by Benítez et al. (2006).

First order stochastic dominance Let's assume that a landowner must decide whether to invest in agroforestry, A, or maize, M, with NPV cumulative distribution functions (CDF) given by $A(x)$ and $M(x)$,

respectively. NPV is the sum of all appropriately discounted net revenues, as later explained with Eq. 6. In empirical analyses, the probability distributions A and M are unknown, and must be estimated from available data. Hence, we consider a finite, discrete sample of observations on returns for agroforestry and for maize as monoculture over T periods, and we interpret the given fluctuations of returns as a result of uncertain states of nature and markets.

Under SD theory, if one investment option dominates another, every non-satiated farmer with a non-decreasing utility function would prefer the alternative that is preferable according to first order stochastic dominance (FSD). Thus, agroforestry dominates maize by FSD if,

$$M(x) - A(x) \geq 0, \quad \forall x \in Z \qquad (1)$$

with at least one strict inequality. $A(x)$ is cumulative distribution function of expected NPVs for alternative A, $M(x)$ is cumulative distribution function of expected NPVs for alternative M, Z is the set of possible NPVs.

FSD contains no considerations about risk aversion. To fulfill the dominance criterion according to FSD, the CDF of possible NPVs must not intersect. In reality, however, the CDFs of NPV for two investment alternatives often intersect, in which case FSD cannot adequately discriminate between the alternatives (Knoke 2008).

If, however, CDFs intersect, or maize would even dominate agroforestry, some among the rational farmers would choose the conservation alternative A, only when a compensation C would shift the CDF of the agroforestry land-use to the right, until FSD of $A+C$ over M is achieved (Fig. 1).

The $A+C$ curve represents the NPVs of the agroforestry option plus a specific conservation payment amount paid to farmers for providing environmental services. Only under this condition, does the agroforestry alternative achieve FSD over the more economically profitable option—maize monoculture.

Second order stochastic dominance Now, let us consider that investors are risk-averse in addition to being non-satiable. In this case, second order stochastic dominance (SSD) can be used to choose between investment alternatives. Note, however, that here decision makers with extremely small risk aversion (who may even be almost risk neutral) are also included.

Publication 1
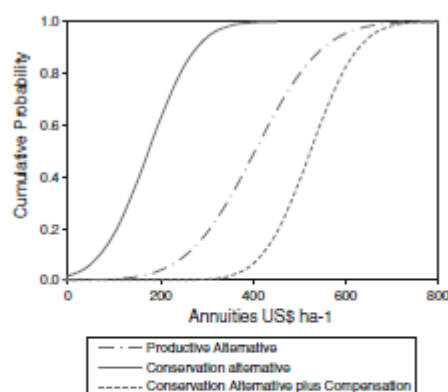
Fig. 1 Effects of compensation on the CDF of annuities of the conservation option

In this case, agroforestry dominates maize by SSD if

$$\int_{-\infty}^{x} (M(z) - A(z))dz \geq 0 \; \forall x \in R \qquad (2)$$

with at least one strict inequality.

SSD requires that the area under the CDF for agroforestry is equal to or smaller than the area under the CDF for maize, for every x. Every risk-averse, non-satiated farmer would then prefer the investment alternative that dominates by SSD. Under normally distributed NPV, the dominant option must have an expected NPV (estimated by the average NPV) at least as great as that of the alternative option. In this case, the amount of compensation required under SSD to make the conservation option dominating must at least be equal to the average land opportunity cost (i.e. the difference between the average NPVs of maize and agroforestry). This is true only if the agroforestry option is less risky than the maize alternative, otherwise a risk premium must be paid on top of the land opportunity costs to convince all risk-averse farmers to opt for the conservation option.

Mean variance decisions rules

In the context of financial theory, risk is often measured in terms of the standard deviation of economic return. Based on this consideration, investors with a risk-averse attitude would demand a greater-than-proportional increase in average NPV in order to accept an additional unit of risk, or they would renounce parts of the expected NPV to reduce their risks. Bearing in mind risk avoidance, various combinations of NPV and risk may generate an identical utility, because a reduced risk may compensate for a lower NPV and vice versa.

MV is widely used in the financial arena, because it can be applied to calculate fairly decent approximations, even in those cases where MV is not strictly compatible with expected utility (Hildebrandt and Knoke 2011). A common approximation used to maximize the utility of a risk-averse person is an estimated certainty equivalent (CE), which is calculated based on the negative exponential utility function $U(z) = 1 - \exp(-\alpha z)$; where α represents the absolute degree of risk-aversion.

Let's come back to our two options; A (agroforestry) characterized by low NPV and M (maize)—the more profitable option. A risk-averse farmer, by theory, would accept a smaller compensation for choosing agroforestry than the expected land opportunity costs, if he or she has the guarantee that the compensation is certain.

The differences in the CE between the two options may result in an adequate compensation amount. Note that Eq. 3 reduces the maximization of expected utility to only two moments of the NPV distribution—expected value (mean) of NPV and its variance being part of the so-called MV decision rules.

$$CE = E(NPV) - \frac{\alpha}{2} \times \sigma_{NPV}^2 \qquad (3)$$

CE is the certainty equivalent, E (NPV) is the expected NPV, α is a constant quantifying the absolute degree of risk aversion, σ_{NPV}^2 is the variance of NPV.

The constant for quantifying the absolute degree of risk aversion α can be estimated by $\alpha = a/I$, with 'a' representing the degree of relative risk aversion (e.g. a value of one for moderate risk aversion and two for strong risk aversion) and I, the initial investment. Spremann (2010) suggests the use of the reciprocal value of the initial investment to estimate the absolute degree of risk aversion α. For instance, the initial investment might be the land that must be purchased in order to start production.

To obtain the absolute degree of risk-aversion, we consider annuitized values rather than the land value. Knoke et al. (2011) use US$ 50 as the alternative

Publication 1

return from selling land and investing the land price (US\$ 1,000 per ha) at an interest of 5 %. Taking this annual amount of US\$ 50 as the initial wealth of farmers, values for α of 0.02 (1/50 for moderate relative risk aversion of one) or 0.04 (2/50 for strong relative risk aversion of two) result.

Diversification opportunities

The first part of our study (comparison of SD and MV) is focused on mutually exclusive land uses. However, under realistic circumstances, risk-averse farmers might find it optimal to have more than just one single asset. In fact, diversification is a common practice carried out by farmers in order to diversify risks—usually applied intuitively, without having enough economic information (Warren 2002; Baumgärtner and Quaas 2010).

Diversification effects are important for farmers showing significant risk aversion. If investors are risk-neutral, they would prefer the asset with the highest expected (average) financial return without considering risks, and thus leaving diversification more or less aside. Bearing in mind that farmers generally are risk averters, the utility gain implied by diversification is, however, notable (Warren 2002).

The selection of an optimum share of land uses (i.e. the optimal land-use portfolio) can be achieved following the approach proposed by Markowitz (1952), who reduces the optimum choice to a set of two criteria—economic reward (mean) and risk (variance). From the universe of all possible portfolios, the farmer should select one from the set of efficient portfolios, which means that for a given value of the mean financial return they minimize the risk, or, for a given value of accepted risk they maximize the mean financial return.

For the selection of a portfolio combining A (agroforestry) and M (maize), we use volatility of product prices and expected return as proxies for risk and reward. Out of the entire universe of possible portfolios, specific ones will provide the maximum reward for a given risk—what Markowitz called the efficient frontier of portfolios. The basic idea for portfolio selection is to compare assets at different ratios by their expected financial returns and their standard deviations. Summing the proportional expected single returns v_i (computed as the NPVs of single options)

results in the expected financial return V_P of a portfolio with two or more alternative investments.

$$V_P = \sum_{i=1}^{n} f_i v_i \qquad (4)$$

V_P is the expected NPV of portfolio, f_i is the fraction of a single asset (fraction of a specific land use in our case A and M), v_i is the expected NPV of a single asset i, n is the number of assets.

The standard deviation of financial returns can then be used to quantify the risk of a mixed investment:

$$\sigma_P = \sqrt{\sum_{i \in N} f_i^2 \sigma_i^2 + \sum_{i \in N} \sum_{\substack{j \in N \\ j \neq i}} f_i f_j cov_{i,j}} \qquad (5)$$

$$\sum_{i \in N} f_i = 1; cov_{i,j} = k_i \sigma_i \sigma_j; \quad f_i, f_j \geq 0$$

σ_P is the standard deviation of portfolio returns (set of risky assets), i, j are indices for specific assets, N is the set of available assets, f_i is the portfolio weight of a specific asset, σ_i is the standard deviation of returns for asset i, $k_{i,j}$ is the coefficient of correlation between the returns for asset i and asset j, $cov_{i,j}$ is the covariance between the returns for asset i and asset j.

Effects of diversification (decrease of risk for a given expected return or increase of return for a given risk) can be identified for different combinations of investments, provided that the variability of their financial return is not perfectly positive correlated ($k \neq 1$). The decision regarding the optimum fraction of the different investments depends finally on the risk tolerance of the investor—expressed by his individual utility function. The selection of the optimal portfolio can be made based on the CE of the portfolios (Eq. 3).

Farmers make choices from among different investment opportunities in order to maximize their expected utilities. One of the necessary conditions for making recommendations for optimal behavior in economic analysis is that an optimal portfolio cannot be inferior to another feasible portfolio.

Calculation of compensation payments (CP)

Deriving land opportunity costs based on the difference between the NPV of the productive options is a common procedure used to determine appropriate financial compensation (Knoke et al. 2008a). The NPV is calculated by means of the sum of all appropriately

Publication 1

discounted future net revenues coming from land management.

$$v_i = \sum_{t=0}^{T} r_t q^{-t} \tag{6}$$

v_i is the NPV of land use i, t is the considered point in time, T is the period of consideration, r_t is the net revenue at a given point in time; and, q is the discount factor ($q = 1 + i$, with i being the decimal interest rate).

To consider the time value of money, we apply a moderate interest rate of 5 %, following recommendations made by Pearce et al. (2003) and Knoke et al. (2009a, b). The average land opportunity costs are then,

$$LO = v_M - v_A \tag{7}$$

LO are the land opportunity costs, v_A is the NPV of agroforestry, v_M the NPV of maize.

Yearly payments needed in order to convince the farmer to choose the conservation alternative instead of the financially more attractive land use can be estimated by annuity calculations.

$$a_i = v_i \left(\frac{(q-1)q^T}{q^T - 1} \right) \tag{8}$$

$$y_c = a_M - a_A \tag{9}$$

where, y_c is the yearly compensation, a_A the annuity of agroforestry, a_M the annuity of maize.

The compensation payments—LO or y_c—would compensate for the expected land opportunity costs of choosing a specific land-use, causing a risk neutral

investor to be indifferent about whether to accept the compensation or choose the more profitable option.

Data collection and modeling

To estimate yearly net revenues for shade coffee and maize, costs and revenues are calculated. For shade coffee, expenditures (costs) include land preparation, planting, cleaning, pruning, shade control, harvesting, pulping, fermentation and drying costs. Revenues are calculated based on yields of coffee as well as plantain sales (*Musa paradisiaca*) because this species is used during the first years to provide shade instead of young trees. We do not consider timber sales because most of the trees used to provide shade have no commercial value. For maize, costs include land preparation, seeds, planting, fertilizers, weeding and pest control, harvesting, threshing and transportation of bags to collection centers. Revenues are calculated based on prices and yields of maize and coffee shown in Table 1.

Based on this information, we estimate net revenues as the product of price and yield minus costs. Yearly net revenues for the two land uses follow quite different trends over the 15-year time horizon, as shown in Fig. 2. Shade coffee for instance, requires a considerable up-front investment to establish the plantation and a delay of at least 4 years until the first harvest, while maize is able to deliver net revenues from the first year onwards.

Price volatility is commonly used to model uncertainty associated with investments in agriculture, because farmers often decide to enter and exit a

Table 1 Input coefficients used to calculate NPVs and sources to derive them

Land-use options	Item	Coefficient	Reference
Shade coffee	Establishment costs	US$ 1,455 ha^{-1}	Own calculation
	Maintenance	US$ 309 ha^{-1}	Own calculation
	Coffee yield	0.33 Mg ha^{-1}	Corral (2008)
	Coffee price*	US$ 1,440 Mg^{-1}	ANECAFE (2011)
	Revenues	US$ 480 ha^{-1}	Own calculation
	Plantain yield	2 Mg ha^{-1}	Own calculation
	Plantain price	US$ 140 Mg^{-1}	Own calculation
	Revenues	US$ 280 ha^{-1}	Own calculation
Maize	Annual planting	US$ 606 ha^{-1}	Own calculation
	Maize yield	3.36 Mg ha^{-1}	MAGAP (2011)
	Maize price*	US$ 264 Mg^{-1}	MAGAP (2011)
	Revenues	US$ 880 ha^{-1}	Own calculation

*Original values are given in US$ per hundredweight

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Publication 1
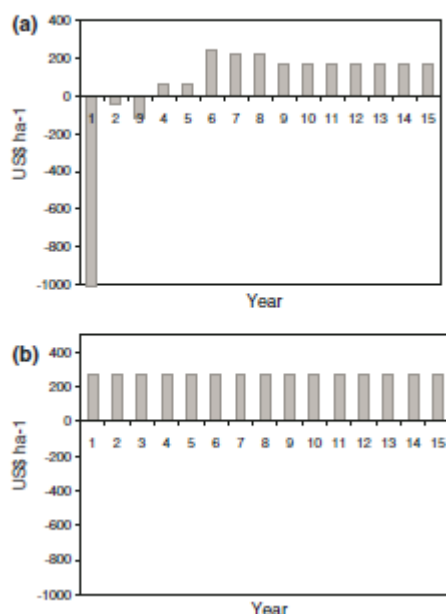
Fig. 2 Net revenues for a shade coffee and b maize produced in Pindal, southwest Ecuador

business based on price fluctuations in recent years (Dixit and Pindyck 1994; Benítez et al. 2006; Aimin 2010; Lewis et al. 2011). Following this criteria, we use price volatility to integrate risk into our modeling. To do so, price volatility for coffee, plantain and maize are estimated from time series data available from FAOSTAT (FAO 2010a). As price per ton is recorded in Ecuador's former currency "sucre" before 2000, conversion to US$ is carried out using annual exchange factors (Almeida 1992). Information after 2000 is available in US$. Statistics of the prices used during the modeling are presented in Table 2.

Table 2 Descriptive statistics for prices of cropping assets in Ecuador (US$ Mg^{-1}). FAO (2010a), with alterations

	Maize	Coffee	Plantain
No. of observations	38	42	42
Mean	253.0	914.1	43.9
Variance	12959.8	202867.6	256.7
Standard deviation	113.8	450.4	16.0
Variation coefficient (%)	44	49	36

Even though yield variability is also considered a factor of risk in agriculture (Price and Wetzstein 1999), we must mention that we have not included this variable due to the unavailability of records at the farm level. Revenues of maize and coffee are derived based on current production levels. Moreover a steady productivity for the three products is assumed. Obviously, neglecting yield variation can lead to an overestimation of returns since productivity is expected to decline over time due to overuse of land and/or natural hazards (Benítez et al. 2006).

As mentioned before, we focus on analyzing the performance of the mutually exclusive land uses in a first step. Probability distributions of returns are generated using bootstrapping. From the set of all feasible outcomes we draw a sample of 1000 repetitions to model CDFs for both options. To figure out whether FSD (Eq. 1) and/or SSD (Eq. 2) are given between mutually exclusive land uses, it is necessary to compare the CDFs of the annuities of shade coffee and maize. Land opportunity costs and compensations are then calculated using Eqs. 7 and 9, respectively.

The second step consists of testing the effectiveness of diversification for improving farmers' welfare. Land-use portfolios combining both shade coffee and maize are tested; however, the combination does not imply an intermingled mixture of maize and coffee, but rather separated areas of maize and coffee on the same farm. Correlation of prices from year to year is not considered. It is known that inter-annual correlation increases volatility, and might even justify more diversification. To compute net revenues, the corresponding prices of all three products are drawn from the same year; in this way we consider price correlation between product prices. Portfolio returns are calculated applying Eq. 4, while the standard deviation (risk) of the land-use portfolios is obtained with Eq. 5. Bearing in mind that farmers are risk aversive, the coefficient alpha is calculated considering two degrees of risk aversion (one for moderate, and two for strong aversion). From the set of feasible combinations, the shares with highest CE (Eq. 3) are selected as optimal land-use portfolios.
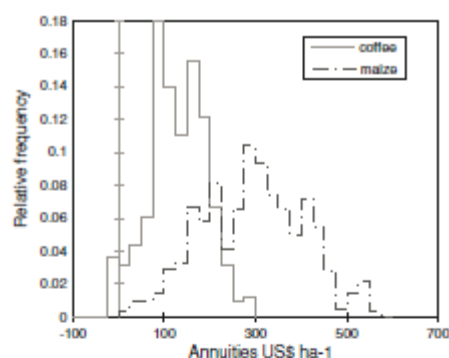
Results

Frequency distributions of the annuitized NPVs (annuities from here onwards) for shade coffee and maize
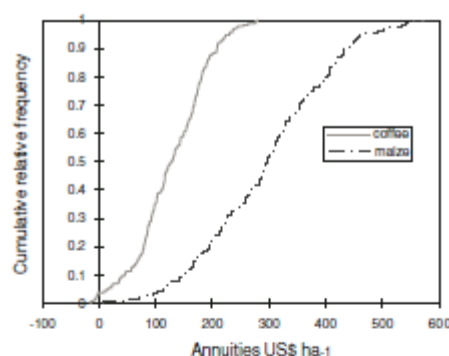
Publication 1

Fig. 3 Simulated distributions of annuities for shade coffee and maize obtained by bootstrapping

Fig. 4 Cumulative distribution function of shade coffee and maize in southern Ecuador

derived by resampling are shown in Fig. 3. Annuities of maize fluctuate from US\$ 6–584, with a mean value of US\$ 294 ha^{-1} year^{-1} (SD ± US\$ 111). The wide dispersion of simulated financial returns shows a considerable exposure of maize to price risks. Annuities for shade coffee range from US\$ −14 to 279, having a mean value of US\$ 128 ha^{-1} year^{-1} (±US\$ 62).

Since risk is measured in terms of the standard deviation, our results show that shade coffee holds less risk than maize, in spite of the higher volatility of coffee prices. The factor contributing most to reduce risk in this specific situation is the diversification achieved by farmers during the first stage by combining plantain and coffee. The standard deviation of shade coffee as land use is affected by the individual risk of each asset, and in the case of plantain the risk is lower than that of both of the other crops (see Table 2). In general, diversification of assets helps to reduce the exposure to unsystematic risk. This topic will be addressed in detail later.

Consequences of stochastic dominance for CPs

Regarding SD decision rules, maize dominates shade coffee by FSD, since the CDF of maize is always to the right of that of coffee (Fig. 4). As a consequence, every non-satiated decision maker with a non-decreasing utility function would always prefer maize over coffee. In order to convince all landowners to choose shade coffee, a compensation that assures FSD of coffee over maize by moving the CDF of coffee to the right of the one for maize is required. To

achieve FSD of shade coffee over maize and thus convince farmers to grow it, they require a CP as high as US\$ 294 ha^{-1} year^{-1} (the difference between the maximum annuities of both options). With compensation at this high level, all investors (farmers) will be persuaded to grow coffee—even the risk-seeking ones.

Given FSD of maize over shade coffee, maize also dominates shade coffee by SSD (Fig. 5). Since the mean financial return of coffee is US\$ 128 ha^{-1} year^{-1} and the mean financial return for maize is US\$ 294 ha^{-1} year^{-1}, a payment amount equal to the land opportunity costs (US\$ 166 ha^{-1} year^{-1}) would be an acceptable compensation to convince risk-averse landowners following SSD rules to plant coffee instead of
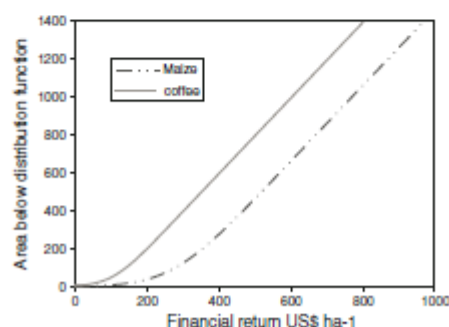
Fig. 5 Second order stochastic dominance of maize over shade coffee

87

Publication 1

maize. In our case, no additional risk premium is needed, since shade coffee holds less risk than maize.

As we have already mentioned, the term "risk-aversion" is much more inclusive under SSD as compared to MV. MV assumes one specific, usually higher degree of risk aversion than SSD, while SSD includes all degrees of risk attitudes, even very weak risk aversion. The application of MV thus results in lower compensation amounts because farmers with a stronger aversion to risk would accept a lower financial compensation compared to weakly risk-averse farmers, provided that compensation is not uncertain. The difference between the CE of maize and shade coffee would, in theory, be an amount capable of convincing risk-averse landowners. The necessary compensation derived by MV amounts to US$ 86 ha^{-1} year^{-1} for farmers with moderate risk aversion, which is only 29 % of the necessary compensation under FSD and 51 % of the necessary compensation under SSD. Farmers with strong risk aversion would demand only US$1 ha^{-1} year^{-1}, which basically means that they would not convert coffee plantations into maize. Please note, however, that this holds only under the artificial situation of considering shaded coffee and maize as mutually exclusive land-use options.

Diversification of land-use options

We also consider farms where diversification may take place through combining shade coffee and maize. We test several combinations of shares of both land-use assets and choose the land-use portfolios depicting the highest CE (certainty equivalent) as optimum (Fig. 6).
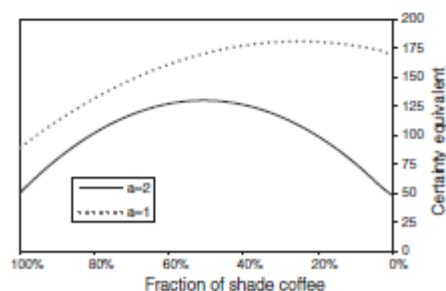
Fig. 6 Optimal portfolio of assets combining shade coffee and maize based on the CE

For farmers with moderate risk aversion (a = 1), the CE becomes maximal for shares of 73 % maize and 27 % shade coffee. The mean expected return of this portfolio is US$ 261 ha^{-1} year^{-1} ($\pm$US$87). This portfolio surpasses the returns obtained by growing shade coffee alone by about 51 %. Moreover, compared to maize alone it achieves a lower standard deviation—in other words, it is less risky—and implicitly provides a (slightly) higher level of biodiversity by means of including 27 % of the area as coffee plantation.

The fraction of shade coffee increases if strong risk aversion is assumed (a = 2); in this case the CE reaches its maximum at shares of 51 % shade coffee and 49 % maize. Since shade coffee holds less risk than maize, it logically results that a larger ratio would be preferable for risk aversive land-users. This land-use portfolio has a mean expected value of US$ 218 ha^{-1} year^{-1} ($\pm$US$71) performing better than shade coffee with regard to revenue as well as risk.

Nevertheless, maize covers the greatest fraction of land in the optimal portfolio, given moderate risk aversion. The question now is thus: How much compensation is needed to increase the fraction of coffee? Through our work, we calculate the compensation level that would be required to increase the share of coffee through a range of percentages (Table 3).

Table 3 Compensations required to obtain a specific share of shade coffee in portfolios calculated for moderately and strongly risk-averse farmers in Pindal (US$ ha^{-1} year $^{-1}$)

Portfolio share		Moderate risk aversion	Strong risk aversion
Coffee (%)	Maize (%)		
27	73	0	0
33	67	1	0
39	61	3	0
45	55	6	0
51	49	11	0
57	43	16	1
63	37	23	5
69	31	31	11
75	25	40	19
81	19	51	30
87	13	62	43
93	7	75	58
99	1	89	76
100	0	92	80

A value of zero has been assigned when the estimated payment is negative

Publication 1

Agroforest Syst

Like other financial decisions, the calculation of effective CP is directly affected by the attitude of the investor towards risk (Torkamani and Haji-Rahimi 2001). Risk-seeking decision makers, for instance, demand a higher compensation than their risk-averse peers for the situation we have investigated. Our results show that risk-seeking investors in southwest Ecuador, who are included in our calculations to achieve dominance of agroforestry under FSD, might demand a high level of compensation to preserve shade coffee: The amount of CPs that we have calculated is much higher, for example than that calculated by Benítez et al. (2006). The compensation calculated by applying FSD might convince every landowner, because the assumptions about risk are quite flexible and the amount may include almost every land-user. However, such high levels of compensation are not actually likely to be financially feasible.

Gloy and Baker (2001) have stated that, in general, the criteria for SD lack discriminatory power, which explains why the resulting set of compensations tends to be so large. Even the SSD rule includes decision makers with only negligible risk aversion—meaning land-users for whom basically "more is better",—and real risk-averters are not explicitly addressed here. The required CP calculated by SSD is still high however, and from the point of view of any conservation agency, it would be preferable to concentrate efforts in areas where opportunity costs are lower, as suggested by Benítez et al. (2006). The advantage of the compensation calculated by SSD is, however, that while the expected financial performance of shade coffee plus CP is the same as that of maize the risk is lower, so that one may assume SSD could actually convince farmers to preserve shade coffee plantations.

If one wishes to consider landowners who would renounce part of their potential economic returns to achieve less risk—let's call them real risk-averters—MV may be more suitable than SD because it explicitly addresses risk aversion through a specific concave utility function. This assumption narrows the range of possible investors, and also the set of CPs. Being that risk avoidance is the typical behavior adopted by farmers, MV appears more appropriate to derive compensations. The criterion for the calculation of CP is the CE of the options—in other words, the value of an investment option after adjusting for risk. Here, farmers might accept a lower compensation, thus renouncing part of the financial return in favor of a guaranteed compensation amount, provided that shade coffee involves less risk than maize. Only when the compensation is uncertain, is a higher average payment necessary to address the risk-avoiding attitude of farmers regarding MV rules (Knoke et al. 2008a, 2009b). This kind of decision making is not applicable under SSD, where the dominant option must have an expected NPV at least as great as that of the alternative option. Each approach thus has considerably different perceptions about risk.

CP schemes are regarded as a cost-effective method to prevent negative land-use change (Wunder et al. 2008), however most projects compare only mutually exclusive land uses: The alternative of considering various land-use types simultaneously to optimize the land-use share has thus far been relatively ignored (Knoke et al. 2011). Moreover, considering only mutually exclusive land uses increases the risk of leakage, because farmers participating in CP programs are not prevented from causing land-use change elsewhere. Knoke et al. (2009b) thus recommend including traditional land uses in CP programs to increase people's enthusiasm toward conservation initiatives. Taking into account farmers' local diversification strategies might allow the calculation of more realistic compensations, and could possibly also reduce concerns among locals about sovereignty and self-determination which can sometimes hinder the implementation of CP, especially in developing countries (Bacon 2005). An appropriate allocation of resources can help farmers increase their revenues, while keeping them productive and maintaining some biodiversity-rich areas (Knoke et al. 2009b).

Benefits of diversification in the face of uncertainty

One common strategy used by farmers to cope with financial risks is the establishment of agro-biodiversity-rich orchards, where a wide variety of species are combined (Rice 2008). Knoke et al. (2009a) highlight the financial benefits of combining assets having independent fluctuations of net revenues: One option may generate large net revenues while net revenues of the other asset might be less than expected, and vice versa. Diversification thus becomes an effective buffer against market fluctuations—reducing the impacts of economic booms and busts (Chapin et al. 2010). Adding forestry crops to traditional row crops on a

Publication 1

farm, such as planting additional timber or fruit trees, is a key strategy to maintain food sovereignty and manage risk within the household (Bacon 2005). Conservation policies that are based on compensation payments should be created using caution so that they do not serve to discourage this behavior: Financial subsidies can negatively affect diversification as it is no longer necessary as a risk reducing strategy (Di Falco and Perrings 2005). CP should thus be made conditional to the application of appropriate productive and diversified land-use alternatives.

Diversification also plays an essential role with regard to natural hazards, since it enhances adaptability. The positive interaction of trees and crops facing pests, diseases or weather events is a feature well documented in literature (see Torquebiau 2000; van der Werf et al. 2007; Nair et al. 2008), and among agroforestry systems, shade coffee is acknowledged for its advantages in this regard (Gordon et al. 2007; López-Gómez et al. 2008). The capacity to adjust to climatic changes and fluctuations in weather and in insect populations and to sustain ES is more limited in homogeneous landscapes when compared to rich biodiversity areas with greater capabilities for environmental response and functional diversity (Chapin et al. 2010).

Unfortunately, most farmers in the tropics still make decisions about the shares of assets intuitively and not necessarily based upon reliable economic information. Optimization of portfolios is thus a helpful tool for farmers, because it identifies the best shares of assets while holding risk to a minimum, and thus, the application of this technique may lead to better land allocation schemes. However, it is important to transfer this knowledge and these techniques to farmers in order to improve actual land-use.

Cost-effective conservation payments

One major concern arising from our results is the large quantity of funds, arising from the practice of considering land-use alternatives as mutually exclusive, that a conservation program would need to raise in order to compensate farmers for growing shade coffee. Our paper shows that considering mutually exclusive land-use options leads to excessive compensations, which appear to be not realistic. In reality, it may be sufficient to achieve considerable shifts in current land-use practices leading to greater fractions of the

environmentally desirable land-use options. It is thus rather unnecessary or even unrealistic to have only the conservation option, without including profitable land-use options at all. Considering mutually exclusive land-use options push conservation policies into ethical conflicts: the need to produce enough food is a high priority. We may thus state conclusively that in deriving appropriate CP, multiple land-use options must be considered simultaneously (Knoke et al. 2011).

Effectiveness of CP could be improved by either concentrating efforts in areas where opportunity costs are lower, or by reducing opportunity costs. This last option is essential, since low yields are often a triggering factor for agricultural expansion and land-use change. Perfecto et al. (2005) indicate that rustic coffee systems with very dense shade produce lower yields, and Staver et al. (2001) determined that yield is maximized between 35 and 65 % of shade cover. Since most of the coffee fields in our study area are old and poorly managed, activities including shade control and the renewal of coffee plants are needed to increase yields. However, to avoid negatively affecting the biodiversity and ecosystem services, intense thinning and pruning may not be acceptable (Perfecto et al. 2005). Future research should focus on seeking out the optimal balance between biodiversity conservation and profitability, which is feasible, according to Gordon et al. (2007), as long as the canopy structure is maintained.

Since we are dealing with private areas, we must be aware that in the end, every land-user will weigh the ratio of each "asset" based on his/her own goals. Assuming that the relationship between biodiversity and profitability is a trade-off (if one wants to save biodiversity one has to bear the forgone income, and conversely, the highest profits are achieved in biologically simplified "conventional" systems) the society must provide farmers with enough incentives to convince them to opt for the most environmentally desirable assets (Gordon et al. 2007; Rice 2008).

Certification is considered an attractive alternative for supporting agro-biodiversity-rich landscapes (Kilian et al. 2006; Bacon 2005), due to the stability of the resulting premium price for certified products compared to those for conventionally produced crops (Valkila 2009). A major disadvantage of certification, however, is that transaction costs can play an important part in overall costs. Valkila (2009) states that

Publication 1

certification may imply a long process, and this delay creates sunk costs that must be borne by the farmers themselves. The high cost of certifying individual farms makes it nearly impossible for small-scale farmers to acquire organic certification without the support of cooperatives and development organizations. Low interest credits (see Knoke et al. 2009a) and assistance are essential to helping small farmers to participate in such programs.

Potential markets for environmental services

Economists and policy makers highlight the responsibility of the government, with support from the civil sector, to provide ecosystem goods and services. Despite the fact that most ecosystem services are public goods, the physical structure that provides them is often privately owned. Thus, addressing property rights is a necessary and complex aspect of insuring the provision of ecosystem services (Kemkes et al. 2010).

An important task for the future is to identify "potential buyers" for the ecosystem services provided by shade coffee—either government agencies or coffee consumers. A "government-financed" CP scheme is one method of reducing the transaction costs and avoiding free riding (Engel et al. 2008; Kemkes et al. 2010). The Ministry of the Environment of Ecuador should assess whether agroforestry systems should also be included in the "Forest Partner" program, which so far includes forests and moors alone (Programa Socio Bosque). Even though the compensations offered by Socio Bosque are comparatively small, they might be effective. Our results show that, given risk-averse land-users, also small payments are likely to achieve significant shifts in current land-use portfolios, although they would certainly not lead to complete conservation of all shade coffee plantations.

Price premiums for certified products are incentives that can also finance CP. The willingness to pay a higher price for a certified product depends strongly on the level of awareness of the consumer (Ponte 2002; Leigh 2005). Sometimes though, a higher price can reduce the consumption of shade grown coffee. According to our results, the price of coffee must increase by about 20 % in order to compensate for the land opportunity costs, assuming the shade cover and yield reported in Pindal. Unfortunately, we do not have references about the consumer's willingness to pay for coffee produced in wildlife-friendly landscapes. Further research for assessing whether consumers would be willing to pay more for this product should be carried out in the future.

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9.2. Publication 2

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Publication 2

RESEARCH ARTICLE

Ecuadorian Banana Farms Should Consider Organic Banana with Low Price Risks in Their Land-Use Portfolios

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Abstract

Organic farming is a more environmentally friendly form of land use than conventional agriculture. However, recent studies point out production tradeoffs that often prevent the adoption of such practices by farmers. Our study shows with the example of organic banana production in Ecuador that economic tradeoffs depend much on the approach of the analysis. We test, if organic banana should be included in economic land-use portfolios, which indicate how much of the land is provided for which type of land-use. We use time series data for productivity and prices over 30 years to compute the economic return (as annualized net present value) and its volatility (with standard deviation as risk measure) for eight crops to derive land-use portfolios for different levels of risk, which maximize economic return. We find that organic banana is included in land-use portfolios for almost every level of accepted risk with proportions from 1% to maximally 32%, even if the same high uncertainty as for conventional banana is simulated for organic banana. A more realistic, lower simulated price risk increased the proportion of organic banana substantially to up to 57% and increased annual economic returns by up to US$ 187 per ha. Under an assumed integration of both markets, for organic and conventional banana, simulated by an increased coefficient of correlation of economic return from organic and conventional banana (ρ up to +0.7), organic banana holds significant portions in the land-use portfolios tested only, if a low price risk of organic banana is considered. We conclude that uncertainty is a key issue for the adoption of organic banana. As historic data support a low price risk for organic banana compared to conventional banana, Ecuadorian farmers should consider organic banana as an advantageous land-use option in their land-use portfolios.

95

Publication 2

Introduction

The intensification of agricultural systems has resulted in a substantial increase in the amount of food produced in the last decades through the application of technologies such as high-yielding crop varieties, chemical fertilizers and pesticides, irrigation and mechanization [1]. Reaching current levels of food production would hardly have been possible without the use of these technologies [2]. Nonetheless, poorly managed intensification can ultimately lead to a drop in soil fertility, pollution of ground water, increased release of greenhouse gases and overall losses in biodiversity [1, 3–6]. Such detrimental impacts on the environment and on ecosystem services highlight the need for more sustainable methods of producing food [7].

In practice, however, the adoption of sound practices, such as organic farming, is still limited, due to the economic attractiveness of conventional agriculture and government policies that continue to encourage the use of synthetic inputs [1]. In general, little is known about the economic performance of sustainable land-use practices [8], for example, organic farming. Consequently, a full accounting of both the costs and the benefits of sustainable agriculture should form the basis for policy, ethics and action [7, 9]. Indeed, assessing the ecological and economic tradeoffs between organic and conventional farming, and identifying the economic perspectives from which the adoption of organic farming could be advantageous forms a major challenge.

Evidence confirms that organic farming delivers lower yields than conventional farming [2, 10–13]; nonetheless, a positive aspect of producing organically is the meaningful reduction of external inputs such as fertilizers, energy and pesticides due to enhanced soil fertility and higher biodiversity [10]. The fact that organic systems may require 35% more labor than conventional does not make organic agriculture necessarily more expensive than conventional as reduced costs of fertilizers and pesticides represent an important component on overall costs [14]. In addition, the extra costs generated by adopting organic standards are supposed to be more than offset by the price premium that consumers pay when purchasing bananas with a sustainable agriculture label [15].

A reduction in yield for instance, does not imply that organic farming might not be attractive at all for farmers, because organic and conventional products are sold on different markets [16]. The prices for organic and conventional products may thus show merely small correlation, and price volatility may be lower for organic products [17]. In many countries, price premiums for organic products appear to be non-declining over time (e.g. for pineapples) [18]. Additionally, net returns in conventional systems have been reported to be more variable and thus more risky than in organic corn-soybean systems [14]. Moreover, the volatility of crop yields may differ between organic and conventional production. Microbial biomass and activity as well as soil organic carbon are almost always significantly higher in soils of the organic farming systems than in those of the conventional system and microbial communities are more active under the organic system. In the organic soils, microbial activity is positively correlated with soil fertility [19]. If organic farming would also achieve reduced volatility of market prices, this would suggest that organic farming systems would be a well suited option to diversify conventional land-use systems. However, to the best of our knowledge there are hardly any studies which have tested whether organic farming systems are suited as valuable components to diversify conventional land-use portfolios.

Our study will focus on banana production in Ecuador and we intend to test the following hypothesis:

H: "The inclusion of organic banana into efficient economic land-use portfolios in Ecuador is driven by the uncertainty of their economic return"

96

Publication 2

A land-use portfolio is named "efficient," if there is no other land-use portfolio with a higher economic return for the given level of economic risk. We test the impact of the volatility of economic returns for organic banana and the influence of the correlation between economic returns from organic and conventional banana on the inclusion or exclusion of organic banana into or from the optimal land-use portfolios.

The approach followed: Land allocation based on economic return and risk

Farmers' decisions about how best to use their land are driven by the goal of improving their own well-being. Well-being is defined across many dimensions, including income, security of livelihood, and health [16]. Decisions about land use are influenced by the relative potential economic return or benefit of each activity, which, in turn, depends on the available technology and prevailing market and environmental conditions [20].

In general, it is reasonable to expect that farmers will choose productive activities that maximize their well-being, given the resources and opportunities available to them. However, as farmers are typically regarded as risk-averse, strategies to reduce the uncertainties inherent to agricultural production may provide beneficial effects [21, 22]. Farmers will, consequently, not only seek high average, but also low standard deviation (SD) of discounted future net revenues. Risk-averse farmers may achieve high levels of risk reduction by mixing two or more land-use options whose financial yields fluctuate independently from one another (with low correlations) [23]. In other words, in periods when returns from one asset drop, another one may generate unexpectedly high returns, thus, moderating the effects of economic booms and busts [22, 24].

The level of land-use diversification may range in intensity from intermingled cropping (e.g. agroforestry) to landscape-level approaches [1, 25]. Diversification at the landscape level consists of producing crops in separated parcels that are relatively small in size but still large enough to permit agricultural intensification (e.g. mechanization) [25]. A well-recognized method for finding the optimal diversification strategy is the Portfolio Theory [26]. This theory has been used, for instance, to further develop Thünen's [27] economic land-use theory using a portfolio-theoretic reformulation [28]. Our paper builds on the portfolio-theoretic enhanced Thünen approach by modeling farmers' options for balancing economic return and risk. It may be used, on the one hand, to find an appropriate land allocation to various land-use practices on new banana farmland. FAO Statistics tell us that in Ecuador, from 1980 to 2012 the area of banana farms increased by 4400 ha per year. On the other hand, also in existing farms the exhausted banana plants have to be replaced all five to ten years making it necessary to renew the investment. This gives an opportunity to alter the existing land distribution to land-use practices. For example, assume a farm with 200 ha pure banana, where banana plants have to be replaced all ten years. In order to balance the annual work a portion of 20 ha could be renewed every year so that all banana plants are replaced once during a 10-year time span. A completely new land-use portfolio may, in this way, be created within ten years without stopping the banana investment before plant productivity reduces.

Our approach attempts, by means of the allocation of land to various land-use practices, to maximize the expected economic return (in the form of the average annualized net present value), for a given level of accepted risk, which is represented by the SD of economic return, through careful selection of the proportions of total available land area occupied (so called portfolios) by various land-use options. Those portfolios that provide the largest economic return for a given SD are termed efficient portfolios. All others are considered inefficient.

97

Appendix

Publication 2

Markowitz [29] proposed his famous portfolio theory in a normative sense, as a recommendation for portfolio selection, and in a positive sense, too, as a hypothesis about investor behavior. Here, we apply Markowitz' theory in combination with the Thünen approach in a normative sense. Thus, our model shows how land *should* be allocated to the available land-use practices to achieve the highest economic return for an accepted level of risk. This does not necessarily mean that the model output is a proper prediction of future land allocation, nor will it necessarily describe the past land allocation practices. It may just help risk averse land owners to achieve their economic objectives in a consistent way. Normative models like ours may hardly be tested empirically (see Roll's [30] critique to the Capital Asset Pricing Model), but still can help forming comprehensible land-use scenarios and delivering valuable hints for risk-return efficient land-use strategies [28]. These kinds of models have been applied in the past in order to model decisions on land allocation to various land-use practices from an economic perspective [27] and to derive cost-effective conservation strategies [28].

Our model has a static nature, although the time structure of net revenues, such as lacking of significant positive net revenues in the first three years of organic banana, are considered for the single land-use options. However, it is investigated how land should be allocated to land-use practices, but not when this should take place, because the timing of crop conversion is much influenced by the nature of the investment. For example, when banana or cocoa plants are exhausted, they must be replaced, whereas it would not be wise to stop the investment before. The optimal allocation of land to land-use practices delivered by our model is, thus, valid in general for the future, regardless when it will be achieved. Our consideration assumes that the same land-use practices with the same economic characteristics are available in each time period. Of course, new price, cost or uncertainty levels may establish themselves in future periods, which would alter economic returns, their uncertainties and correlations. However, to predict these changes at this time would be speculative. We, thus, prefer the static approach, which still allows for computing revised allocation of land to land-use practices, when new information is available. However, we have to keep in mind the static, single period nature of our analysis, which is embedded in a many-period reality [29], where the economic coefficients may actually change from period to period. To consider this we actually recommend to revise the analysis of land-use portfolios from time to time in practical applications.

We use the classical SD as a measure for risk and uncertainty, while we do not distinguish between risk and uncertainty [31]. Of course, uncertainty would cover also the right tail of the probability distribution of possible economic returns, with actual returns being higher than expected, which is not to be considered a "risk". It is well known that available options to react in response to the actual development of prices, costs or productivities may produce economic returns that are located on the right tail of return distributions. The options to defer, abandon, contract, expand or switch the investment [32] may increase the economic return in comparison to results delivered by the classical net present value approach [33]. This flexibility can be considered on the formal basis of the options approach to capital investments [34]. However, the consideration of multiple real options in a portfolio approach is very complex. For example, the option values for the single land-use practices are not additive [32]; we, thus, should be aware that using one option could compromise the use of other options. If we exercise the option to expand or switch to organic banana, the options to expand or switch to other practices will be limited. Also, if we wait too long with exercising, competition may have eroded the option value already [35]. In making solutions to the real options problem manageable, most of the applications of the real options approach in land management, as a result, reduce their problem perspective to consider only one investment project or the replacement of only one project by another one. For example, Yemshanov et al. recently investigated when, if at all, to convert agriculture into a bio-fuel poplar plantation and vice-versa [36]. In another study

98

Publication 2

Capozza and Sick priced agricultural land with a real option to convert into urban land [37]. In contrast to these studies we are interested in the optimal structure of land-use portfolios, potentially consisting of many land-use options. We are aware that the options inherent in the single land-use practices considered can have an impact on their economic returns and risks, as studies have shown for mixed forests in comparison with pure forests [38, 39]. The structure of land-use portfolios might, thus, be altered by the options approach in theory, if option values differ greatly between the land-use practices considered. Here, the land-use practices with the greatest volatility of economic returns would have the greatest potential to bear significant option values. However, these practices may also be the riskiest and (improper) option pricing may include the possibility of greatly overestimating the value of the most uncertain projects. We will discuss possible effects of applying the options approach on the composition of land-use portfolios at the end of our paper. Indeed, it would be very challenging to adequately determine an inclusive set of relevant options (e.g., timing of inclusion, exclusions, conversion and possible re-conversion) for all the land-use practices considered simultaneously. And this without inflating the economic risk—due to the incorporation of many uncertain, partly speculative elements—beyond the level which the landowners would be willing to accept. Although theoretically attractive, real options are often considered by managers to overestimate the value of uncertain projects, encouraging decision makers to overinvest in them and to gamble in the extreme case [35].

There are also technical problems, which rather detract from the real options approach. For example, Plantinga pointed out that decisions on the optimal timber harvest under uncertain prices depend strongly on the underlying process to simulate prices [40]. Also Insley showed that applying either the Geometric Brownian Motion or mean-reverting prices had a great impact on the outcome of option values and when to best harvest (replace) existing trees [41]. Due to problems with the acquisition of appropriate data and the choice of the appropriate price/cost processes plus the very complicated modelling of interacting options in a portfolio, the actual computation of option values is still considered problematic, although the conceptual value of the approach is acknowledged [42]. Some studies, thus, consider the practical application of the real options approach critical [43, 44]. In summary, we justify our static approach as being helpful to analyze the attractiveness of organic banana, because it is more informative then studies considering organic and conventional farming as mutually exclusive land-use options [13, 45, 46] and less speculative compared to the option value approach.

According to the theory of portfolio selection the expected economic return of a portfolio with two or more assets, R_p, is obtained by adding the expected economic returns, r_i, weighted by their proportions, f_i, of the single land-use options.

$$R_p = \sum_i f_i \cdot r_i \tag{1}$$

with r_i as the annualized sum of all appropriately discounted (discount factor $q = 1+d$ and d as the discount rate) net revenues, n_i, of land-use option, i, over a time period, t, of 30 years:

$$r_i = \left[\sum_t n_i \cdot q^{-t} \right] \cdot \frac{(q-1) \cdot q^{30}}{q^{30} - 1} \tag{2}$$

We applied a discount rate, d, of 0.05, and thus $q = 1.05$, as this discount rate has been used in the past to assess forestry and farm strategies in the tropics [47–49]. Using a higher discount rate would of course, substantially reduce the economic returns. Equation 2 converts the net present value directly into an annuity. This is practical for the modelling, because the annuity

99

Publication 2

may be compared well between the land-use practices considered and has the same unit as the net revenue per year of annual crops (for which annuity and yearly net revenue is identical).

The SD of economic returns for the portfolio, σ_p, is quantified as follows,

$$\sigma_p = \sqrt{\sum_i \sum_j f_i \cdot f_j \cdot \mathrm{cov}_{i,j}} \tag{3}$$

With:

$$\sum_i f_i = 1 \quad f_{i,j} \geq 0 \quad \mathrm{var}_i := \mathrm{cov}_{i,i} \quad \mathrm{cov}_{i,j} = \rho_{i,j} \cdot s_i \cdot s_j \tag{4}$$

where i and j are the indices for the specific land-use options; f_i is the proportion of land occupied by a specific agricultural land-use practice in the portfolio; s_i is the SD of returns for land-use practice i; $\rho_{i,j}$ is the coefficient of correlation between the economic returns for options i and j; var_i is the variance and $\mathrm{cov}_{i,j}$ is the covariance between the economic returns for options i and j. Using this method, the effects of diversification can be identified for different combinations of land-use options, provided that the variability of their economic return is not perfectly positive correlated ($\rho \neq 1$).

Land-use options considered and economic modeling

### Crops selected for the land-use portfolios

The area selected for our modelling—the Babahoyo sub-basin—is located in the littoral region of Ecuador. This region is a flat floodplain cross-cut by many rivers. Alluvial soils of volcanic origin prevail, which are typically well-drained sandy clay soils with variable textures. Intensive agriculture covers 65% of the land [50]. Permanent crops common to the region consist of banana (*Musa acuminata*), sugar cane (*Sacharum officinarum*), African palm (*Elaeis guineensis*), cocoa (*Theobroma cacao*) and coffee (*Coffea arabica*). The main annual crops in the region are maize (*Zea mays*), rice (*Oryza sativa*) and soybeans (*Glycine max*) [51].

We modeled a typical medium-sized farm (100 hectares) across a time horizon of 30 years using the crops with the highest relevance for the region, based on information from the III Census of Agriculture and Livestock (Fig. 1). The selected land-use options were banana (conventional and organic), cocoa, rice, maize and soybean as well as two tree species.

Banana is the main export-oriented agricultural commodity in Ecuador, thus it is generally produced under very intensive management [52]. The methods and inputs used to produce banana are more intensive and expensive than every other crop used in this study (Table 1 and S1 Dataset). Due to the importance of banana to the local economy, the extent of the area currently under production and the impacts caused by the use of synthetic inputs, we considered it imperative to assess whether partial conversion to organic production might be economically attractive for local farmers. This step was shown to be feasible and may also be meaningful in terms of risk reduction, because prices for conventional and organic products are subject to different market conditions [11], thus, we may also expect positive effects of diversification. Two aspects support this assumption: organic production delivers better ecosystem services than conventional production, and the demand for organic products has risen significantly during recent years [18]. Although organic banana still represents only a small fraction of Ecuadorian banana exports (3%), the area allocated to organic banana rose nearly threefold between 2004 and 2007, from 4700 to 13800 hectares [15].

As mentioned before, conversion from conventional to organic farming can be carried only on part of the available land [53], for example, when the existing banana plants have to be

Publication 2
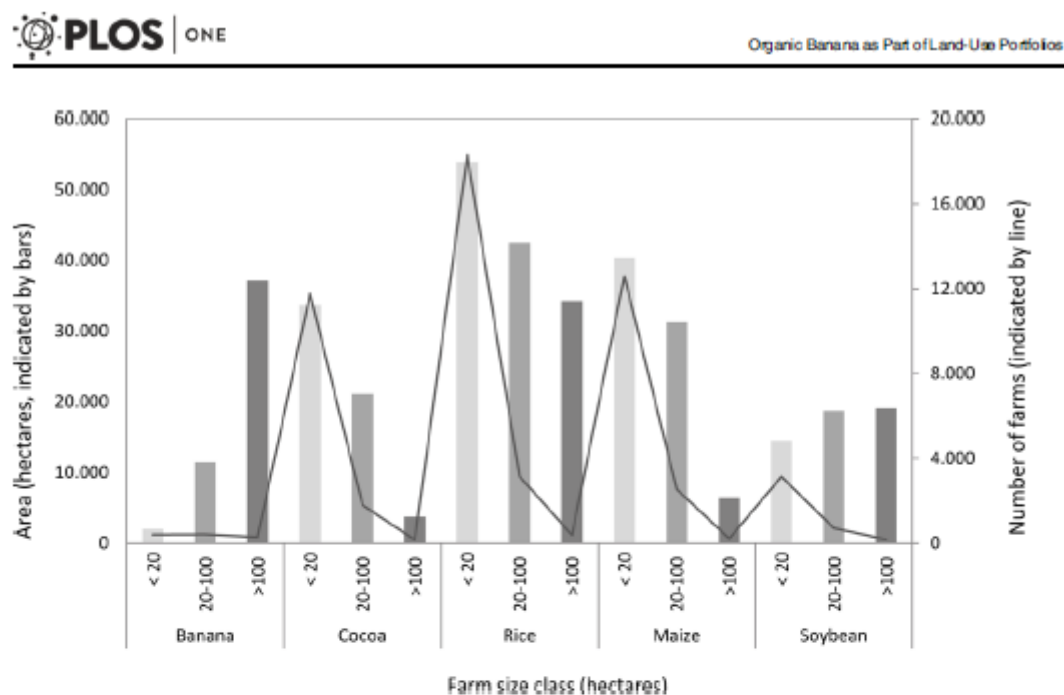
Fig 1. Farms in the Babahoyo sub-basin producing the land-use options modeled, arranged by size and area of production.

renewed anyways. This is the case according to our modelling every 10 years (see S1 Dataset). Partial conversion means that potential problems with the new production system can be better managed and buffered. For example, evidence shows that in combination with organic farming, conventional farming helps to keep levels of pests low in the organic parcels. However, the share of organic farming should not exceed certain thresholds [12].

Despite forestry is not a traditional land use in the coastal area of Ecuador, in recent years landowners have shown interest for investments in fast-growing species such as balsa (*Ochroma Pyramidale*) and laurel (*Cordia alliodora*) as a complement to agriculture. Both species are able to thrive in lands formerly dedicated to agriculture [54], which make them ideal for reforestation in abandoned or degraded land. Thus, we included these two species in our diversification modeling as a mechanism to increase the supply of timber from non-native forest species and to foster restoration of abandoned agricultural land [25, 55].

Modeling economic performance of land uses

Price and yield statistics for each land-use option were collected from official sources at both the national and international levels (Table 1). Later, we calculated the costs and revenues for each land-use option (S1 Dataset). The costs considered included land preparation, planting, pest control, fertilization, maintenance, harvesting and infrastructure (irrigation, roads, etc.). Due to modeling constraints, we did not consider intra-annual crop rotations.

The costs considered for reforestation included those for stand establishment, protection, thinning and final harvest. Management plans detailing the intensity of interventions and the parameters of the plantations of both species are presented in Table 2. We included an

Appendix

Publication 2

Table 1. Coefficients used to compute net returns of agricultural assets in the Babahoyo sub-basin.

Land-use option	Item	Coefficient	Source
Cocoa	Establishment costs	US$1606 ha^{-1}	Every 15 years, own calculation
	Annual costs	US$ 353 ha^{-1}	Own calculation
	Price	US$ 1694 Mg^{-1}	[51]
	Yield	0.3 Mg ha^{-1}	[51]
Conventional banana	Establishment costs	US$ 2835 ha^{-1}	All 10 years, own calculation
	Annual costs	US$ 4745 ha^{-}	Own calculation
	Price	US$292 Mg^{-1}	[52]
	Yield	23 Mg ha^{-1}	[52]
Organic banana	Establishment costs	US$ 3150 ha^{-1}	Every 10 years, own calculation
	Annual costs	US$ 4945 ha^{-1}	Own calculation
	Price	US$398 Mg^{-1}	[52]
	Yield	15 Mg ha^{-1}	[52]
Rice	Costs	US$ 744 ha^{-1}	Own calculation
	Price	US$ 300 Mg^{-1}	[51]
	Yield	3.7 Mg ha^{-1}	[51]
Maize	Costs	US$ 603 ha^{-1}	Own calculation
	Price	US$ 277 Mg^{-1}	[49]
	Yield	3.1 Mg ha^{-1}	[49]
Soybean	Costs	US$ 520 ha^{-1}	Own calculation
	Price	US$ 404 Mg^{-1}	[51]
	Yield	1.7 Mg ha^{-1}	[51]
Balsa	Establishment costs	US$ 1584 ha^{-1}	All 6 years, adapted from Proforestal*
	Stand growth	45 m^3 ha^{-1} year^{-1}	
	Density	833 trees	
	Harvesting costs	US$ 600 ha^{-1}	
	Revenues	US$ 6000 ha^{-1}	
Laurel	Establishment costs	US$ 1554 ha^{-1}	All 15 years, adapted from Proforestal*
	Stand growth	18 m^3 ha^{-1} year^{-1}	
	Density	833 trees	
	Harvesting costs	US$ 2200 ha^{-1}	
	Revenues	US$ 10621 ha^{-1}	
Discount rate	5%		

*Proforestal is the Office for the Promotion of Forestry in Ecuador (MAGAP)

doi:10.1371/journal.pone.0120384.t001

estimated mortality rate of 20% of the planted tree seedlings [48, 56], and, a fluctuation in growth of 10% [48]. Returns were calculated by multiplying the number of logs harvested by the price received for raw logs.

We used the prices and productivities for the period 1970–2009 published in FAOSTAT (Table 3) to model uncertainty and characteristic correlation structures between product prices and productivities. These series contain country-level data; nevertheless, we considered them to be applicable to our study area, because the region is one of the most productive areas in the country, thus the data is not overoptimistic. Prices for the period prior to the year 2000 were first converted from Sucre (Ecuador's former currency) into US$, using annual exchange factors [57]. To adjust the historical data to the current price level, annual prices were divided by the average price of the time series, and this quotient was then multiplied by the current price

102

Publication 2

Table 2. Harvest planning for balsa and laurel, adapted from Proforestal.*

Variables	Balsa		Laurel	
Age	Year 3	Year 5	Year 8	Year 15
DBH** (m)	0.20	0.35	0.20	0.35
Commercial height (m)	8	10	8	12
Form Factor	0.70	0.70	0.70	0.70
% Thinning	0.50	1.00	0.50	1.00
Volume per tree (m³)	0.18	0.67	0.18	0.81
Volume per ha (m³ ha⁻¹)	58.62	224.40	58.62	269.28

*Proforestal is the Office for the Promotion of Forestry in Ecuador (MAGAP)

** Diameter at breast height

doi:10.1371/journal.pone.0120384.t002

for each crop. Similarly we also adjusted the data series of yields for every land-use option using the same procedure we applied to the prices.

Bootstrapping—sampling with replacement—was utilized to generate frequency distributions for the annuities (Equation 2) of each land-use option. Prices and productivities were drawn from the same year to produce a sample of 1000 repetitions. By applying this procedure, we did not consider correlation between the prices and productivities from one year to the next year for the same option, but rather the correlation between prices and productivities between all land-use options. Given that time series for prices and productivity of organic banana were not available in FAOSTAT, we used, in a first attempt, the coefficient of variation of prices (65%) and productivity (22%) for conventional banana as proxies to model uncertainty for organic banana. The very important coefficient of correlation between organic and conventional banana ($\rho_{conv,org}$) was derived from price changes of documented wholesaler prices [58, 59]. These support a coefficient of correlation of about zero between the economic returns of both variants of banana, when prices for conventional banana are on the decrease and a positive correlation, when prices for conventional banana are on the increase. Finally, we provided a coefficient of correlation of zero between economic returns for organic banana and those for other crops, similar as the correlations found between conventional banana economic return and that other crops. Given these data and assumptions, we simulated the frequency distributions of the annual economic returns for organic banana by means of Monte Carlo Simulation (MCS).

A low coefficient of correlation between economic returns of both conventional and organic banana is also supported by the finding of another author that organic price changes are actually largely independent from conventional price changes, unless changes in conventional prices are quite large [18]. However, we nevertheless tested the effect of increasing correlation between economic returns of conventional and organic banana, possibly due to—so far not observed—growing integration of both markets, by assuming $\rho_{conv,org}$ of up to +0.7. Moreover, as our modelling led to a very high SD for organic banana with a coefficient of variation of their economic return of 81%, we also tested the impact of a lower uncertainty of organic banana on the optimal land allocation in our portfolios. Assuming lower uncertainty is well justified and may be even more realistic compared to our initial high-uncertainty scenario, because the available price data suggest that prices for organic banana are very stable, showing only 50% of the volatility compared to prices of conventional banana. A lower price uncertainty is a very important aspect, because the price uncertainty of conventional banana, which we adopt in the initial scenario to model the fluctuation of gross revenues for organic banana, dominates the large uncertainty of the economic returns. By setting the uncertainty of the crop productivity

103

Publication 2

Table 3. Yields and prices during the period 1970–2009 for main crops in Ecuador (obtained from FAOSTAT) [70].

	Land-use options i									
	Cocoa		Maize		Banana		Soybean		Rice	
Year T	Price US\$ Mg^{-1}	Yield Mg ha^{-1}	Price US\$ Mg^{-1}	Yield Mg ha^{-1}	Price US\$ Mg^{-1}	Yield Mg ha^{-1}	Price US\$ Mg^{-1}	Yield Mg ha^{-1}	Price US\$ Mg^{-1}	Yield Mg ha^{-1}
1970	381.1	0.2	54.0	0.9	24.3	15.0	144.0	1.0	68.2	2.7
1971	364.5	0.3	101.2	0.7	20.2	15.2	76.4	1.1	60.1	3.5
1972	383.6	0.3	116.7	0.7	20.8	15.1	156.7	1.2	69.4	2.1
1973	791.8	0.3	162.9	0.9	26.3	15.4	187.2	1.3	84.7	2.8
1974	931.4	0.4	207.7	0.9	27.8	17.6	368.1	1.4	126.0	2.6
1975	1028.3	0.3	208.1	1.0	29.9	23.2	335.6	1.5	153.9	3.0
1976	1310.0	0.3	195.8	1.0	30.2	24.0	332.2	1.5	157.9	2.6
1977	1687.5	0.3	201.5	0.9	33.2	24.4	348.6	1.3	175.8	3.1
1978	2105.7	0.3	210.6	1.0	36.7	28.0	371.2	1.5	197.0	2.8
1979	2055.6	0.3	204.1	1.0	37.0	30.1	362.7	1.3	192.8	2.9
1980	1857.2	0.3	220.7	1.1	38.9	32.2	371.8	1.3	203.0	3.0
1981	1061.3	0.3	196.5	1.2	35.2	31.4	331.5	1.6	221.3	3.3
1982	822.5	0.4	129.7	1.5	36.3	30.7	207.4	1.8	153.0	2.9
1983	1286.8	0.2	204.7	1.1	19.9	27.7	242.1	1.4	165.9	2.9
1984	1522.9	0.3	192.5	1.3	30.1	27.7	185.2	1.7	201.1	3.1
1985	1395.5	0.5	180.5	1.6	22.6	30.2	251.5	1.8	234.8	2.7
1986	1313.3	0.3	137.0	1.0	27.7	20.7	305.0	1.9	225.1	2.5
1987	1563.4	0.2	158.9	0.9	33.6	20.0	284.9	1.8	122.7	2.8
1988	903.5	0.3	135.4	0.9	13.5	20.2	174.3	1.8	122.3	3.3
1989	891.7	0.3	134.7	1.1	115.9	19.7	266.6	1.9	181.4	3.1
1990	843.7	0.3	142.7	1.1	130.1	21.3	300.7	2.0	154.7	3.1
1991	686.2	0.3	254.2	1.1	147.3	20.9	274.3	1.9	122.0	3.0
1992	651.7	0.3	219.3	1.1	131.6	21.6	261.6	1.6	142.0	3.3
1993	725.3	0.3	455.1	1.2	126.8	21.7	263.7	1.8	139.2	3.5
1994	991.6	0.2	292.4	1.1	128.5	23.0	255.2	2.2	161.5	3.7
1995	907.7	0.2	452.8	1.1	116.5	23.7	246.1	1.1	169.2	3.3
1996	908.1	0.3	362.7	1.1	132.9	25.3	258.2	1.3	167.3	3.2
1997	1113.9	0.2	397.5	1.2	131.8	35.5	199.7	1.1	203.3	3.4
1998	1025.6	0.1	359.5	1.1	109.2	26.4	226.4	1.3	169.1	3.2
1999	913.7	0.3	270.8	1.2	164.0	33.0	141.0	1.8	157.0	3.5
2000	793.2	0.2	380.0	1.4	165.4	25.6	247.9	1.7	160.0	3.7
2001	816.5	0.2	473.0	0.8	146.0	26.5	227.0	1.9	136.0	3.6
2002	1397.7	0.2	450.0	1.4	160.0	24.4	256.0	2.0	130.0	3.9
2003	1379.5	0.3	345.0	1.7	153.0	27.6	229.0	1.7	149.0	3.9
2004	1175.2	0.3	308.0	1.9	124.0	27.1	242.0	1.7	226.0	4.2
2005	1242.7	0.3	345.0	2.1	116.0	27.7	188.0	2.0	191.0	3.9
2006	1491.9	0.3	355.8	1.9	117.3	29.3	271.9	1.2	165.4	4.2
2007	1901.6	0.2	398.4	2.3	138.0	30.4	358.7	1.7	238.2	4.4
2008	1543.7	0.3	853.3	2.2	133.1	31.1	469.3	1.6	291.8	4.1
2009	1803.1	0.3	855.0	2.2	149.8	35.3	488.3	1.7	262.5	4.0

104

Publication 2

equal to zero we still observed, through the price uncertainty alone, a standard deviation of 95% compared to the combined standard deviation from crop and price volatility. Given this background information, a scenario with reduced uncertainty of economic return for organic banana appears quite realistic. In summary, we assumed in one variation of our consideration a reduction of the SD for prices from actually US$ ±55 per Mg (conventional banana) to US$ ±30 per Mg for organic banana resulting in a coefficient of variation of organic banana's economic return of ±50%.

We faced the same challenges regarding data availability as described for organic banana with the historical data for the prices of timber. In this case, we assumed volatility in the price of timber of 10% [48]. Random prices for balsa and laurel were simulated assuming a normal distribution. The probability distributions of returns for balsa and laurel were then estimated using MCS, also with 1000 repetitions.

To calculate the expected economic returns for each of the land-use portfolios, Equation 2 was applied, while Equation 3 delivered the SD as our risk indicator for each portfolio.

Results

Economic return and risk for single land-use options

We will first present the simulated annual economic returns of each of the agricultural products when produced as single options (Fig. 2). Conventional banana was the option with the
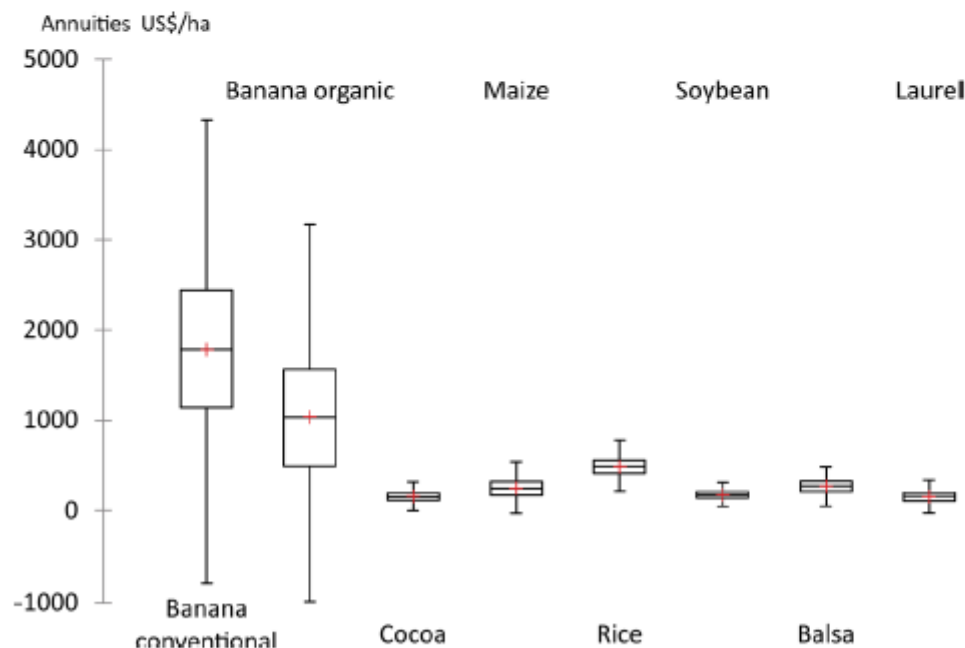
Fig 2. Simulated annuities for land-use options produced in the Babahoyo sub-basin. Whiskers represent the lowest and the highest annual returns in US$ ha⁻¹.

doi:10.1371/journal.pone.0120384.g002

Publication 2
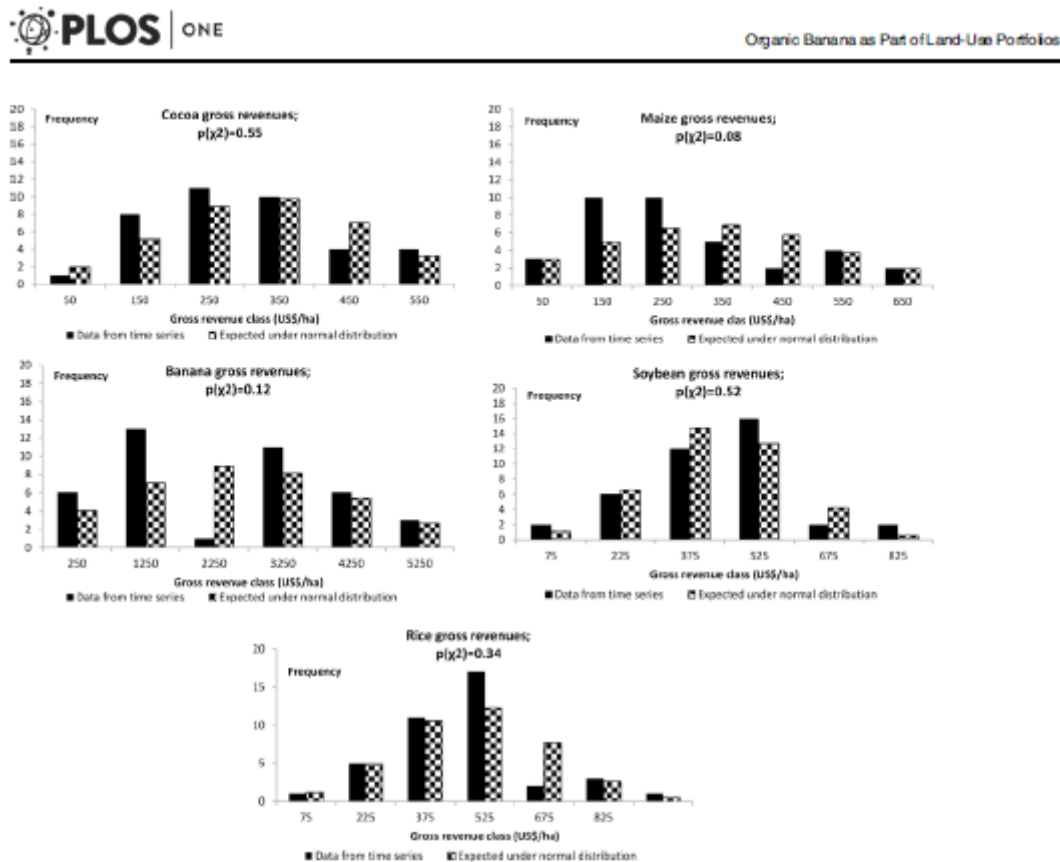
Fig 3. Distributions of gross revenues from time series data used for bootstrapping and expected distribution under the normality assumption. Organic bananas as well as forestry options were modelled by means of assumed normal distributions.

doi:10.1371/journal.pone.0120384.g003

highest mean annual economic return (US\$ 1786 ha^{-1} ±945) and also the option with the highest SD (risk). The great volatility of prices and yields which has been documented for conventional banana is the cause for these large fluctuations (Table 3, Fig. 3). For this reason, even negative economic returns are possible. Maximum calculated annual returns per ha were as high as US\$ 4804, while potential annual losses were found to be as much as US\$ -1557 per ha (Table 4).

Organic banana yielded mean annual returns of US\$ 1040 ±843, under this high-uncertainty scenario even with a higher coefficient of variation than conventional banana (81% versus 53% for conventional banana). Its return was substantially lower than that of conventional banana due in part to higher costs of establishment and management, but also due to a by 35% reduced productivity (see Table 1). Here, the worst case losses amounted to as much as US\$ -1897.

In general, the annual economic returns for all of the non-banana options were below US-\$500 ha^{-1}. Annual returns of rice amounted to US\$ 486 ±101. An economic advantage of rice found by our modeling was that, even in the worst case, it still yielded a positive annual return

106

Publication 2

Table 4. Descriptive statistics of financial data of land-use options considered for optimization.

Land-use option	Minimum return US$ ha⁻¹	Maximum return US$ ha⁻¹	Mean return US$ ha⁻¹	SD
Conventional banana	-1557	4804	1786	945
Organic banana	-1897	3913	1040	843
Cocoa	-9	473	159	70
Maize	-31	600	247	108
Rice	170	834	486	101
Soybean	-20	313	174	52
Balsa	-20	552	271	84
Laurel	-71	429	154	70

(SD: Standard deviation)

—a minimum of US$ +170 ha⁻¹—and thus rice may be considered the single option with the smallest economic risks. Among the annual crops, maize was the crop with the largest SD (US$ 247 ±108 ha⁻¹), while soybean had the lowest SD (US$ 174 ±52 ha⁻¹).

Permanent crops—forestry and cocoa—had dissimilar financial performances. For cocoa and laurel, the mean annual returns were similar—US$160 ±70 ha⁻¹. Balsa however, achieved a mean economic return of US$281 ±84 ha⁻¹ year⁻¹. This value was higher than those for annual crops such as soybean and maize, and even in terms of risk, balsa performed better than the latter. Descriptive statistics and correlation coefficients between the land-use options are summarized in Tables 4 and 5.

The distribution of the gross revenues derived from time series data was largely not significantly different from an expected normal distribution (Fig. 3) with $p(\chi^2)$ from 0.12 to 0.55. Only for maize the statistic, $p(\chi^2)$, was with 0.08 below the required threshold of 0.10. We may thus regard the requirement for the analysis of economic portfolios for economic returns to be normally distributed as more or less fulfilled.

Correlation between prices for conventional and organic banana

Plausible information on the correlation between economic returns is a precondition for any portfolio-theoretic analysis. The necessary data could be derived from FAO statistics for most of the crops considered (Table 5), but it is hard to be obtained in the case of organic banana. However, some time series have been documented on wholesaler prices of organic banana

Table 5. Correlation coefficients of land-use options.

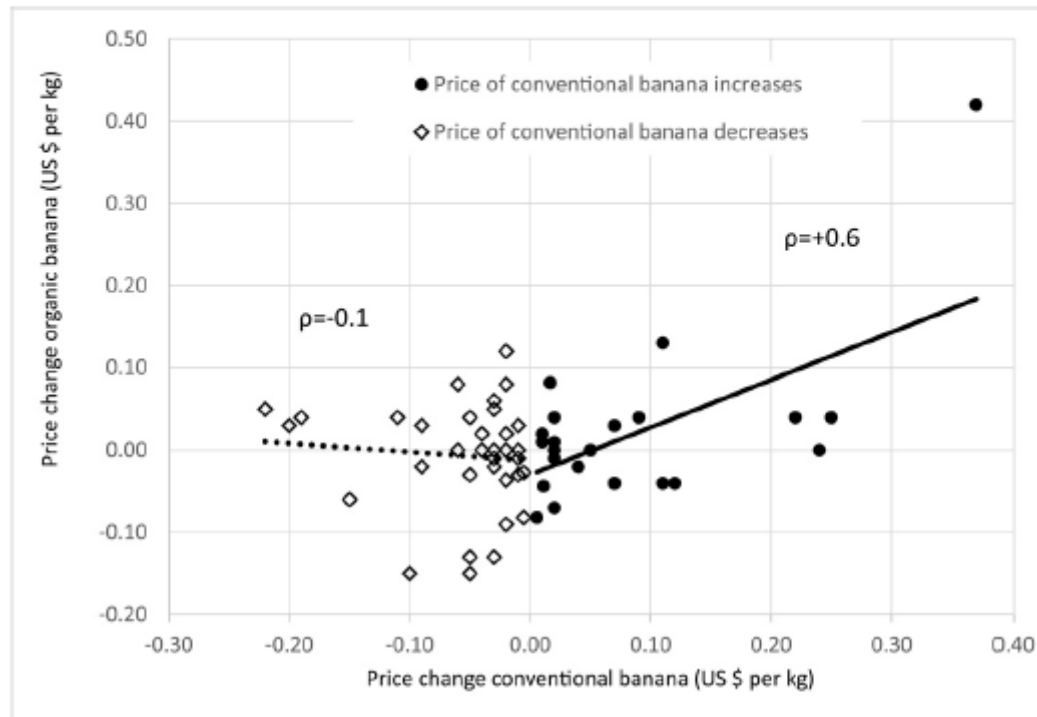|	Banana conventional	Banana organic	Cocoa	Maize	Rice	Soybean	Balsa	Laurel
Conventional banana	1.00							
Organic banana	0.02	1.00						
Cocoa	-0.01	-0.03	1.00					
Maize	-0.06	-0.01	-0.02	1.00				
Rice	0.02	-0.03	0.43	0.02	1.00			
Soybean	0.03	-0.01	0.36	0.01	0.59	1.00		
Balsa	0.04	0.02	-0.02	0.02	-0.02	0.00	1.00	
Laurel	0.01	0.02	0.03	-0.01	-0.02	-0.02	0.08	1.00

107

Appendix

Publication 2

Fig 4. Correlation of price changes for conventional and organic banana [58, 59].

[58, 59]. It is due to the fact that we found that the volatility of the economic return for banana is mainly driven by price uncertainty, that the correlation between prices for organic and conventional banana may be regarded as a good indicator for the correlation between economic returns. The analysis of price changes showed that price shifts for organic banana are independent or even slightly negatively correlated with price shifts of conventional banana, when prices for conventional banana decline ($\rho_{conv,org}$ = -0.1, see Fig. 4). However, when prices for conventional banana increase, also the prices for organic banana show a tendency to increase ($\rho_{conv,org}$ = +0.6). This makes organic banana an ideal complement for the conventional banana, obtaining stable or even slightly increasing prices, when conventional banana price declines and when it increases, respectively.

Forming land-use portfolios

In our reference scenario organic banana was not a considered option (Fig. 5). While the single option with the lowest risk (soybean) shows a SD of ±52, a diversified portfolio with 14% cocoa, 10% maize, 37% soybean, 15% balsa, and 23% laurel obtained a smaller risk of ±34, which is the minimum risk achievable for the considered land-use. However, the economic return of this portfolio is relatively small (US$ 191 ha^{-1} yr^{-1}). By accepting the same level of risk

108

Publication 2
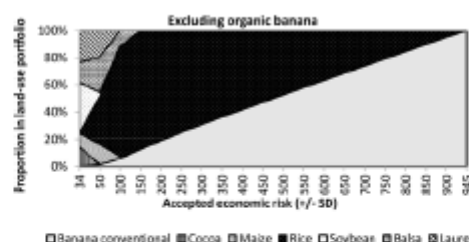
Fig 5. Structural composition of various land-use portfolios without organic banana for increasing levels of accepted economic risk.

doi:10.1371/journal.pone.0120384.g005

as that inherent in soybean (±52) the farmer would be greatly rewarded when forming a land-use portfolio of 2% conventional banana, 15% maize, 38% rice, 27% balsa, and 18% laurel with an annual expected economic return of US$ 352 ha^{-1} yr^{-1}. This is ≈US$ 160 more than achievable at the risk minimum and the risk to be tolerated is still not higher than the risk of single soybean.

Tolerating more risk results in higher expected economic return in our example, which is normal—at least when starting from the portfolio with the minimum of risk. Our land-use portfolios are highly diversified for farmers with low risk tolerance and contain forestry options as well, while the proportion of high-return conventional banana increases with increasing risk tolerance (Fig. 5). However, rice is also included over a large range of possible risk tolerances to diversify risks, while only those farmers who would totally disregard risks should work with conventional banana as a stand-alone option.

Interestingly, when considering organic banana as an option available for tropical banana farmers in Ecuador, this option would be included in the risk-return-efficient portfolios for a very large range of tolerated risks, and this despite its, in this initial high-uncertainty scenario, quite large own risk as a single option. This means that organic banana increases the expected economic return compared to portfolios excluding this crop. The magnitude of this effect will be demonstrated later. Organic banana obtains proportions between 1%, for a low tolerated risk of ±50, and 32%, for a tolerated risk of ±650 (68% of the SD of pure conventional banana). The proportion of organic banana sinks again to 5% for a very high tolerated risk level of ±900 (Fig. 6a).

As organic banana holds a quite high simulated risk as a single option in the initial scenario, rice plays a major role in the portfolios containing organic banana to hedge against the uncertainties involved with the organic crop. Embedded in a portfolio with rice and conventional banana, the same economic return as with pure organic banana (US$ 1040 ha^{-1} yr^{-1}) may be achieved by a diversified land-use portfolio, but at a risk of only ±369 instead ±843 for pure organic banana. Here, the portfolio structure would be 35% conventional banana, 19% organic banana, and 46% rice. This diversified land-use portfolio would thus hedge the great simulated risks of pure organic banana quite effectively.

However, the modelling results depend strongly on the assumptions made: a) If the simulated very high risk of organic banana was not ±843 (coefficient of variation ≈80%), but ±506 (coefficient of variation ≈50%), the portfolio's structure changed significantly. Reduced price volatility for organic banana is not unrealistic according to their much lower observed historical price changes compared to conventional banana. If we leave one outlier aside we find price changes between -0.23 and +0.26 US$ per kg for conventional and changes between -0.15 and

109

Publication 2
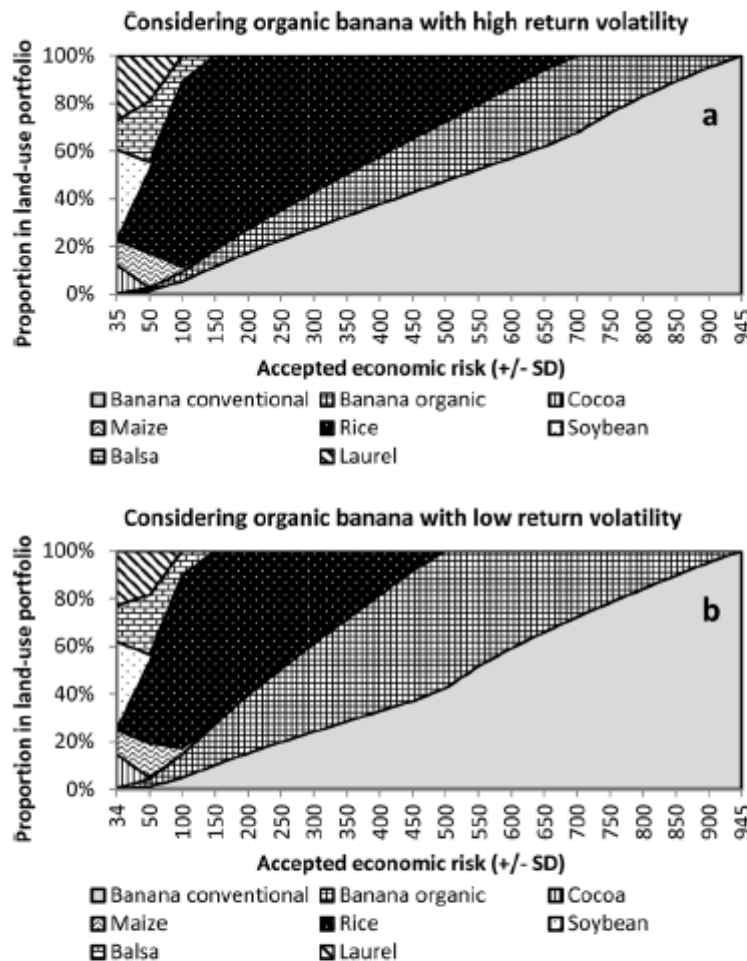
Fig 6. Structural composition of various land-use portfolios for increasing levels of accepted economic risk when organic banana is included and has high (a) or low economic risks (b).

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+0.12 US$ per kg for organic banana (Fig. 4). Acknowledging a lower price risk, the proportion of organic banana was greatly increased, up to 57%, while the proportion of rice was reduced (Fig. 6b).

  b) If we assume an increased coefficient of correlation between the economic returns of organic and conventional banana ($\rho_{conv,org}$ of +0.5 or +0.7), then the sensitivity of the results largely depends on the assumed price risk of producing organic bananas. For the case that the risk of organic banana is as high as modelled in our initial scenario, the increased correlation

Publication 2
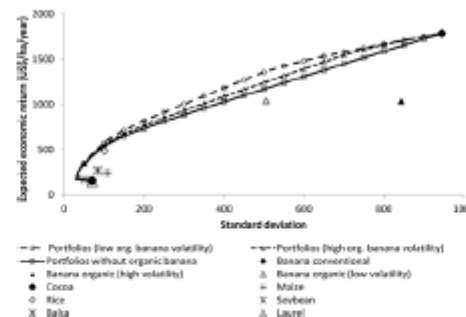
Fig 7. Maximum expected economic return achievable of diversified land-use portfolios for various levels of potentially accepted economic risk compared to economic returns of single land-use options.

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would reduce the proportion of organic banana to a maximum of only 1% ($\rho_{conv,org}$ of +0.5). Organic banana is then replaced by rice. However, if a reduced price risk is considered, which appears to be a quite realistic assumption, the proportions of organic banana remain relatively stable, even if the correlation, $\rho_{conv,org}$ of the economic returns is quite high ($\rho_{conv,org}$ +0.5 or +0.7). For example, given $\rho_{conv,org}$ = +0.7, organic bananas still hold a proportion of 8% for a very high tolerated SD of ±900.

Finally, through including organic banana into their land-use portfolios, farmers may increase their economic returns for a large range of tolerated economic risks (Fig. 7). Farmers may obtain 7% higher economic return (+US$ 96 ha^{-1} yr^{-1}) from a land-use portfolio including an assumed high risk organic banana, when tolerating an economic risk of ±700. If a reduced price risk of organic banana is acknowledged, farmers could even obtain US$ 187 ha^{-1} yr^{-1} more, when accepting an economic risk of ±500 and including 57% organic banana. In summary, although organic banana appears less attractive as a single option, this option may, when embedded in land-use portfolios together with other crops, improve the economic return of Ecuadorian banana farms. We have, thus, found supporting evidence through our modelling approach for our hypothesis:H: "The inclusion of organic banana into efficient economic land-use portfolios in Ecuador is driven by the uncertainty of their economic return"

Discussion and Conclusions

Comparing conventional and organic agriculture

Long-term sustainability of agriculture will hardly be attainable if current, conventional intensive practices continue to be applied. Agricultural intensification must therefore be coupled with sustainable land-use practices in order to be efficient [25, 60]. Nevertheless, the economic assessment of such a change towards more sustainable ways of producing food must receive more attention, if we are to better understand the decision-making process of resource allocation at the farm level as well as at the landscape and national levels [22, 23].

We have assessed the effects on the overall economic returns of a farm by considering organic banana and forestry options as potential land-use practices for future land-use portfolios and found this perspective more informative than the existing approaches where conventional and organic productions systems are seen as being mutually exclusive [13, 45, 46]. In the region under study, intensive and very high yielding agriculture (banana) is the *business as usual*

111

Publication 2

alternative. Due to high capital requirements of the *business as usual* banana option, we do not assume in our modelling that the banana farmers have limited access to capital.

The economic returns for both conventional and organic banana were impressive and very high in comparison with the other crops. Wunder has already shown that banana achieved by far the highest gross incomes in Ecuador, even when compared with other high profit crops such as sugar cane, potatoes, or African palm [61]. Another study [62] has reported high annual economic return for banana between ~US\$ 1200 to 2000 per ha for India, but lower annual economic return has been documented for banana in Bangladesh (~US\$ 870 per ha). However, the estimates for economic return of bananas reported in the literature are extremely variable, with annual economic returns up to ~US\$ 3800 per ha, a value being reported for Bangladesh [63], while the maximum included in our Monte Carlo simulations was US\$ 4808 per ha for conventional banana. These studies show that the high computed annual economic returns for banana (i.e. averages of US\$ 1786 per ha for conventional and US\$ 1040 per ha for organic banana) in our study range in a realistic order of magnitude.

While the forestry options diversified the land-use portfolios effectively rather for very cautious, risk-avoiding farmers, organic (and also conventional) banana enter the land-use portfolios only, if higher risks are tolerated. Regarding organic banana, we found that despite the possibly too high simulated risk it is well be balanced in land-use portfolios containing rice and conventional banana, if the correlation between economic returns of organic and conventional banana is not too high.

Nevertheless, the degree of diversification was limited when the combination of land-use practices included high-yielding crops as conventional banana. In our case, including high-yield banana as a portfolio option certainly lowered the resulting degree of land-use diversification, limiting the portfolio often to only a few land-use options. But still, in every portfolio we generated (except the maximum risk portfolio), we had at least two crops, with no single-crop turning out to be optimal.

One potential criticism to our model could be that only a modest ecological benefit can be expected because a high degree of diversification was not achieved—unless we assumed great risk aversion. Nevertheless, the fact that a land-use portfolio consists of only few options does not necessarily mean that a similar landscape structure to those observed in monocultures will be reproduced. Growing crops in relatively small compartments is one way to break up the landscape and also to achieve reduced erosion caused by wind and water, while still allowing for some level of mechanization [25]. Additionally, structural elements such as hedgerows should be implemented on around 5% of the land in order to enhance the structural diversity of the landscape. However, including these areas might represent a reduction in the amount of land available for farming and thus result in an accordant reduction in revenue. The considerable future challenges in economic comparisons of organic and conventional agriculture include the quantification of more synergies or antagonisms. While we found rather synergistic risk interactions of conventional and organic banana farming, also the interaction between pest management in conventional parcels and the susceptibility for pests in organic parcels should be further investigated.

Reductions in economic returns by means of pests might also be the main constraint to the implementation of sustainable agricultural practices. We assumed a reduction in productivity of 35% for organic compared with conventional banana. This reduction is similar to the yield losses which organic plantations may face compared with conventional plantations, due to infestation with the Black Sigatoka fungus (*Mycosphaerella fijiensis*) [45]. Still, more and better information can perhaps encourage farmers to adopt practices leading to environmental improvements. This is particularly true when changes in farming and land-management practices intended to enhance ecosystem services also benefit farmers themselves. In situations when

112

Publication 2

such changes imply a reduction in farmers' income, implementation can only be achieved through enforced regulations or when some form of compensation is provided [16].

Attractiveness of diversification and possible impacts of option values

Diversification is an acknowledged strategy for coping with risks; however, if farmers have access to other means of hedging risks, the effects might be undermined [24]. Based on the principle of risk-return reciprocity, the planting of high-yield crops corresponds to higher risk [64], as confirmed by our study. Wealthy farmers, consequently, not only hold portfolios which require higher levels of investment, they are also disposed to receive higher average profits per unit of wealth despite their greater exposure to risk [65]. As farmers become wealthier they may tend to be less averse to risk and also tend to be less interested in any form of risk-reducing intervention [23]. Although our results have shown that some diversification is highly meaningful, even for less risk-averse farmers, more intensive diversification is probably more important for poorer farmers [65]. Poorer farmers are both more exposed to and more averse to risk, and they usually lack strategies to hedge against risks [16]. Ultimately, wealthier farmers can afford better technologies and infrastructure and have better access to information [23].

One can also speculate about how options inherent in a flexible conversion strategy could alter the structural composition of the land-use portfolios obtained. For example, farmers could speculate for the optimal timing for conversion to organic banana, when particularly high prices are to be expected for this crop. A similar question has been investigated for the field of forest science, where Knoke and Wurm have adopted the Monte Carlo simulation technique to test the consequences of a flexible timing of timber harvest against a more conservative strategy with pre-defined harvest times [39]. The flexible harvest strategy allowed timber harvesting only, when a before defined reservation price was exceeded by simulated timber price scenarios. This strategy led to higher average timber prices, but also to variable additional costs for holding timber capital on the forest land by postponing the harvest times. While the average net present value could be enhanced by the flexibility strategy, its SD showed the tendency to increase, too. Although the variation of the timber prices achieved was reduced through the flexibility strategy, the then variable harvesting times increased the variability of the simulated net present values. In a mixed forest the flexible harvest strategy, thus, led to an increase of the proportions of the less risky (but also less profitable) timber species. This underlines the importance of the economic uncertainty of the single land-use options for the composition of land-use portfolios. If we, for example, could increase the economic return for organic banana by utilizing flexible management options and would increase the economic uncertainty at the same time, a reduced proportion of organic banana in the land-use portfolios could be the result.

Are organic farming and forestry appealing to relatively wealthy farmers?

The alternative we explored was the introduction of organic farming on part of the farms, as a strategy to enhance ecosystem services provision while also reducing health hazards caused by the application of agrochemicals and reduce the dependency of farmers to rising prices of fossil fuels [15]. Producing organic crops provides an opportunity for farmers in developing countries to participate in new markets [16]. Nevertheless, a shift towards organic production is tricky, and also quite risky, due to the changes and uncertainties which occur during the transition. Yield decline may be an important obstacle for farmers who are used to producing high-yielding crops like banana. However, for such a situation our study proved great advantages of embedding the organic banana parcels in a more diversified portfolio together with other land-use practices. The effect of transition on farmer's revenues can be better managed, provided

113

Publication 2

that the trend of the price premium for organic products remains stable and the market is still growing without strong integration between the markets for organic and conventional products [18]. However, the certification process should be adapted to the conversion towards organic products only on parts of the farms, which is not accepted by all certification bodies [15]. Thus, increased flexibility during the certification process and permanent support is essential to enable farmers to move from conventional to organic farming [53].

Moving now to the forestry options, we were surprised that in the portfolio calculated for very risk-averse farmers, the options including trees accounted for about 40%. Even though forestry is a non-traditional land use in the area where this research took place, it has great potential as a complement to agriculture, especially when implemented using short-rotation species. Afforestation is particularly valuable when used to restore abandoned farmlands [66]. Reducing the life span of forestry options may have a tremendous impact on farmers' investment decisions, because one of the primary obstacles to investing in forestry is the long-term nature of most forestry projects, which makes farmers reluctant to invest in plantations [42]. Species such as balsa, which is able to deliver returns after only five years, might completely change the perception of investors. This factor is especially important in the tropics, where the lack of financial incentives for investing in forestry activities sets the scene. We believe that the potential of forestry could be increased even more if accompanied by appropriate measures.

Policies to encourage adoption of sound practices

As a final point, we insist that implementation of sustainable practices in agriculture will only be possible if accompanied by appropriate scientific advice, policies and supported by fair markets [5]. Farmers will not automatically shift to this type of agriculture, as the economic returns from conventional agriculture are still higher. Up to now, incentives to foster sustainable land-use practices are insufficient to induce socially desired levels of adoption [1].

The role of governments and development agencies in the coming years is that of supporting farmers in implementing sustainable, possibly organic practices by means of technology transfer and capacity-building. We must keep in mind that applying sound practices requires time and expertise, and farmers need training [15]. In addition, governments should contemplate policies that will facilitate this transition by means of financial incentives, tax reductions and access to certification bodies that help regulate organic agriculture and sustainable forestry [15]. Finally, given that the development and application of technologies for sustainable farming is expensive [4], a strong public role will continue to be necessary to support research and diffusion of knowledge among farmers, especially poorer ones [67–69].

Supporting Information

S1 Dataset. Economic coefficients and results of Monte-Carlo simulations.
(XLSX)

Acknowledgments

114

Publication 2

Author Contributions

Analyzed the data: LMC BC TK. Wrote the paper: LMC TK.

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115

Publication 2

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9.3. Publication 3

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Publication 3- Manuscript version

Integrated bio-economic models as tools to support land-use decision making: potential and limitations

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Abstract

Bio-economic modelling has become a useful tool for anticipating the outcomes of policies and technologies before its implementation. Recent advances in mathematical programming have made it possible to build more comprehensive models. Throughout an overview of bio-economic models applied to land-use problems, we evaluated how aspects such as uncertainty, multiple objective functions, system dynamics and time have been incorporated into models. The analysis has shown that none of the models have incorporated all of the aspects at the same time. Uncertainty was occasionally considered in land-use models. In those cases where it is incorporated, stochastic approaches were more frequent than non-stochastic robust methods. In multiple-objective models integration of uncertainty was often missing. Static approaches continue to be more recurrent than truly dynamic models, especially for models addressing multiple objectives. Application of systems dynamics has increased, with more emphasis on the relation between inputs and crop yield than on inter-species interactions and land degradation. Even though integrating multiple aspects may enhance our understanding of a system; it involves a tradeoff between simplicity and accuracy. Complex models have the disadvantages of being specific, expensive and time demanding. We consider that simpler models, even of static nature, which produce plausible results are a feasible alternative for modelling land-use issues. However, it is recommendable to integrate uncertainty and multiple objectives, which is possible even with limited information based on modern techniques. Additionally, periodic updates can improve their overall performance when new information is available.
Keywords: optimization, uncertainty, system dynamics, time, objective functions

JEL Code: Q57

Publication 3- Manuscript version

1.   Introduction

Bio-economics integrates two disciplines, economics and biology (Landa and Ghiselin 1999, Kragt 2012). Integrating both components together requires the collaboration of multiple disciplines to address the dynamic interrelationships between ecological and socio-economic systems (Flichman and Allen 2015). In practice, there exists a large variation in bio-economic models, forming a continuum between biological process models to which an economic component has been added, and economic models which include some biophysical components (Brown 2000).

Different approaches are described in the literature to guide resource allocation and decision making (e.g. Eastman et al. 1998, Lambin et al. 2000). Bio-economic models can be developed following positive or normative approaches depending on the goal pursued by the researcher (Janssen and van Ittersum 2007). Positive approaches for instance describe what is observed; they model the actual behavior of decision makers and predict what will happen in the future based on this knowledge (Louhichi et al. 1999). Normative approaches instead, suggest the best scenario to achieve a pre-defined aim in the most efficient way when new factors have been added to an existing formula (e.g. new policies, techniques or resources) (De Wit 1992).

Bio-economic models can be built from empirical observations (econometric model) or can be developed from theory (mechanistic model) (Brown 2000, Janssen and van Ittersum 2007). Mechanistic models are suitable for extrapolations and long-term predictions, because they may simulate system behavior outside the range of observed data. The advantage of mechanistic models compared to empirical models is that they produce optimized solutions based on objective functions (Pandey and Hardaker 1995).

Mechanistic bio-economic models have long been applied in the fields of fisheries, forestry and agriculture to support decision making (for fisheries see: Knowler 2002, Homans and Wilen 2005, Anderson and Seijo 2009; for forestry see: Vanclay 1994, Touza et al. 2008, Knoke and Seifert 2008; for agriculture see: Flichman et al. 2011, Rădulescu et al. 2014). Several authors coincide that optimal equilibrium levels may only be accomplished if production functions and ecological interactions are properly addressed (Grigalunas et al. 2001, Larkin et al. 2011, Kragt 2012). Nevertheless, methodological shortcomings have sometimes prevented an appropriate consideration of sustainability issues. Brown (2000) and Kragt (2012) suggest applying integrated bio-economic modelling, a comprehensive approach which enables the inclusion of a series of interactions occurring in economic systems and the environment in a more proficient way. Inclusion of aspects such as a suitable objective function, uncertainty, system dynamics and time is at the core of this approach (Fig 1).

Bio-economic models applied to land use have been evaluated by Janssen and van Ittersum (2007) as well as Delmotte et al. (2013). However, we consider that some important aspects have not been

Publication 3- Manuscript version

fully addressed in these reviews, such as: a) the suitability of a specific programming technique according to the objective functions; b) the consideration of uncertainty in multiple-objective modelling, and c) the use of non-stochastic optimization instead of probabilistic approaches. Thus, our research aims to address these gaps and to analyze the application of bio-economic models for land use problems.

We have organized our research according to the following scheme. Section 2, describes the key factors suggested in literature to achieve integrated bio-economic modelling. Section 3 describes acknowledged mathematical programming techniques for optimization, and briefly explains the suitability of each approach according to the goal pursued by the researcher. Section 4 includes a review of 30 studies addressing land-use problems where bio-economic modelling was applied. The list of studies was used to identify strengths and shortcomings in existing models by analyzing whether or not uncertainty, time scale and systems dynamics were included and which type of objective function was used in each study. Based on the preceding information, we draw conclusions and recommendations in section 5.
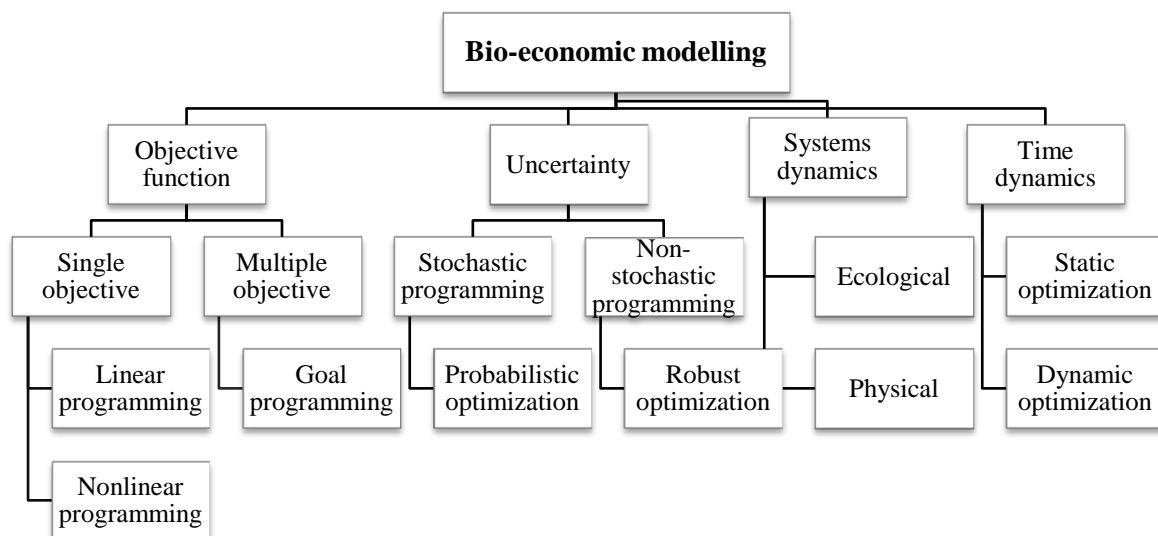
Fig. 1 Description of components of integrated bio-economic modelling

Publication 3- Manuscript version

2.   Fundamental aspects of an integrative approach

2.1. Objective functions

As a general rule, any bio-economic model derived for optimization must have the following three basic elements: i) an objective function, which represents the economic rationale of the decision process; ii) a description of the possible range of activities within the system with coefficients representing their productive responses; and iii) a set of constraints that define the operational conditions and the limits of the activities (Herrero et al. 1999, Ten Berge et al. 2000, Delmotte et al. 2013).

Basic models usually consider one objective function, for example profit maximization (Kragt 2012). However evidence suggests that few individuals maximize financial gain alone (Dent et al. 1995, Falconer and Hodge 2000). A more comprehensive way to analyze land owners´ decision should consider multiple objectives instead of a single one. It is important to recognize that there may be a number of objectives among which trade-offs arise.

Brown (2000) indicates that the identification and specification of decision makers´ objectives is one of the factors for significant improvement of bio-economic models. Thus, significant efforts need to be made to understand decision-makers' objectives and to incorporate them into the modelling framework.

2.2. Integration of uncertainty

In order to consider the variability of natural indicators and other risks factors, mechanistic models should include uncertainty analysis (Finger et al. 2010). For this purposes, the terms uncertainty and risk can often be used interchangeably, as suggested by Hirshleifer and Riley (2002) and Levy (2006). In fact, uncertainty is one of the most important aspects that a model aimed to predict future events should address (Rădulescu et al 2014). In the literature, two methods for including uncertainty are described: i) stochastic programming and ii) non-stochastic programming (Birge and Louveaux 1997, Beyer and Sendhoff 2007, Bertsimas et al. 2011). Stochastic programming is a framework for modelling optimization problems that involve uncertainty represented by probability functions for parameters of real systems. Non-stochastic programming is of deterministic nature instead (Knoke et al. 2015). Parameter variation is achieved using uncertainty sets, which pre-define possible parameter ranges over which optimization is carried out, resulting in robust solutions.

Stochastic programming is usually applied for problems dealing with random uncertainties (Beyer and Sendhoff 2007). The decision alternatives addressed by the objective function can be either discrete or continuous; being fundamental to distinguish between optimization methods (Estrella et al. 2014). The optimization routines to solve these decision problems can also be either discrete (integer programming) or continuous (model fitting, adaptive control, signal processing, and experimental design) (Birge and Louveaux 1997, Gentle et al. 2004). Discrete optimization, for

Publication 3- Manuscript version

example integer programming, is a large subject with applications on resource allocation, and policy planning (Gentle et al. 2004).

Approaches for modelling decision making within a probabilistic framework are stochastic dominance, downside risk and mean-variance (Benitez et al. 2006, Hildebrandt and Knoke 2011). Stochastic dominance considers the entire probability distribution of outcomes (Hadar and Russell 1969). Downside risk defines risk as expected outcomes below a certain minimum. So, risk measures are based on negative deviations4. Mean-variance decision rules depend on only two moments of the probability distribution. The mean-variance approach is limited to only those cases when the underlying probability distribution is a normal distribution (Hildebrandt and Knoke 2011). Other decision models such as the Maximin, Maximax, Hurwicz, Laplace, Savage-Niehans- and Krelle-rule ignore probabilities and assume that the decision maker knows the possible outcomes (Hildebrandt and Knoke 2011).

The second approach under analysis is a variant of robust optimization, which is a reasonable alternative when the parameter uncertainty is non-stochastic or if no distributional information is available (Bertsimas et al. 2011). Robust optimization constructs solutions that are deterministically immune to realizations of the uncertain parameters in specific sets (Bertsimas et al. 2011). In contrast to stochastic optimization, robust optimization gives all considered data perturbations an equal weight and does not assign various probabilities to specific events (Ben-Tal et al. 2009, Bertsimas et al. 2011). Even though robust optimization does not require a normal return distribution, this method needs at least some specification of possible input data variations (see Knoke et al. 2015). Thus, robust optimization has the advantage of being less data demanding because assumptions about variation need not to be as detailed as under stochastic optimization. Despite this advantage, robust non-stochastic optimization has rarely been applied in bio-economic modelling.

It is relevant to mention that robust optimization is distinctly different from sensitivity analysis (Ben-Tal and Nemirovski 2000). In robust optimization, fluctuating parameters within the prescribed uncertainty set are part of the optimization routine. Sensitivity analysis is a post optimization tool to test how results would change if assumptions on the data set on which the model was built were to change (Bertsimas et al. 2011, Yu and Li 2012).

2.3. Integration of time dynamics

In an integrated modelling context, the time-scale over which choices are made is of considerable importance. Throughout the literature it is possible to identify two methods to specify the time issue,

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4 Skewness measures the asymmetry of the probability density function around the mean. An increase in skewness to the right of the distribution implies a reduction in downside risk exposure. Greater negative skewness generates greater exposure to downside risk and higher positive skewness indicates less exposure to downside risk (Hildebrandt and Knoke 2011).

either static or dynamic. Static models have the ability to show what happens over time, but time itself is not embodied in the model (Bertsimas et al. 2011); therefore during the optimization process all decisions are implemented considering a single period. This feature of static models makes them restrictive and conservative, as these type of models neglect the variation of objectives over time, which impedes to adjust the decision making process (Delmotte et al. 2013).

Dynamic models incorporate time into their structure to consider decision variables as functions of time (Blanco Fonseca and Flichman 2002). In an economic sense "dynamic" means that decisions in one period grow out of developments in a previous period. Agents make decisions being aware that one period later more knowledge would be available. Depending upon the new knowledge, decision makers revise decisions for the next period (Samuelson 1969). For another example of a dynamic relation, refer to Schumpeter (1954), who stated: "… the quantity of a commodity that is offered at a point of time (t) is considered as dependent upon the price that prevailed at the point of time (t-1) …" (Schumpeter 1954, p. 1143). Unless we consider these relationships between variables from period to period, we cannot talk about a real dynamic approach.

Dynamic programming is applied to situations where a time horizon and the feedback mechanisms are integrated to the model (Kall and Wallace 2003, Bertsimas et al. 2011). Dynamic models are designed in sequential stages; they can be classified in recursive, dynamic recursive and inter-temporal models (Janssen and van Ittersum 2007). Recursive models are run over several periods; the starting values for each period are the end values of the last period. While recursive models optimize for each period separately, dynamic recursive models optimize over the whole period. Inter-temporal models optimize an objective function over the whole time period, however at every point in time a decision can be made considering trade-offs that may arise (Härtl et al. 2013).

If a sequential decision process excludes seasonal variability and tactical responses it can provide incorrect estimates of the economic benefits of a technology involved in complex biological and dynamic systems, thus, any plan needs to be adjusted over time (Marshall et al. 1997, Behrendt et al. 2016). As a consequence decision makers can decide which option is more beneficial in specific periods, and how the whole project would develop over the years. The possibility of analyzing the effect of different mechanisms before, during and after their implementation makes dynamic modelling being a great tool for supporting decision making.

2.4. Integration of system dynamics

Another key issue in bio-economic modelling is to capture the interactions and feedbacks that occur among ecological processes, human decisions and the range of decision options available (Brown 2000, Heerink et al. 2001). The dynamic relationship between natural resources and optimal investment

Publication 3- Manuscript version

decisions can often be non-linear, characterized by either multiple dynamic equilibria or extended periods of disequilibrium (Stephens et al. 2012). Conventional methods do not permit capturing non-linear dynamic relationships and to model the linkages and feedbacks between components of the systems. System dynamics is a process-based modelling technique that builds upon an observed reference problem which considers a limited numbers of outcomes each generated by an underlying structure of stock variables, flow variables and feedback loops (Ford 1999,Van den Belt 2004). These models are systems of nonlinear differential equations solved by numerical integration, which allow the introduction of different economic and biophysical shocks to examine a range of outcomes, which would be difficult to include in a multi-stage optimization model (Stephens et al. 2012).

Incorporating system dynamics into modelling has become very useful to analyze the complex interactions between ecosystem performance and human behavior. By analyzing the links and feedbacks of human intervention on natural landscapes, it is possible to assess the tradeoffs among economic and ecological goals and give them the right weight to guide decision making in a more efficient way. Nevertheless, it is important to mention that according to Clark (2006) complex models which include interactions between species might not always provide results that are more plausible than those achieved by simple models. Larkin et al. (2011) highlight that results achieved using dynamic models in fisheries were as plausible as those achieved with basic static single-species models. Thus integration of system dynamics might not necessarily improve the overall performance of a model, this aspect explains somehow why static and single species models are often favored over them.

3. Optimization techniques applied to bio-economic models

Optimization is at the core of most modelling of decision-making. Optimization routines can be adapted depending on the type of objective function selected, the uncertainty approach (stochastic or non-stochastic optimization), the treatment of time (static or dynamic), and the goals considered (single or multiple-objective programming). In this section we present an overview of optimization techniques applied for bio-economic modelling.

3.1. Linear programming

Mathematical programming offers several optimization techniques, among which linear programming is the most commonly used. Linear programming represents each possible option as a linear combination of activities characterized by a set of coefficients with corresponding inputs and outputs that express the activity's contribution to the realization of defined goals. As inputs are limited resources, constraints to the activities are defined, which represent the minimum or maximum amount of a certain inputs or resources that can be used. This system of activities and constraints is then optimized for some objective function, reflecting a user-specified goal, for example profit (Ten Berge et al. 2000, Janssen and van Ittersum 2007).

125

Publication 3- Manuscript version

Linear programming is quite versatile; it is equally applied for stochastic optimization problems, as long as the model setup contains no nonlinearities, but also for robust optimization. An optimization is usually achieved by allocating scarce resources (e.g. land or money) to pre-defined activities, which could be land-use options. The resources to be allocated are called decision variables and the distribution of them to land-use options usually forms the decision problem for the optimization model.

A standard mathematical formulation of a linear programming model is:

$$max \ (or \ min) \, Z = \sum_{i=1}^{n} c_i x_i$$

$$(a_{ji} x_i \leq b_j)_{j=1,\dots,m \, ; \, i=1,\dots,n}$$

$$x_i \geq 0$$

Where Z is the objective function: a linear function of the n production activities, where x stands for the quantity of a scarce resource allocated (decision variable) to a specific activity c, for example land, and their respective standardized (to a unit of x) contributions (c – coefficients) to the objective; ax ≤ b represents the m linear constraints (Janssen and van Ittersum 2007).

3.2. Nonlinear programming

Linear programming assumptions lead to appropriate representations over the range of the decision variable for linear relations. For some problems, however, nonlinearities in the form of either nonlinear-objective functions or nonlinear constraints demand a nonlinear programming solution (Bradley et al. 1977). In these cases the definition of activities must be such that all nonlinearities are embedded in the values of the input-output coefficients (Ten Berge et al. 2000).

Applications of nonlinear programming in bio-economic modelling refer, inter alia, to the portfolio theoretic framework (e.g. Clasen et al. 2011, Castro et al. 2013, 2015, Härtl et al. 2013) and have also been used for instance to maximize the return of land-use portfolios for pre-defined accepted levels of risk. In such applications the investor prefers to maximize his/her expected economic return and at the same time limit his/her financial risk as far as possible. As both of these objectives cannot be achieved simultaneously using linear programming, nonlinear programming offers a feasible solution by combining expected return and risk in an objective function.

Nonlinear programming models can be expressed by a variety of mathematical formulations, one exemplary formulation of a nonlinear programming model in the context of land-use decision making is:

$$max \ (or \ min) \ Z = \sum_{i=1}^{n} c_i x_i + n(x_i, cov_c)$$

Herein, n(xi,covc) represents a nonlinear function, in this example, nonlinear portfolio risks are considered, formed by the decision variables xi and all covariances covc, between income of the land-use activities considered.

The risk associated with a particular portfolio, that is, a particular set of values xi such that

$$\sum_{i=1}^{n} x_i = 1$$

is given by the variance of its return, σ_x^2, where

$$\sigma_x^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} cov_{ij} x_i x_j$$

in which xi is the proportion of land devoted to land-use option i, and cov_{ij} is the covariance between the returns on the ith and jth land-use option.

3.3. Multiple-objective programming

Solving a single-objective problem is the most classical optimization method. However, considering a single-objective function prevents a comprehensive understanding of actual problems (Caramia and Dell'Olmo 2008). Multi-objective optimization is a useful tool to integrate more information and to

include goals beyond profit maximization. The simplest way to handle multiple goals is to select one that would be maximized (or minimized) in the model and specify the remaining goals as inequality constraints (Hazell and Norton 1986). A limitation of this approach is that the goals included in the constraint set must be rigidly enforced; if they cannot be met then the problem would be unfeasible.

An alternative approach, known as goal programming (Charnes et al. 1955, Charnes 1977), establishes a target for each goal but rather than forcing compliance seeks to minimize the deviations between the achievement of the goals and their target levels (Hazell and Norton 1986). Goal programming is classified into two major subsets according to Tamiz et al. (1998). The first type is known as weighted goal programming, where the unwanted deviations are assigned weights according to their relative importance to the decision maker. The algebraic formulation of weighted goal programming is given as follows:

Publication 3- Manuscript version

$$\min Z = \sum_{i=1}^{n} (u_i n_i + v_i p_i)$$

s.t. $f_i(x_i) + n_i + p_i = b_i x_i \in C_s$

where $f_i(x_i)$ are linear functions of the decision variables x_i and b_i the target value for that functions. n_i and p_i represent the negative and positive deviations from this target value. u_i and v_i are the respective positive weights attached to these deviations in the achievement function Z. These weights take the value zero if the minimization of the corresponding deviational variable is unimportant to the decision makers. Cs is an optional set of hard constraints as found in linear programming.

The second type is known as lexicographical goal programming (Ijiri 1965, Ignizio 1976), where the deviation variables are assigned into a number of priority levels and minimized in a lexicographic sense as a sequential minimization of each priority while maintaining the minimal values reached by all higher priority level minimizations.

The algebraic representation of lexicographical goal programming is given as:

$$Lex \min a = (g_1(n, p), g_2(n, p), \dots g_L(n, p))$$

s.t. $f_i(x_i) + n_i + p_i = b_i, \quad i = 1 \dots n$

This model has L priority levels g, and n objectives, a is an ordered vector of these L priority levels. n_i and p_i are deviational variables which represent the under and over achievement of the ith goal, respectively. x_i is the set of decision variables to be determined. Any linear programming style hard constraints are placed, by convention, in the first priority level. A standard `g' (within priority level) function is given by

$$g_1(n, p) = u_{l1} n_1 + \cdots + u_{lq} n_q + v_{l1} p_1 + \cdots + v_{ln} p_n$$

where u_l and v_l represent inter-priority level weights, as in weighted goal programming, a zero weight is given to any deviational variable whose minimization is unimportant.

Other techniques rooted in Multiple Criteria Decision Making such as compromise programming and reference point methods, aiming to minimize the distance between a certain point and the actual achievements for each of several objectives under consideration can be re-formulated as goal programming problems. This condition makes goal programming one of the most versatile techniques for multiple-objective modelling (Romero et al. 1998).

Publication 3- Manuscript version

4. Review of bio-economic models applied to land-use problems

In this section, we present a review of 30 studies where bio-economic models have been applied to assist land-use decision-making. We conduct an extensive literature search in ISI Web of Knowledge, Scopus and Google Scholar. Considering as relevant for our analysis, we selected only the bio-economic models which followed a mechanistic and normative approach in the field of agriculture and forestry applied at the farm or forest level, with only few examples at the regional or landscape level (Koschke et al. 2012, Estrella et al. 2014, Kolinjivadi et al. 2015, Knoke et al. 2016). We then organize the models by considering the following important aspects for analysis: uncertainty, the type of objective function, the optimization routine (e.g. linear, nonlinear, multiple objective programming) time dynamics, and the type of system dynamics interactions (Table 1).

Table 1. Overview of bio-economic models applied to land use

Study	Uncertainty approach	Type of objective function	Optimization routine	Time dynamics	System dynamics
Barbier and Bergeron (1999)	Not applied	Maximize revenues	Linear programming	Dynamic	Soil erosion, nutrient depletion, water sedimentation
Pacini et al. (2004)	Not applied	Maximize revenues	Linear programming	Static	Nitrogen and soil losses, pesticide use, herbaceous plant biodiversity
Pfister et al (2005)	Not applied	Growth function	Dynamic programming	Dynamic	Crop mixing, fertilizer use, labor, climate scenarios
Acs et al. (2007)	Not applied	Maximize revenues	Dynamic linear programming	Dynamic	Nutrient loss, pesticide use, organic matter input, crop planning
Schönhart et al. (2016)	Not applied	Maximize revenues	Mixed integer	Static	Climate, crop productivity, crop prices
del Prado et al. (2011)	Not applied	Multiple objective	SIMS Dairy	Static	Climate and soil losses of nitrogen, phosphorus and carbon
Koschke et al. (2012)	Not applied	Multiple objective	Multiple criteria aggregation/ Analytical Hierarchy Process/ GISCAME	No details	Ecosystem services provision
Estrella et al. (2014)	Not applied	Multiple objective	Multiple Criteria Decision Model/ Iterative Ideal Point Thresholding/Compromise Programming	No details	Land use types, Ecosystem services provision
Eyvindson and Kangas (2014)	Not applied	Multiple objective	Multiple Criteria Decision Model/ Compromise Programming	No details	Forest management planning, preferences of stakeholders

Study	Uncertainty approach	Type of objective function	Optimization routine	Time dynamics	System dynamics
Paracchini et al. (2015)	Not applied	Multiple objective	SOSTARE model	No details	Agronomic and ecological aspects
Cortez-Arriola et al. (2016)	Not applied	Multiple objective	Pareto-based multi-objective optimization	Static	Socio-economic, environmental and production (agriculture and livestock)
Townsend et al. (2016)	Not applied	Multiple objective	/ MEETA (Managing Energy and Emissions Trade-Offs in Agriculture)	Static	Profit, energy, and greenhouse gas emission
Kolinjivadi et al. (2015)	Discrete optimization	Multiple objective	Discrete multi-criteria approach NAIADE (Novel Approach to Imprecise Assessment and Decision Environments)	No details	PES with varying emphasis on conditionality, efficiency, equity and poverty alleviation
Holden et al. (2004)	Stochastic optimization	Maximize welfare	Non-linear programming	Dynamic	Soil erosion and nutrient depletion
Semaan et al. (2007)	Stochastic optimization	Maximize revenues/Minimize risk	Agronomic Simulation Model EPIC/ Multi-objective programming	Dynamic	Crop growth, soil water balance, erosion, pesticide and nutrients movement
Acs et al. (2009)	Stochastic optimization	Maximize revenues	Discrete stochastic utility-efficient programming (DUEP)	Dynamic	Nutrient surplus, organic matter input and pesticides use
Clasen et al. (2011)	Stochastic optimization	Maximize revenues/Minimize risk	Non-linear programming	Static	Natural hazard risks, timber price fluctuations
Doole et al. (2013)	Stochastic optimization	Maximize revenues	Non-linear programming/Integer programming	Static	Nitrogen input, energy demand per cow,
Härtl et al. (2013)	Stochastic robust optimization	Maximize revenues/Minimize risk	YAFO model/ AIMMS model/ Nonlinear programming	Dynamic	Tree drop-outs as function of leading tree species, mixture conditions, and stand age

Study	Uncertainty approach	Type of objective function	Optimization routine	Time dynamics	System dynamics
Griess and Knoke (2013)	Stochastic optimization	Maximize revenues/Minimize risk	Static Nonlinear programming	Static	Survival probability of tree species, returns
Rădulescu et al. (2014)	Stochastic optimization	Multi-objective	Mixed-integer programming	No details	Weather and market risks
Kanellopoulos et al. (2014)	Stochastic optimization	Maximize revenues	Data Envelopment Analysis/ Linear programming FSSIM	Static	Effects of climate change temperature rise, change of air circulation, precipitation change, CO_2 concentration
Komarek et al. (2015)	Stochastic optimization	Certainty equivalent	Simulation Model APSIM (Keating et al., 2003), SERF (Hardaker et al., 2004),	Dynamic	Climate and price variability
Castro et al. (2015)	Stochastic optimization	Maximize revenues/Risk reduction	non-linear programming	Static	Productivity of crops and price volatility
Alary et al (2016)	Stochastic optimization (Target MOTAD)	Maximize revenues	Mathematical programming (General Algebraic Modelling System, GAMS)	No details	Agronomic coefficients, livestock income, yield, price
Behrendt et al. (2016)	Stochastic optimization	Maximize revenues	Stochastic programming	Dynamic	Climate risk, technology, composition of pasture
Liu et al. (2016)	Stochastic optimization	Maximize revenues/Risk reduction	mixed integer nonlinear programming	Dynamic	Yield subject to management (liming, fertilizing)
Hildebrandt and Knoke (2009)	Robust stochastic optimization	Maximize revenues/ Minimize risk	Worst-case optimization	No details	Natural hazards and price volatility
Knoke et al. (2015)	Stochastic optimization/Robust optimization	Maximize revenues/ Risk reduction	non-linear and linear programming	Static	Productivity of crops and price volatility
Knoke et al. (2016)	Robust optimization	Multiple objective	Goal programming (Compromise programming)	Static	Carbon stocks, climatic and hydrological regulation, soil properties, economic return, payback periods

Publication 3- Manuscript version

4.1.   Approaches to deal with uncertainty

Throughout our search, we observed that uncertainty was a topic occasionally addressed in bio-economic models applied to land use (see Table 1). According to our list, fifteen studies applied the stochastic approach to integrate uncertainty into their models. This approach was applied mainly to a single objective function e.g. maximize revenue (Acs et al 2009, Doole et al. 2013, Kanellopoulos et al. 2014, Alary et al. 2016, Behrendt et al. 2016) and to portfolio studies to maximize revenues subject to risk reduction in fields such as forestry (Clasen et al. 2011, Härtl et al. 2013, Griess and Knoke 2013) and agriculture (Semaan et al. 2007, Castro et al. 2015, Knoke et al. 2015). Only one application of stochastic programming addressed multiple objectives (Rădulescu et al. 2014), while the work developed by Komarek et al. (2015) aimed to optimize certainty equivalent of farmers.

Applications of robust optimization were less frequent despite the advantage of demanding less information. Hildebrandt and Knoke et al. (2009) applied robust stochastic optimization to maximize revenues subject to risk reduction applying worst case optimization. Knoke et al. (2015) applied both non-stochastic robust optimization and stochastic optimization to assess their suitability to address farming issues. Their study demonstrated that robust optimization is a suitable approach when information on input parameters is limited. Their results showed that land-use portfolios derived following robust optimization led to a higher degree of diversification than those obtained by stochastic optimization. Concerning the economic outcome the returns were only slightly lower in robust non-stochastic portfolios but offered a higher protection against shortfall. The only study addressing robust optimization and multiple objective functions was Knoke et al. (2016).

We noticed that uncertainty was often neglected in multiple-objective models (del Prado et al. 2011, Koschke et al. 2012, Estrella et al. 2014, Paracchini et al. 2015, Cortez-Arriola et al. 2016). Disregarding uncertainty reduces the range of scenarios that decision makers may consider at the moment of allocating resources. This shortcoming prevents the development of strategies to cope with worst case scenarios, impede response and adaptability to problems which could be anticipated. Thus, we consider that uncertainty should be included in bio-economic modelling to help land-users to make better decisions, and methodologies are available to facilitate its inclusion.

4.2.   Time dynamics

The importance of time and its effects on decision making and resource allocation is being acknowledged by researchers. The improvements of dynamic modelling have made it possible to increase the number of studies modelling time dynamically. It has been applied to single objective models solved with dynamic linear programming (Pfister et al. 2005, Acs et al. 2007), dynamic non-linear programming (Holden et al. 2004, Härtl et al. 2013), mixed integer non-linear programming (Liu et al. 2016) and discrete stochastic programming (Acs et a.. 2009). Other applications of dynamic modelling including other methodologies were Barbier and Bergeron (1999) Komarek et al. (2015) and Behrendt et al. (2016).

Publication 3- Manuscript version

Interestingly, we found that dynamic modelling applied to land-use topics has rarely been applied in combination with multiple-objective modelling (Semaan et al. 2009). We found that most multiple-

objective models analyzed throughout this research applied static approaches (del Prado et al. 2011, Cortez-Arriola et al. 2016, Townsend et al. 2016, Knoke et al. 2016). Additionally, static models were applied for single-objective modelling (Pacini et al. 2004, Doole et al. 2013, Kanellopoulos et al. 2014) and for portfolio applications (Clasen et al. 2011, Castro et al. 2015)

Based on this review, we consider that static models continue to be a good option to model land-use problems despite the disadvantage of modelling with fixed coefficients over time. An alternative for enhancing the results of static approaches is to update the results when new information is available.

4.3.   System dynamics

The advances in the field of system dynamics supported the inclusion of a series of interactions in land-use systems. Studies such as Pacini et al. (2004), Acs et al. (2007), Acs et al. (2009) and Paracchini et al. (2015) have addressed the relation between inputs and crop yields in detail. These models have analyzed the trade-offs of improved technological management in agriculture and the response of farming systems in terms of yields.

The impact of nutrient flow, climate change, water availability and soil management and farm profitability has also been analyzed in bio-economic modelling (del Prado et al. 2011, Kanellopoulos et al. 2014). were analyzed Pfister et al. (2005) and Semaan et al. (2007) studied biotic relations - mainly competition for nutrients- using crop growth models while Ghebremichael et al. (2013) and Doole et al. (2003) applied animal growth models. Examples in forestry and agroforestry where models have accounted for interactions in mixed species stands (Knoke and Seifert 2008, Griess et al. 2012, Neuner et al. 2015). These studies have highlighted the benefits for reduction of risk against natural hazards and improved growth rates.

Few models have incorporated land degradation. Barbier and Bergeon (1999) included soil erosion equations, and interactions among livestock, crops and forest. Holden et al. (2004) assessed the impact of improved access to non-farm income on household welfare, agricultural production, conservation investments and soil erosion. Other interesting topics included the effects of policies on nitrate leaching and farmers´ income (Barbier and Bergeron 1999, Semaan et al 2007, Doole et al. 2015) willingness to accept payments for ecosystem services (Kolinjivadi et al. 2015) measures to mitigate and adapt to climate change at the farm level (Schönhart et al. 2016).

The application of system analysis and dynamics has made it possible to include a larger number of variables and to simulate feedbacks of processes occurring in nature, which helps to explain interrelations in land use systems. A disadvantage of including a large number of variables and processes in a model

Publication 3- Manuscript version

is that the results turns out to be very specific, limiting transferability to other contexts (Behrendt et al. 2016). In addition, this branch of modelling may be quite costly and time demanding, limiting the number of possible applications.

4.4.   Single objective versus multiple-objective models

Multiple-objective models are increasingly applied in topics related to land-use planning. Studies which consider multiple-objective functions are Paracchini et al. (2015), Rădulescu et al. (2014), Eyvindson and Kangas (2014), Estrella et al. (2014) and Koschke et al. (2012), Knoke et al (2016) and Cortez-Arriola et al. (2016). Nevertheless, a sound integration of uncertainty in multiple objective models is still required. Knoke et al. (2016) is one of the few examples in which a model considering multiple objectives has included uncertainty applying robust methods. We expect that future applications of such approaches will increase due to the development of enhanced optimization techniques and the relevance of considering more comprehensive approaches to support decision making.

5. Conclusions

In general, we can conclude that bio-economic modelling applied to land use has experienced great progress in the last years due to accessibility to improved programming techniques, which have made it possible to create more comprehensive models that embrace complex interactions and feedbacks. Nevertheless, from a theoretical and mathematical perspective researchers should be cautious when incorporating complex interactions and feedbacks, because the resulting complexity might lead to black boxes. As a trade-off between simplicity and accuracy is unavoidable, researchers must be wise enough to select the information that helps to understand the specific phenomena and to identify feasible solutions. At the light of this research, simpler models even of static nature show interesting results; up to now, they are more frequently applied than complex models to analyze landowners´ preferences and predict scenarios concerning land-use topics. Nevertheless, we consider that a sound integration of uncertainty and multiple objectives could significantly improve the performance of land-use models and produce more plausible solutions than those models considering a single objective function.

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