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Empirical Analyses of Selected Chinese Policies for Sustainable Development

Xiaojie Wen

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Summary

As building a sustainable society has received widespread attention from academia, governments, and international communities, a series of strategies and policies have been developed to support economic, environmental, and social sustainability. Given the diverse natural conditions and socioeconomic characteristics, the development of sustainability-related policies needs to be examined case by case. In light of the global significance of Chinese sustainable development, gaining insights into overcoming sustainability challenges within the Chinese policy context becomes crucial. Reviewing the key sustainable development policies and strategies implemented in China, this thesis endeavors to examine the challenges and weaknesses of policy design and implementation for China's sustainable development and offer insights into viable solutions and future avenues toward environmental, economic, and social sustainability. Importantly, China's experiences and lessons for policy development on sustainability issues contribute to valuable references for improving the performance of sustainability practices inside and outside China.

In the context of one national strategy entitled "Ecological Conservation and High-quality Development of the Yellow River Basin", Study 1 attempts to categorize the counties within the basin into ecological function zones, crop production zones, and core economic zones. Using a three-stage parametric slacks-based measure of efficiency approach, this classification can be achieved by evaluating comparative advantages from an efficiency perspective. The findings not only provide detailed zoning plans but also reveal the significant impacts of advantageous natural conditions on improving sustainability performance. To assess the cost-effectiveness of the Sloping Land Conversion Program (SLCP) in China, Study 2 employs the directional distance function (DDF) with convex expectile regression to estimate shadow prices of the SLCP investments for soil loss control. By comparing the shadow prices of the other two alternative solutions (including downscaling the primary industry and downscaling the non-primary industries), the results suggest that some counties should suspend the SLCP and replace it with other alternative measures.

Given the "Three-year Action Plan for Rural Living Environment Improvement" in China, Study 3 turns its attention to four types of waste disposal behavior among rural households (i.e., domestic waste sorting, agricultural waste disposal, sewage collection, and toilet retrofitting). Based on the geographic networks measured by physical distances among surveyed

households' dwellings, this study unveils whether and how households' waste disposal behavior influences others nearby via geographic networks. Using the Bayesian estimation of a spatial autoregressive probit model, the findings show that close geographic networks could positively stimulate the pro-environmental waste disposal behavior contagion. Apart from these, to evaluate the role of risk mitigation measures in a changing climate, Study 4 offers a systematic assessment of the nexus between agricultural vulnerability, crop yields, and multiple adaptation practices within the regime-switching framework. By utilizing the Markov switching model and panel threshold regression, this study demonstrates that the ex-ante mitigation measures (including irrigation system, reservoir capacity, and soil loss control) play a crucial role in reducing the adverse effects of agricultural vulnerability on crop production. Additionally, the intensity of these mitigation effects varies across different mitigation actions.

Overall, this thesis targets the development of policies and strategies and seeks to address multiple sustainability challenges, including balancing economic growth and environmental improvement (in Study 1), mitigating soil erosion (in Study 2), promoting waste management (in Study 3), and improving climate actions for sustainable agriculture (in Study 4). In terms of policy development, this thesis makes contributions by providing evidence-based recommendations for improving policy design (Study 1), optimizing policy implementation (Study 2), investigating key factors affecting policy implementation (Study 3), and offering quantifiable and operational suggestions for policy innovation (Study 4). By that, the thesis extends the literature on sustainability-related policy development, which aids policymakers in navigating socioeconomic improvement and environmental conservation more effectively.

Zusammenfassung

Die Schaffung nachhaltiger Gesellschaftssysteme ist zentraler Debattengegenstand in Wissenschaft, Politik und internationalen Organisationen. Den Debatten folgend wurden bereits zahlreiche Strategien und Maßnahmen zur Förderung einer wirtschaftlich, ökologisch und sozial nachhaltigen Entwicklung entworfen. Angesichts auf globaler Ebene variierender natürlicher und sozioökonomischer Merkmale, muss die Entwicklung von Nachhaltigkeitsstrategien und -maßnahmen fallspezifisch und unter Einbeziehung regionaler/nationaler Faktoren erfolgen. Dies gilt auch für China, dessen zukünftige Entwicklungspfade für eine nachhaltige Entwicklung des Planeten von zentraler Bedeutung sind. Ähnlich bedeutsam sind Analysen und das Gewinnen von Erkenntnissen im Hinblick auf chinesische politische Ansätze zur Bewältigung von Nachhaltigkeitsherausforderungen. Vor diesem Hintergrund werden in dieser Dissertation in vier Studien wesentliche in China umgesetzte Strategien und Maßnahmen für eine nachhaltige Entwicklung untersucht. Ziel der Dissertation ist es, Herausforderungen und Schwachstellen der Politikgestaltung und -umsetzung mit Schwerpunkt nachhaltige Entwicklung in China zu untersuchen und praktikable Lösungen sowie zukünftige Pfade einer ökologischen, wirtschaftlichen und sozialen Nachhaltigkeit zu entwickeln. Chinesischen Erfahrungen können – wie auch Lehren von anderen Erdteilen – als wichtige Referenzen für eine erfolgreiche Politikgestaltung in Nachhaltigkeitsfragen innerhalb und außerhalb Chinas dienen.

Studie 1 widmet sich einer nationalen Strategie mit dem Titel „Naturschutz und qualitätsvolle Entwicklung im Einzugsgebiet des Gelben Flusses“. Sie versucht, Verwaltungseinheiten innerhalb des Einzugsgebiets basierend auf Kostenstrukturen in ökologische Funktionszonen, Zonen landwirtschaftlicher Erzeugung und Kernwirtschaftszonen einzuteilen. Mithilfe eines dreistufigen, auf parametrischen Slacks basierenden Effizienzmaßansatzes kann diese Klassifizierung durch die Bewertung komparativer Vorteile abgeleitet werden. Die Ergebnisse bilden nicht nur geografisch genaue Schwerpunktzonen ab, sondern verdeutlichen auch, wie stark sich ein guter Naturzustand auf die Nachhaltigkeitsbewertung auswirkt. Studie 2 nimmt das Sloping Land Conversion Program (SLCP) und seine Kostenwirksamkeit in den Blick. Basierend auf einer Distanzfunktion mit konvexer expectile regression werden Schattenpreise der SLCP-Investitionen zur Vermeidung von Bodenerosion ermittelt. Durch den Vergleich der Schattenpreise mit denen zweier Alternativmaßnahmen (Drosselung der landwirtschaftlichen Produktion bzw. Abbau von Kapazitäten in der Industrie und im Dienstleistungssektor) lässt sich schlussfolgern, dass das SLCP nicht in allen Fällen die kostenoptimierte Alternative

darstellt.

Studie 3 richtet ihre Aufmerksamkeit auf den „Dreijährigen Aktionsplan zur Verbesserung der Lebensumstände im ländlichen Raum“ der Kommunistischen Partei Chinas. Sie untersucht ein wesentliches Element des Aktionsplans, den Umgang mit Abfall und Reststoffen in Haushalten des ländlichen China. Im Speziellen wird das Entsorgungsverhalten in den Bereichen „Sortierung von Hausmüll“, „landwirtschaftliche Reststoffe“, „Abwassernutzung“ und „Toilettennachrüstung“ analysiert. Methodisch nutzt die Studie physische Entfernungen zwischen ländlichen Haushalten und ein räumlich-autoregressives Bayes’sches Probit-Modell zur Identifikation geografischer Netzwerke. Diese Netzwerke lassen Rückschlüsse auf die gegenseitige Beeinflussung von Haushalten bezüglich des Umgangs mit Müll und Reststoffen zu. Die Modellergebnisse zeigen, dass enge geografische Netzwerke umweltfreundliches Abfallentsorgungsverhalten positiv stimulieren können. In der letzten Studie wird eine systematische Bewertung des Zusammenhangs zwischen landwirtschaftlicher Vulnerabilität, Ernteerträgen und Anpassungsmaßnahmen vorgenommen, um die Rolle von Risikominderungsmaßnahmen in einem sich verändernden Klima zu bewerten. Mithilfe eines Markov-Switching-Modells und einer panel threshold regression wird ermittelt, dass Ex-ante-Minderungsmaßnahmen (Bewässerungssysteme, Speicherbecken und Erosionsschutzmaßnahmen) eine entscheidende Rolle bei der Abschwächung landwirtschaftlicher Vulnerabilität spielen. Darüber hinaus variiert die Intensität dieser Minderungseffekte je nach Minderungsmaßnahme.

Insgesamt zielt die vorliegende Arbeit also auf die (Weiter)Entwicklung vorwiegend politischer Maßnahmen und Strategien zur nachhaltigen Entwicklung ab und befasst sich nicht zuletzt deshalb mit Herausforderungen aus verschiedenen Bereichen der Nachhaltigkeit. Ein wesentliches Merkmal dieser Dissertation ist der Versuch, die unterschiedlichen Kategorien der Nachhaltigkeit zu beleuchten und ein Gleichgewicht zwischen ihnen herzustellen, insbesondere zwischen wirtschaftlicher/gesellschaftlicher Entwicklung und Naturschutz. Sie leistet folglich einen evidenzbasierten Beitrag zur Politikgestaltung (Studie 1), zur Optimierung der Politikumsetzung (Studie 2), zur Untersuchung von Schlüsselfaktoren, die die Politikumsetzung beeinflussen (Studie 3) sowie zur Entwicklung innovativer politischer Maßnahmen (Studie 4). Ferner ergänzt sie die wissenschaftliche Literatur zur nachhaltigkeitsbezogenen Politikentwicklung, die politische Entscheidungsträgern in ihrem Bemühen um sozioökonomische Verbesserungen und Umweltschutz unterstützt.

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List of Abbreviations

CPC	Communist Party of China
CRS	constant returns to scale
DDF	directional distance function
DEA	data envelopment analysis
DMU	decision making unit
DRS	decreasing returns to scale
EKC	environmental Kuznets curve
GDP	gross domestic product
GHG	greenhouse gas
IRS	increasing returns to scale
MAC	marginal abatement costs
MPs	marginal products
MRTS	marginal rate of technical substitutions
PES	payments for ecosystem services
RSS	residual sum of squares
RUSLE	Revised Universal Soil Loss Equation
SBM	slacks-based measures of efficiency approach
SDGs	Sustainable Development Goals
SFA	stochastic frontier analysis
SLCP	Sloping Land Conversion Program
StoNED	stochastic non-smooth envelopment of data
the13th FYP	the 13th Five-Year Development Program

Publication and submission records

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2. Wen, X., Yao, S., & Sauer, J. (2022). Shadow prices and abatement cost of soil erosion in Shaanxi Province, China: Convex expectile regression approach. *Ecological Economics*, *201*, 107569. https://doi.org/10.1016/j.ecolecon.2022.107569
3. Wen, X., Mennig, P., Li, H., & Sauer, J. (2022). Geographic networks matter for pro-environmental waste disposal behavior in Rural China: Bayesian estimation of a spatial probit model. The paper was presented at the 97th Annual Conference of the Agricultural Economics Society (AES) in 2023. (under review)
4. Wen, X., Mennig, P., & Sauer, J. (2023). Assessing the regime-switching role of risk mitigation measures on agricultural vulnerability: A threshold analysis. (under review)

1. Introduction

The term "sustainable development" literally refers to maintaining development over time (Elliott, 2012, p.16) and originates from the reflections on the negative impacts of human activities on nature (Purvis et al., 2019). In contrast to the assertion regarding the incompatible relationship between economic growth and environmental integrity, the United Nations Conference on the Human Environment in 1972, regarded as the first world conference on the environment, formally proposed to reconcile economic development with environmental conservation. In the 1987 report "Our Common Future" (also known as the Brundtland Report) issued by the World Commission on Environment and Development, sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

To bring the blueprint of sustainable development into the real world, 17 Sustainable Development Goals (SDGs) are outlined in the "2030 Agenda for Sustainable Development" for 2016-2030 and regarded as a guideline to balance economic, social, and environmental considerations for current and future generations (Ranjbari et al., 2021). These SDGs cover poverty alleviation, hunger reduction, clean water and sanitation, sustainable cities and communities, climate change adaptation, and so forth. It is widely accepted that one global challenge is to comprehensively understand the sustainability threats and find a way to address them (Xue et al., 2018). Due to the heterogeneity of natural conditions and socio-economic characteristics, pathways to the SDGs are site-based and context-specific (Liu & Raven, 2010). Accordingly, an overview of threats to sustainable development is presented in Section 1.1. Section 1.2 proceeds to review the typical Chinese sustainability-related policies and introduces the challenges underlying the specific policy context. Moreover, this introduction aids in gaining a comprehensive understanding of the objectives of this thesis, as outlined in Section 1.3.

1.1 An overview of threats to sustainable development

With the increasing importance of sustainable development in various fields (including business, economy, environment, and so forth), this topic has been widely discussed among academia, industries, governments, and international society (Mauerhofer, 2008). Even so, sustainable development still lacks a solid theoretical foundation and remains an open concept with diverse definitions and interpretations based on the specific contexts within different disciplines (Elliott, 2012, p.18; Mebratu, 1998; Purvis et al., 2019; Ruggerio, 2021). This situation has evoked intense debates among researchers and policymakers, which challenges the planning for sustainable development. Nevertheless, there is one foundational consensus in the debates that sustainable development involves “three pillars”: economic sustainability, social sustainability, and environmental sustainability. According to the study of Purvis et al. (2019), this three-pillar conception has been widely applied in the investigations of economic outcomes from both social and ecological perspectives, as well as the explorations into mitigating the conflicts of interests between economic growth, social development, and environmental conservation. Basically, the nature of challenges for sustainable development is closely associated with the interconnections and trade-offs between these “three pillars” (Xue et al., 2018).

A sustainable society is placed in the intersection of three intersecting circles: economic system, environmental system, and social system, which requires actions to promote positive synergies and compromise the negative trade-offs among different systems (Elliott, 2012). However, past development for both agricultural and non-agricultural sectors is always based on extensive economic patterns, which are highly dependent on intensive resource exploitation (Zhang & Wen, 2008). In this context, one main challenge human beings face is the so-called environmental “source limits” or resource scarcity (particularly for non-renewable resources). Given this fact, the dependence of economic sustainability on environmental capacity is one long-standing focus of academic and political debates. Furthermore, the issues regarding environmental limits would be further exacerbated by resource wastage, which is generally induced by insufficient waste recycling, low resource recovery rate, inefficient production activities, and so on. As the environment cannot consistently absorb the growing volume of waste generated by production and consumption, pro-environmental waste management has undoubtedly become an urgent task for global sustainable development (Pujara et al., 2019). More importantly, due to rapid urbanization, industrialization, and population growth, this economic non-sustainability has also triggered and exacerbated adverse ecological consequences (e.g., deforestation, land degradation, air and water pollution, and soil erosion), further threatening social development and human health (Elliott, 2012; Liu & Raven, 2010). Regarding social sustainability, it has always been concerned with equal access to resources, community development, and poverty alleviation, but not limited to these (Ruggerio, 2021). Particularly, rural populations are more vulnerable to social sustainability issues due to the limited access to production resources (e.g., productive lands and advanced agricultural production facilities), essential public services (e.g., education and healthcare), and basic infrastructure (e.g., flush toilets and effective waste disposal system) (Altier & Masera, 1993;

Liu, 2018; Swanson et al., 2001). Thus, improving rural social sustainability is critical in achieving overall sustainable development.

Notably, significant climate change and the increased extreme weather events complicate the aforementioned challenges and further give rise to new sustainable development issues (e.g., climate-induced water stress, ecological disturbance, food scarcity, etc.) (Agovino et al., 2019; Cramer et al., 2018; FAO, 2022c). According to the study of Fuso Nerini et al. (2019), climate change not only exacerbates the ecological, social, and economic vulnerability of human society but also undermines efforts to achieve the SDGs. Furthermore, Balasubramanian (2018) indicates that the intensity and frequency of climate variability vary by regions, further resulting in uneven impacts of climate change and worsening regional inequality. Countries and people with lower economic and social status face more losses than others, even if they are exposed to similar climate-related disasters. Meanwhile, the limited positive impacts of climate change are mainly reported in high-income counties and regions (Fuso Nerini et al., 2019; Wang et al., 2009). Against this background, actions are needed to alleviate the potential climate-induced damages and leverage the opportunities from climatic variation (Nobre et al., 2016). Additionally, by revealing the synergies and trade-offs between climate action and the SDGs, Fuso Nerini et al. (2019) highlight the integration of climate action and the SDGs to maximize the effectiveness of actions in both domains.

1.2 Sustainable development in the Chinese policy context

Since the economic reform and opening up in the late 1970s, China has experienced rapid economic growth and social development. According to the World Bank (n.d.), China's gross domestic product (GDP) volume amounted to 17.82 trillion U.S. dollars, following the United States with a GDP of 23.32 trillion U.S. dollars. Nevertheless, intensive economic growth inevitably poses a range of sustainability issues (such as environmental pollution, land degradation, improper waste disposal, etc.), necessitating effective governance interventions (Jiang et al., 2021; Liu et al., 2020). As the largest developing country with a massive population and vast territory, China encounters rather complex sustainability issues and tricky governance challenges. Promoting the understanding of China's experiences and lessons in sustainable development can provide valuable insights for other countries grappling with similar problems.

In China, the "Ten Strategic Policies for Environment and Development" issued by the National

Environmental Protection Agency in 1992 highlights sustainable development as one fundamental national development principle (Zhang & Wen, 2008). This milestone document marks a critical step in addressing sustainability challenges. As a positive response to the "2030 Agenda for Sustainable Development", the Chinese government has adopted 17 SDGs into the domestic medium- and long-term development plans (Xue et al., 2018). One notable example is "the 13th Five-Year Plan for Economic and Social Development" (hereinafter referred to as the 13th FYP), which was proposed in 2016 by the National People's Congress.[1] The 13th FYP plays a prominent role in national macroeconomic strategy planning and provides guidelines for poverty alleviation, environmental conservation, green economy, and so forth. To date, a package of action plans, strategies, and policies have been implemented to coordinate economic growth, social development, and environmental conservation (Islam & Wang, 2023). By taking a closer look at some of the key sustainability-related strategies and policies implemented in China, the present section illustrates the challenges of building a more effective public policy framework.

The first national strategy outlined here is "Ecological Conservation and High-Quality Development of the Yellow River Basin" proposed in 2019. The Yellow River is the second-longest river in China and flows through nine provinces and autonomous regions with distinct climatic, economic, social, and cultural characteristics (Khan et al., 2021). Due to the intricate natural conditions and fragile ecosystems of this river basin, economic reforms and climate change have accelerated environmental degradation and income inequality (such as soil erosion and poverty), particularly in the face of rapid urbanization and industrialization (Chen et al., 2020; Jiang et al., 2021). For this reason, the central government attaches great importance to ecological conservation and socio-economic advancement in the river basin (Zhang et al., 2021). Apart from these, a fundamental concept mentioned in this national strategy is high-quality development, which was officially introduced in the 19th National Congress of the Communist Party of China (CPC) in 2017. It reflects the growing demands for a better ecological environment, a more sustainable economic growth model, a more comfortable living environment, and a more equitable society. Acknowledging the regional heterogeneity in natural conditions and socioeconomic structures, this national strategy underscores the importance of tailored development approaches. Accordingly, one of the main tasks of this strategy is to categorize the entire basin into three function zones with different development priorities: ecological conservation, crop production, and economic growth. By that, high-quality development should be achieved by effectively leveraging the comparative

[1] In Xue et al. (2018), the detailed content of the 13th FYP has been compared with the SDGs. It helps readers to better understand how the SDGs are integrated with the 13th FYP.

advantages of different function zones. So far, the well-recognized geographical division points of the Yellow River are the Hekou and Huayuankou hydrological stations, which divide the river into the upper, middle, and lower reaches (She et al., 2017). Because this rough division standard is only determined based on the heterogeneous topographic, climatic, and stream features of these three river sections, it fails to capture the socio-economic characteristics of the areas through which the river flows. Therefore, identifying effective division criteria is a key policy challenge of this national strategy.

The second Chinese sustainability initiative discussed in this section is the Sloping Land Conversion Program (SLCP), which was launched in 1999 after severe droughts in 1997 and the massive floods in 1998 (Liu et al., 2008). According to the white paper “Returning Farmland to Forest and Grassland for 20 Years in China (1999-2019)”, China experienced a rapid expansion of farmland by approximately 31.3 million hectares with a significant population growth of 710 million people from 1949 to 1998.[2] Remarkably, the farmland with slopes exceeding 15 degrees is mainly distributed in the ecologically fragile western region, including the upper and middle reaches of the Yellow River Basin (Li et al., 2022). Large-scale deforestation and excessive reclamation trigger severe off-site effects of soil erosion (such as floods and dust storms), deteriorate the ecosystems, and threaten food production and rural development (Yang et al., 2013). To reverse this unfavorable situation, the primary target of the SLCP is to combat soil erosion and alleviate environmental degradation by converting steeply sloping and ecologically fragile farmland into forests and grasslands.

In terms of over two decades of long-term duration, massive total investment, and large implementation scale (involving more than 25 provinces, municipalities under the direct control of the central government, and autonomous regions), the SLCP is recognized as one of the largest payments for ecosystem services (PES) initiatives worldwide (Liu et al., 2008; Wang et al., 2017). According to the statistics published in the white paper, the area of converted farmland reached around 208 million hectares with an investment of 442.48 billion yuan from 1999 to 2013 and 74.92 billion yuan from 2014 to 2019. Despite the remarkable achievements, the SLCP undoubtedly places a financial burden on the central and local governments, thus triggering debates on its cost-effectiveness (Wang et al., 2017). One primary concern about the SLCP implementation is related to the inflexible compensation standards. Generally, to account for the regional heterogeneity, the compensation standards for farmers in the Yellow

[2] This white paper published in 2020 provides a comprehensive overview of the multifaceted aspects of the SLCP implementation. (See the link http://www.forestry.gov.cn/html/main/main_195/20200630085813736477881/file/20200630090428999877621.pdf (in Chinese) for the full text).

River Basin and the Yangtze River Basin are different. To be more specific, farmers are provided with 1,500 kg of grain (or 2,100 yuan at a rate of 1.4 yuan per kg of grain) per ha of converted cropland per year in the Yellow River Basin. In the Yangtze River Basin, the offering is 2,250 kg of grain (or 3,150 yuan at a rate of 1.4 yuan per kg of grain) per ha of converted cropland per year (Liu et al., 2008; Wang & Maclaren, 2012). However, the compensation standard inside the river basin is single and fixed. Without adequate consideration of varying natural and socioeconomic conditions within the river basin, the compensation payments solely depend on the area of total converted farmland (Ding & Yao, 2021; Zhang et al., 2019). In this context, the policy design of the SLCP may lead to cost inefficiency, such as overpayment in one place and underpayment in the other, which calls for a more adaptable and individualized compensation system.

Apart from the environmental policies mentioned above, the Chinese government has also prioritized rural sustainable development challenges (e.g., poverty, poor sanitation, environmental pollution, lagging waste management, etc.) (Yin et al., 2022). One of the critical rural development initiatives is the Rural Revitalization Strategic Plan (2018-2022) published in 2018, which serves as the guideline to support the Rural Revitalization Strategy proposed in 2017.[3] One main challenge mentioned in these documents is the lagging rural waste treatment system. As the world's largest waste generator since 2004, China produced more than 175 million tons of rural solid waste in 2017 (World Bank, 2005 & 2019). Over 40% of the waste was treated by environmentally unfriendly methods, such as open dumping and illegal incineration (World Bank, 2019). Following the principles of the Rural Revitalization Strategy, the "Three-Year Action Plan for Improving Rural Living Environment" was implemented in 2018.[4] For the overall improvement of social sustainability, this three-year action plan highlights the key areas, including proper agricultural and domestic waste treatment, toilet upgrades, and residential sewage management.

More importantly, public engagement in policy action plays a vital role in sustainable development by accelerating social learning and improving the cost-effectiveness of policies (Bautista-Puig et al., 2024). Considering that rural waste management highly relies on citizens' performance in waste treatment, understanding waste disposal behavior and promoting public participation could help policymakers shape individuals' behavior in an environmentally-friendly direction. However, despite top-down action plans and strategies for sustainable waste

[3] More details can be found in the "No.1 Central Document" of the year 2018: https://www.gov.cn/zhengce/2018-02/04/content_5263807.htm (in Chinese).
[4] See the link http://english.www.gov.cn/policies/latest_releases/2018/02/06/content_281476037813748.htm for details.

treatment, little attention has been paid to assessing the factors that influence waste disposal behavior, especially in remote rural locations. As a result, there is limited knowledge and practice on involving individuals and communities in waste management and empowering them to improve the outcomes of policy actions. It further impedes establishing sustainable waste management systems and enhancing the rural living environment.

At last, this section turns the topic to sustainable development in a changing climate. Over the past few decades, it is increasingly recognized that climate change has posed serious challenges to environmental resilience, poverty reduction, food security, and many other aspects. These climate-induced issues closely affect the economic, social, and environmental dimensions of sustainability. Consequently, countries and international communities have actively engaged in climate change adaptation and mitigation under the agreements of the United Nations Framework Convention on Climate Change in 1992, the Kyoto Protocol in 1997, and the Paris Agreement in 2015 (FAO, 2022a). In China, climate change adaptation was formally introduced by the report on “China’s Agenda 21” in 1994.[5] In 2007, the first national global warming policy initiative, "National Climate Change Program of China", comprehensively outlined various adaptation goals. Subsequently, the "12th Five-Year Plan for National Economic and Social Development of the People's Republic of China" was issued in 2010, explicitly incorporating climate change considerations into sustainable development. After the 18th National Congress of the CPC in 2012, the Chinese central government has placed climate change actions in a prominent position and put forward new requirements for climate change adaptation.

Considering the emphasis of the Paris Agreement on limiting the increase in global mean temperature to 1.5 degrees Celsius, ongoing climate actions are primarily focused on the reduction of greenhouse gas (GHG) emissions (Rogelj et al., 2016; Tanaka & O’Neill, 2018). To be consistent with this international goal, most of the climate change actions in China seek to achieve carbon neutrality by curbing GHG emissions across all industries, enhancing the carbon sink capacity of the ecosystems, and promoting advanced carbon emission reduction technologies. Notably, as agriculture is the most vulnerable economic sector in a changing climate, it is crucial to promote more resilient agrifood systems and overcome global hunger (Balasubramanian, 2018; FAO, 2022b). Despite a series of climate mitigation measures, China still lacks overarching guidelines to support agricultural adaptation to climate change (Chen & Gong, 2021). Additionally, since the agricultural challenges posed by climate change are site-

[5] The specific content of “China's Agenda 21” can be viewed through the following link: https://english.mee.gov.cn/Events/Special_Topics/AGM_1/1994agm/meetingdoc94/201605/t20160524_345213.shtml.

based and context-specific, mitigation measures vary significantly among farmers, regions, and countries, leading to difficulties in evaluating actual practices (FAO, 2022c).

In summary, achieving sustainable development requires joint efforts and collaboration from all stakeholders and should be guided by effective strategies and policies tailored to different sustainability concerns. However, as shown in Table 1, some potential issues and challenges of the current policies have been identified, involving unclear division standards for zoning strategies (discussed in Study 1), inflexible compensation standard of the SLCP (discussed in Study 2), undervalued public participation in rural waste treatment (discussed in Study 3), and insufficient attention on climate adaptation measures for a resilient agricultural system (discussed in Study 4). In pursuit of more effective policy design and implementation, specific empirical studies in this thesis attempt to find solutions for these challenges. The experience and lessons learned from Chinese sustainable development practices can also provide a reference for other developing countries (Liu & Raven, 2010; Zhang & Wen, 2008).

Table 1 Policy challenges for sustainable development in China

Strategies and policies	**Development Priorities**	**Main policy challenges**
Ecological Conservation and High-Quality Development of the Yellow River Basin	Environmental and economic sustainability	Unclear division standard to categorize the Yellow River Basin into different function zones for high-quality development
Sloping Land Conversion Program	Environmental sustainability	Inflexible compensation standard within the Yellow River Basin and cost inefficiency
Three-Year Action Plan for Improving Rural Living Environment	Environmental and social sustainability	Limited consideration of the role of individuals and communities in improving waste treatment
Climate change actions to sustainable agriculture	Economic sustainability	Insufficient evidence to develop effective agricultural mitigation measures

1.3 Objectives and structure of this thesis

In previous sections, I have briefly summarized the threats to economic, environmental, and social sustainability and presented China’s key strategies and policies for sustainable development from the perspectives of implementation background, essential contents, and challenges. Focusing on different sustainability concerns, this thesis involves multiple domestic policies and strategies, including the national strategy of Ecological Conservation and High-Quality Development of the Yellow River Basin (Study 1), Sloping Land Conversion Program (Study 2), Three-Year Action Plan for Improving Rural Living Environment (Study 3), and detailed climate mitigation measures to sustainable agriculture (Study 4). In this Chinese policy context, four empirical studies covered in this thesis help to asses the development status of achieving SDGs (especially SDG 6 and SDG 12) (Study 3), identify the gaps between this status and ultimate development goals (Study 3), detect potential challenges and problems underlying the specific policy (Study 1 and Study 2), and provide empirical evidence for formulating efficient specific implementation strategies (Study 1, Study 2, Study 3, and Study 4). In terms of research objectives, these four empirical studies are conducted at different research scales, varying from households (Study 3) to counties (Study 1 and Study 2) and provinces (Study 4). The multiple-level research can support authorities in developing a holistic understanding of the role of different stakeholders in achieving the SDGs and further emphasize the importance of integrated planning and governance for sustainable development. To better serve policy development, the heterogeneous natural endowment and local socioeconomic characteristics are incorporated into the assessment of policy implementation.

Figure 1 graphically illustrates how different policies are positioned in the sustainable development framework, which development priorities these policies focus on, and which stakeholders are considered. It must be mentioned that sustainable development in this thesis is portrayed by the intersection part of three interlocking circles representing economic, environmental, and social systems, respectively. Another common way of depicting sustainable development is based on three nested circles in which economic and social domains are embedded in a wider environmental domain. This approach stresses the environmental constraints placed on economic growth and social development, which are further captured as “contextual conditions” in this thesis. Additionally, the dashed arrows in Figure 1 show the links among the three dimensions of sustainable development, which capture the minimization of negative trade-offs and maximization of synergies among these three sustainability goals (Elliott, 2012; Xue et al., 2018).

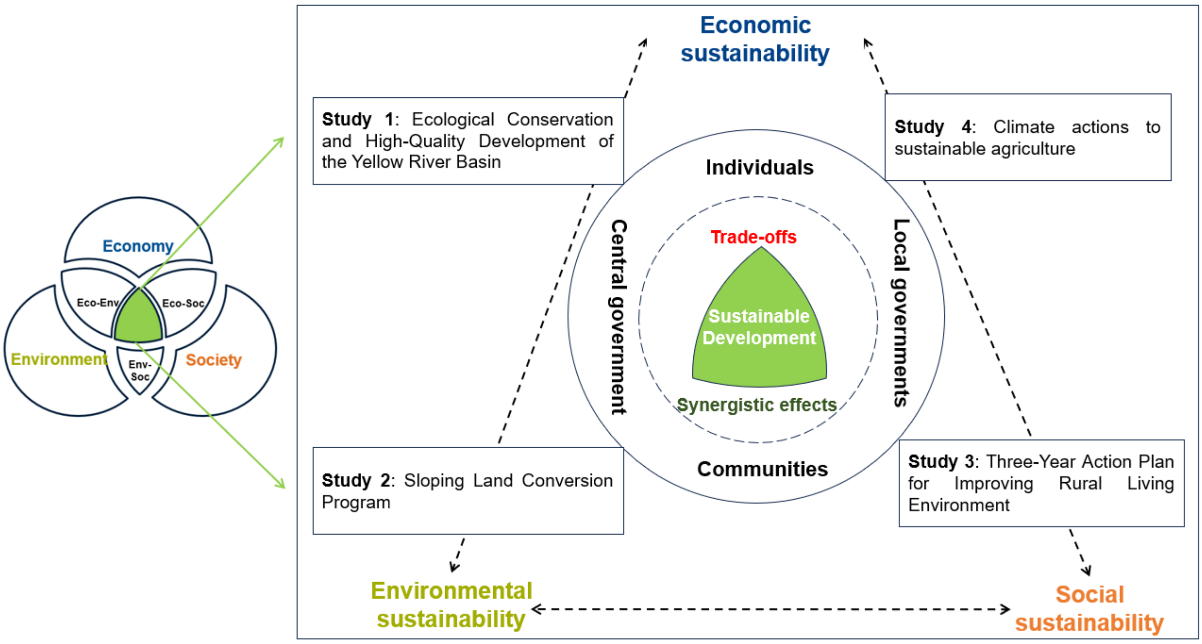

Figure 1 Overview of sustainable development in the Chinese policy context.

(Source: own depiction)

To better understand the research objectives of this thesis, Table 2 lists the main research questions that are formally answered in empirical studies. Specifically, Study 1 seeks to explore reliable zoning plans for high-quality development in the Yellow River Basin by investigating trade-offs between economic and environmental performance. Furthermore, it is believed that favorable natural conditions can act as catalysts to optimize governance performance on economic growth and environmental conservation. Conversely, unfavorable natural conditions are often seen as inhibitors that are harmful to governance performance. Consequently, governance performance may be overestimated when benefiting from favorable natural conditions and underestimated when adversely affected by unfavorable natural conditions (Zhao et al., 2017). In light of this, Study 1 undertakes a more in-depth examination of how natural conditions (e.g., precipitation and temperature) affect economic and environmental outcomes. This exploration aids in a more precise assessment of actual governance performance without the disturbance of natural conditions.

The SLCP has been at the center of academic debate for a long time due to the high economic cost, long duration, and broad implementation scale. Accordingly, Study 2 aims to answer whether the SLCP is the most cost-effective approach for soil erosion control compared to the other two solutions (i.e., adjusting agricultural production scale and non-agricultural production scale) from the perspective of marginal abatement costs. Based on this comparison, the decision of whether the SLCP should be continued can also be made. Moreover, the impacts of natural conditions (such as annual average temperature and precipitation) on abatement costs are examined to further explain how the environment influences policy decisions. Overall, this analysis contributes to identifying the most economical abatement solution for soil loss control and offers empirical evidence for the SLCP development.

Furthermore, Study 3 pays attention to public participation in rural sustainable waste treatment. One central assumption verified in this study is that waste disposal behavior can be learned and improved by observing others' pro-environmental waste disposal behavior. This learning process based on observing others' behavior is less studied compared with the peer effects of social relationships (i.e., psychological distances) on spreading behavior. Therefore, utilizing the geographic information of surveyed households, the geographic networks are defined by physical distances between households' dwellings and treated as the key prerequisites to achieving the spillover effects of others' waste disposal behavior. This behavior-learning process underscores the crucial role of positive examples of individual participation and community construction in improving policy implementation. To better serve policy development, this study comprehensively assesses the role of geographic networks on four types of waste disposal behavior- namely, domestic waste sorting, agricultural waste disposal, sewage collection, and toilet retrofitting.

Lastly, in the context of climate change and extreme weather events, reducing agricultural vulnerability and building a sustainable agricultural system has been of great interest to academia, governments, and international organizations. Achieving this goal necessitates a thorough examination of the intricate relationship between agricultural production, agricultural vulnerability, and mitigation measures. Even though the positive influence of mitigation measures on agriculture has been widely acknowledged, there is still a need for policymakers to tailor implementation measures to specific circumstances. Thus, Study 4 endeavors to assess the impacts of different mitigation measures on agricultural vulnerability and crop yields at different implementation scales and further provides a reference to optimize pathways for climate change actions efficiently.

The remainder of this thesis is organized as follows. Chapter 2 introduces the core concepts and theoretical supports for each case study. The methodological approaches applied in the empirical work are presented in Chapter 3. Chapter 4 summarizes four studies with the full texts only included in the appendix to avoid copyright infringement. Chapter 5 highlights the main conclusions, limitations, and future outlook.

Table 2 Overview of the objectives of four empirical studies in this dissertation.

Title	Policy context	Main research questions
Study 1: Evaluation of sustainable development considering natural conditions: A parametric slacks-based measure of efficiency approach	Ecological Conservation and High-Quality Development of the Yellow River Basin	1) How can the entire basin be divided into different function zones based on economic and environmental performance instead of geographical demarcation points? 2) How do natural conditions influence economic and environmental performance?
Study 2: Shadow prices and abatement cost of soil erosion in Shaanxi Province, China: Convex expectile regression approach	Sloping Land Conversion Program	1) From the perspective of shadow prices and abatement cost, was the SLCP investment excessive? 2) With the consideration of geographic heterogeneity, was the cost-efficient abatement solution for soil erosion control to increase the SLCP investment or to scale down the primary or non-primary industries?
Study 3: Geographic networks matter for pro-environmental waste disposal behavior in Rural China: Bayesian estimation of a spatial probit model	Three-Year Action Plan for Improving Rural Living Environment	1) What is the current status quo of rural waste treatment, and does it meet the requirements of this action plan? 2) Geographic networks are defined by physical distances and are differentiated from social networks. Do geographic networks influence rural households' waste disposal behavior? If so, how do geographic networks influence different types of waste disposal behavior?
Study 4: Assessing the regime-switching role of risk mitigation measures on agricultural vulnerability: A threshold analysis	Climate change actions to sustainable agriculture	1) How do different mitigation measures affect crop yields under the threat of agricultural vulnerability? 2) Do mitigation measures help to alleviate the negative impacts of agricultural vulnerability on crop yields? If so, how do the influence mechanisms work in this context?

2. Concepts and theoretical backgrounds

Policies mentioned in this thesis aim to the improvement of economic, environmental, and social sustainability. With this in mind, assessing and improving these policies requires a comprehensive examination of environmental, economic, and social outcomes and takes into account the role of diverse stakeholders (e.g., local governments and citizens) in this process (Wu et al., 2020). To better serve policy design and implementation in the context of Chinese sustainable development, Chapter 2 introduces core concepts and theories to support empirical analyses in identifying policy barriers, finding relevant solutions, and optimizing pathways to a sustainable future.

2.1 Production theory and efficiency measurement

In addition to research on the conceptualization and characterization of sustainability, a significant number of studies have focused on the evaluation of sustainable performance at both micro and macro levels through different methodologies in the last decades (Büyüközkan & Karabulut, 2018; Hristov et al., 2021; Kaymaz et al., 2022). One commonly used tool for assessing sustainability performance is productivity and efficiency analysis rooted in production theory (Caiado et al., 2017). The existing literature related to this topic is closely associated with the following sustainability concepts: eco-efficiency (Xue et al., 2021), environmental efficiency (Reinhard et al., 1999; Woo et al., 2015), green economic efficiency (Tao et al., 2016), green total factor productivity (Chen et al., 2021; Lee et al., 2022; Li & Chen, 2021), sustainability efficiency (Chen et al., 2022), etc. Considering that the production function framework is used to measure the economic and environmental sustainability performance of local governments in Study 1 and Study 2, basic concepts in this respect are laid out as follows.

2.1.1 Theoretic representation of a production technology

In order to better understand the application of production theory in measuring sustainable development, I start this subsection with a production process describing the transformation technology of multiple inputs (e.g., labor, land, capital) into multiple outputs (e.g., economic and environmental outcomes). This multi-input, multi-output production technology can be represented by the following technology set S:

$$S = \{(X, Y): can\ produce\ Y\}. \tag{2.1}$$

where the notation X denotes the $N \times I$ input matrix for all decision making units (DMUs) I, while Y represents the $M \times I$ output matrix (Chambers, 1988). It should be emphasized that outputs here not only refer to marketable goods but also include environmental outcomes, such as the improvement of vegetation coverage discussed in Study 1 and the reduction of soil loss mentioned in Study 2. In both studies, DMUs refer to county-level governments, which play a powerful role in policy design and implementation.

In production theory, a production possibility curve is used to visualize the production technology set S and illustrates the various combinations of all technologically feasible outputs and inputs. For convenience, the technological possibilities for an input vector x and an output vector y can be formulated by the following production function:

$$y = f(x). \tag{2.2}$$

The above function refers to the production frontier and describes the attainable maximum outputs given the fixed inputs (Coelli et al., 2005, p.12). Taking into account the potential inefficiency, the production function can be rewritten as

$$y = f(x) \cdot TE. \tag{2.3}$$

By function (2.3), TE represents the technical efficiency, ranging from 0 to 1. When a production unit operates on the production frontier, it is technically efficient ($TE = 1$). By contrast, a production unit beneath the production frontier is technically inefficient ($TE < 1$). To better understand these terms, Figure 2 shows a production frontier, the line 0F', which is specified by the maximum outputs obtainable at each input level. As illustrated in this figure, DMU B and DMU C operate on the frontier and are technically efficient, while DMU A is below the frontier and is not technically efficient. In this case, a production manager may consider either expanding the output of DMU A at the current input level, or reducing the input use without altering its output. Besides, the specific mathematical representation of $f(x)$ depends on the selected techniques for frontier analysis. The mainstream techniques to construct frontier include stochastic frontier analysis (SFA) and data envelopment analysis (DEA). In general, both methods measure the relative efficiency among DMUs. The fundamental difference, however, is that SFA is based on parametric estimation and captures the error term, whereas DEA does not involve any assumptions regarding parametric distributions and allows the observed data to speak for itself. Since Study 1 and Study 2 are conducted based on DEA, the stochastic approaches are not described further.

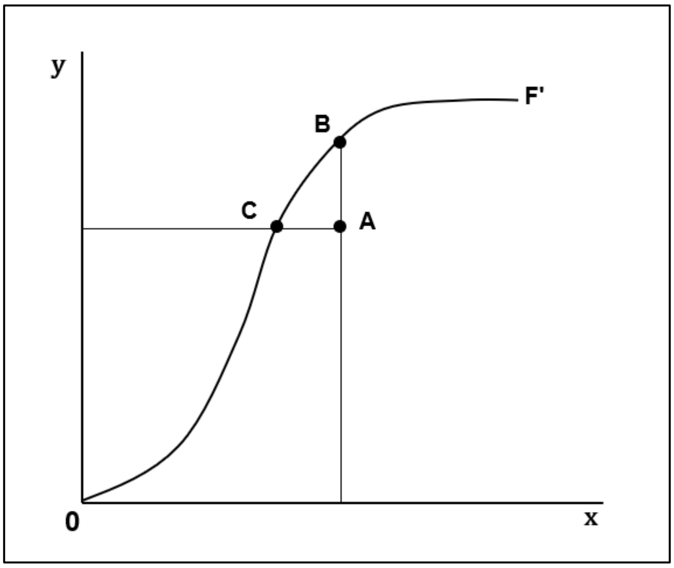

Figure 2 Illustration of a production frontier and technical efficiency.
(Souce: adapted from Coelli et al. (2005))

Theoretically, the following properties are required to capture a well-defined production function: a) non-negativity of x and $f(x)$; b) weak essentiality (i.e., $f(0) = 0$); c) monotonicity in x (i.e., non-decreasing in x); d) concavity in x (more explanations seen in Chambers (1988)). However, some assumptions may be violated in more realistic settings. For example, the heavy input usage (that is, the input congestion) can lead to a violation of the monotonicity assumption. In agricultural production, the overuse of fertilizer may damage the output (Coelli et al., 2005, p.13). Apart from these, the twice-continuous differentiability of $f(x)$ is essential to deduce the marginal products (MPs) shown in function (2.4) and the marginal rate of technical substitutions (MRTS) expressed in function (2.5):

$$MP_n = \frac{\partial f(x)}{\partial x_n} \tag{2.4}$$

and

$$MRTS_{nm} = \frac{\partial x_n(x_1, \dots, x_{n-1,}x_{n+1,\dots,}x_N)}{\partial x_m} = -\frac{MP_m}{MP_n}. \tag{2.5}$$

MP_n measures the change of output quantity to an infinitesimally small change in input n, while other inputs are held constant. Based on the definition of MP_n, the output elasticity regarding input n can be further computed by

$$E_n = \frac{\partial f(x)}{\partial x_n} \cdot \frac{x_n}{f(x)}. \tag{2.6}$$

The output elasticity E_n reflects the percentage change in output from a given percentage change in input n, while other inputs are held constant. Furthermore, when all inputs are varied simultaneously, the output changes can be calculated by summing up all individual output elasticities, as shown in the following equation:

$$\varepsilon = \sum_{n=1}^{N} E_n . \tag{2.7}$$

This overall output elasticity ε is known as the elasticity of scale. It can be categorized into three main types: decreasing returns to scale (DRS) ($\varepsilon < 1$), constant returns to scale (CRS) ($\varepsilon = 1$), and increasing returns to scale (IRS) ($\varepsilon > 1$).

2.1.2 Distance functions with undesirable outputs

Since sustainable development requires pollution reduction and environmental deterioration mitigation, accounting for undesirable outputs in production theory and model settings has become one of the main interests of production economics. The following output set is used to represent the joint production technology involving desirable outputs and undesirable outputs:[6]

$$P(x) = \{(y, b): x\ can\ produce\ (y, b)\}, \tag{2.8}$$

Function (2.8) indicates the input vector $x = (x_1, x_2, \dots, x_n)' \in R_+^n$, the desirable output vector $y = (y_1, y_2, \dots, y_m)' \in R_+^m$, and the undesirable output vector $\mathrm{b} = (b_1, b_2, \dots, b_s)' \in R_+^s$. The production possibility set includes all feasible input-output combinations whether or not the (x, y, b) is the actual technology (Färe et al., 2006).

The classic axioms of the output set $P(x)$ can be summarized below (Coelli et al., 2005; Färe & Primont, 2012).

A1. $P(x)$ is bounded and convex;

A2. Desirable outputs y satisfy the strong disposability: if $y \in P(x)$ and $y^* \leq y$, then $(y^*, b) \in$

[6] Since the joint production technology emphasizes bad environmental outputs, and the output set and input set are alternative descriptions of the same production technology, the input set is unnecessarily described again here.

$P(x)$;

A3. Inputs x satisfy the strong disposability: if $y \in P(x)$, then if $x^* \geq x$, y can be produced by any level of x^*;

A4. An alternative assumption for undesirable outputs b is weak disposability: if $(y, b) \in P(x)$ and $0 < \theta < 1$, we have $(\theta y, \theta b) \in P(x)$;

A5. $P(x)$ meets null-jointness: $(y, b) \in P(x)$ and if $b = 0$, then $y = 0$.

Specifically, A2 and A3 characterize monotonicity to state that desirable outputs y can increase as inputs x enlarge. Meanwhile, we assume that undesirable outputs b can increase by producing more y but cannot be reduced freely (Chung et al., 1997). Such that A4 implies that reducing undesirable outputs requires cutbacks in production. Inheriting the properties from the output set $P(x)$, the output distance function with bad outputs can be defined as follows (Shepard, 1970).

$$D_o(x, y, b) = inf\{\theta: ((y, b)/\theta) \in P(x)\} \tag{2.9}$$

Theoretically, distance functions consider the radial contraction and expansion concerning the benchmark set by the production frontier. The output distance function emphasizes the maximization of the expansion of the output vector, given an input vector. Function (2.9) indicates that the good and bad outputs (y, b) are scaled simultaneously at the same rate θ (also known as the inefficiency scaler). This function can be further modified to the directional distance function formulated in function (2.10), which allows for the reduction of bad outputs with the good outputs increase by defining the direction vector g.

$$\overrightarrow{D_o}(x, y, b; g) = sup\{\beta: (y, b) + \beta g \in P(x)\} \tag{2.10}$$

The direction vector g represents how the DMUs are projected to the production frontier. One of the most common settings for the direction vector is $g = (y, -b)$. Furthermore, the corresponding directional distance function (DDF) could be formulated as follows.

$$\overrightarrow{D_o}(x, y, b; g_y; g_b) = sup\{\beta: (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{2.11}$$

Based on the properties of the output set $P(x)$, Figure 3 helps interpret how technically inefficient DMUs can be projected to the frontier by Shephard's distance function (2.9) and directional output distance function (2.11), given the input vector (Chung et al., 1997; Färe et al., 2005). In Figure 3, the boundary of the output set $P(x)$ is defined as the production frontier. The DMUs falling on this production frontier are considered technically efficient DMUs (such as DMU A and DMU B), while the DMUs located inside the frontier are not technically efficient (like DMU C). Under the specification of Shephard's distance function (2.9), a DMU at Point C can be radially projected to Point A, thereby increasing both good and bad outputs by a factor of OA/OC. By contrast, the DMU at Point C can be projected to Point B with the increase of good output and the reduction of bad output because of the given direction vector $g = (y, -b)$. Moreover, if $\overrightarrow{D_o}(x, y, b; g_y; g_b) = \beta^*$ is assumed, the inefficient DMU at Point C can be projected to Point B with the coordinate of $(y + \beta^* g_y, b - \beta^* g_b)$.

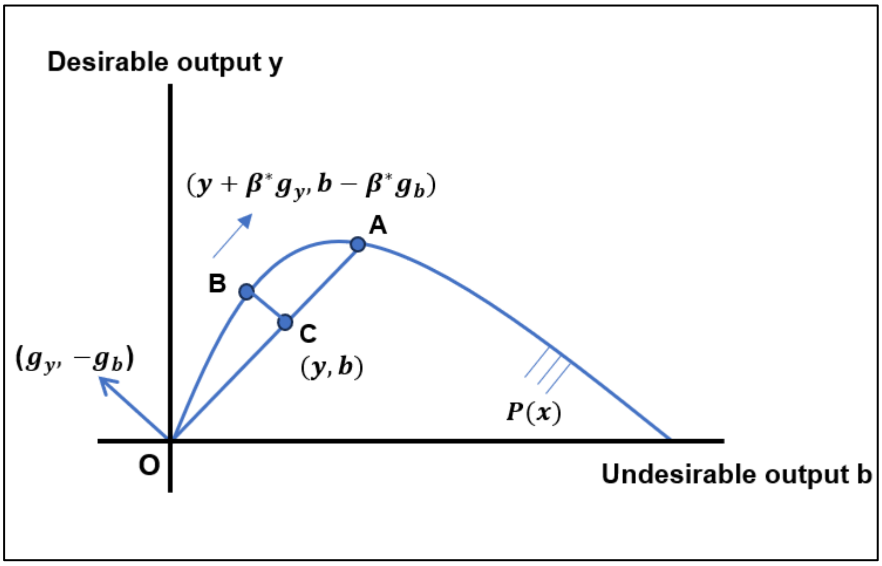

Figure 3 Output directional distance function.
(Source: adapted from Chung et al. (1997))

Due to a focus on pollution reduction for sustainable development, some incentive policies (such as the SLCP discussed in Study 2) are developed to motivate individuals and communities to participate in production and consumption in a more environmentally friendly manner. One of the main challenges facing these policies is to design appropriate compensation standards for an effective incentive system, which requires an accurate evaluation of the economic value of non-market goods. In this context, shadow price estimation is valuable for measuring the economic value of non-market desirable and undesirable outputs. By examining the economic value of non-market goods, policymakers can utilize evidence-based information to decide on reasonable compensation standards for pollution control measures (Färe & Grosskopf, 1998; Färe et al., 2005). Given the duality relationship between the directional distance function and revenue function, the shadow pricing formula for undesirable output via the function (2.11) can be derived as follows (Färe et al., 1993; Färe et al., 2006; Zhou et al., 2014):

$$q_b = -p_y \cdot \frac{\partial\, \overrightarrow{D_o}(x, y, b; g_y, g_b)/\partial b}{\partial\, \overrightarrow{D_o}(x, y, b; g_y, g_b)/\partial y}, \tag{2.12}$$

where p_y represents the prices of tradable outputs and q_b is the estimated shadow prices of non-market goods. Based on the output directional distance function illustrated in Figure 3, Figure 4 further shows that the slope of the tangent line on the frontier of $P(x)$ is equivalent to the shadow price ratio (Färe et al., 2006).

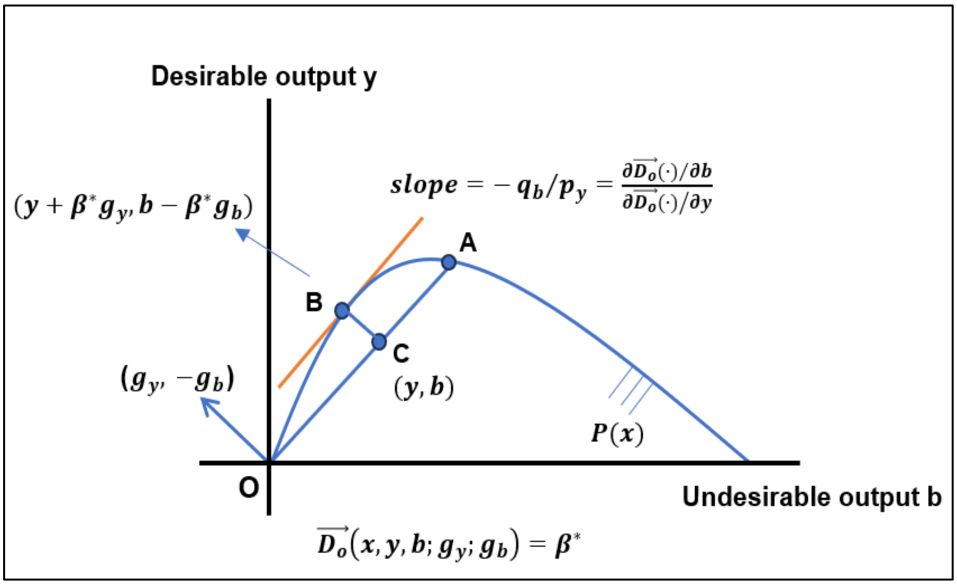

Figure 4 Shadow price ratio based on output directional distance function.

(Souce: adapted from Färe et al. (2006))

2.2 Behavioral contagion theory and geographic networks

Economics with behavioral sciences plays a crucial role in studying the shift of individual and group behavior towards more sustainable patterns (Polasky et al., 2019). In theory, behavioral economics emphasizes homo sapiens instead of homo oeconomicus (Thaler, 2000) and suggests that individuals are boundedly rational and influenced in a more complicated mode (Pasche, 2016). Nowadays, one of the main tasks for behavioral economists is to optimize the design of behavior-based environmental policies for desirable societal outcomes by stimulating human environmental behavior (Kotchen & Segerson, 2019; Pasche, 2016).

Since humans are a social species and always belong to certain social communities, numerous studies have demonstrated the profound impacts of group interaction on individual environmental behavior (Polasky et al., 2019; Shogren & Taylor, 2008). One of the most classic empirical findings is that there exists a tendency for people to mimic each other unconsciously (Zorell, 2020). This peer influence can be categorized under the behavioral contagion theory (Polansky et al., 1950). In Polansky et al. (1950), behavioral contagion is conceptualized as a social phenomenon wherein the behavior of one individual (the actor) can change the behavior of others (the recipients). It is believed that this behavior shaping can occur without the actor expressing an intention to evoke such a change (Wheeler, 1966). In the absence of such communicative intention, behavioral contagion usually happens when the recipients can observe the actor's behavior (Rosenbaum & Blake, 1955). In behavioral environmental economics, behavioral contagion theory lays the groundwork for emphasizing the intricate dynamics of behavioral interventions in environmental policy decision-making. For instance, Fu et al. (2023) find that decisions on environmental responsibility can spread among contractor managers by perceiving great organizational pride in others' practices. Additionally, Zorell (2020) indicates the impact of behavioral contagion on sustainable behavior by providing behavioral interventions.

In order to better serve the specific research topics, the behavioral contagion is often measured on a case-by-case basis. The tailored measurement approaches not only consider the intricacies of contagion dynamics but also allow researchers to more effectively reveal the complexities of behavioral contagion within distinct research contexts. Because a prerequisite for behavioral contagion is the opportunity to observe an actor's behavior (Polansky et al., 1950), geographic networks measured by physical distances can serve as competent proxies for the likelihood of observing others' behavior. In general, the closer the physical distance between the actor and the recipient, the more easily the actor's behavior can be observed. Therefore, effective geographic networks for behavioral contagion are more likely to exist in neighborhoods and do not necessarily require actual social exchanges or relationships among people. More importantly, closer geographic networks have the potential to expand individuals' exposure to a broader range of environmentally sustainable practices and generate a beneficial spillover effect on waste treatment practices (Wang et al., 2021; Zheng et al., 2019; Zhou et al., 2019). In view of this, Study 3 formally answers how behavioral contagion affects different types of waste disposal behavior by geographic networks and concludes the importance of setting good examples of sustainable waste disposal behavior within neighborhoods.

In addition, when it comes to the impacts of social interactions on pro-environmental behavior, another concept frequently mentioned in the existing literature is social relationships or networks between friends, relatives, colleagues, etc. (Geiger et al., 2019; Rajapaksa et al., 2018; Wan & Du, 2022). In contrast to geographic networks, social networks reflect psychological distances among people. The high closeness of social networks can affect the willingness to engage in pro-environmental behavior through environmental information communication. In Study 3, both geographic and social networks are identified as drivers that could enhance social learning processes and improve pro-environmental behavior.

2.3 Agricultural vulnerability and regime switching

Climate change has posed serious challenges to stable agricultural production and food security, further impeding sustainable development (Angeon & Bates, 2015). Thus, reducing the negative response of agriculture to climate change and enhancing the adaptive capacity of agricultural systems to such a changing environment has been a central topic in building sustainable agricultural systems. According to the literature, the concept of vulnerability is recognized as a powerful tool to capture the susceptibility of physical and social systems to unexpected environmental variations (Adger, 2006). Given the often-cited definition developed by the Intergovernmental Panel on Climate Change (IPCC), vulnerability is a negative term that defines the extent to which a system cannot recover from certain environmental shocks (McCarthy et al., 2001). To be more specific, this definition theorizes vulnerability in terms of three different dimensions: exposure, sensitivity, and adaptive capacity (Turner et al., 2003). However, as Berkes et al. (2000) point out, when characterizing the vulnerability, it is hard to reach an agreement without a universally accepted approach. Moreover, the focus of vulnerability assessments depends on specific research needs and objectives. Since agriculture is a fundamental component of economic production, alleviating the climatic vulnerability of agricultural production and adapting effective mitigation measures have attracted increasing attention. Given the nonlinear relationship between crop production and weather conditions (Burke et al., 2015; Olper et al., 2021), Study 4 aims to examine agricultural vulnerability and its response to multiple mitigation measures under a nonlinear regime-switching framework.

As for regime switching, it describes a phenomenon where the dynamics of a system change or shift abruptly over time (Granger & Terasvirta, 1993). In essence, switching regimes imply the existence of multiple regimes or states in one system. Importantly, these regimes are significantly different in structure and implications (Aslanidis & Xepapadeas, 2008; Hansen, 1999). From an econometric point of view, the shifting regimes of one system reflect the changing parameters among different regimes due to certain triggers. Because of the complexity of real-world scenarios, switching regimes play a key role in describing the non-constant dynamics in economic, social, and environmental systems or the interactions between any different systems. In the field of environmental economics, attempts have been made to develop the regime-switching framework through empirical analyses in terms of the nexus between environment, energy, economy, and globalization (Aslanidis & Xepapadeas, 2008; Bilgili et al., 2020; Charfeddine, 2017; Tetteh & Baidoo, 2022; Ullah et al., 2021).

Technically speaking, the idea behind regime switching is linked to the nonlinear relationships between elements in a system. The environmental Kuznets curve (EKC) is regarded as one commonly detected nonlinear relationship and captures the regime switching regarding the relationship between environmental degradation and income (Halkos & Tsionas, 2001; Koyuncu et al., 2021). Besides, some regime shifts are characterized by an inverted U-shaped relationship between different elements from environmental, economic, and social systems. Bilgili et al. (2020) confirm three different switching regimes of environmental sustainability in the context of globalization. Charfeddine (2017) and Ullah et al. (2021) investigate the structural breaks (i.e., nonlinear relationship) behind sustainable performance by connecting energy consumption, ecological footprint, and economic development. According to the literature, Study 4 takes into account the nonlinear dependencies between crop yields, climate mitigation measures, and agricultural vulnerability and reveals the significance of regime switching in mitigating agricultural vulnerability.

3 Methodology

Building upon the concepts and theories discussed in Section 2, this section offers a methodological overview of this thesis. The methodology presented in this section contributes to conducting solid empirical analyses and providing tailored solutions for specific issues and challenges of policy development mentioned in Section 1. Specifically, the zoning strategies for the high-quality development in the Yellow River Basin are investigated in Study 1 by a three-stage parametric slacks-based measure of efficiency approach (hereinafter referred to as parametric SBM). Moreover, each stage in this method serves different research purposes of this study. Drawing on the principles of the multi-output production and duality theory, Study 2 employs a novel directional distance function with convex expectile regression to assess the shadow prices and abatement costs of soil erosion precisely. It is worth noting that this approach offers a means to identify optimal abatement strategies within varying socioeconomic contexts. In Study 3, geographic networks are constructed using geoinformation (i.e., geographic coordinates) and reflect the channels for waste disposal behavioral contagion. To combine spatial information with econometrics, this study applies spatial probit models to examine how spillover effects of waste disposal behavior arise through shared geographic networks. At last, Study 4 assesses how climatic mitigation actions can reduce the detrimental effects of agricultural vulnerability on crop yields. These complex interactions between agricultural vulnerability, mitigation measures, and agricultural production are explored under the regime-switching framework and evaluated by a Markov switching model and panel threshold regression.

3.1 Three-stage parametric slacks-based measure of efficiency approach

Given the growing significance of sustainable development, many efforts have been made to improve resource use efficiency in China (Liu & Raven, 2010). Because of the flexible nonparametric production technology, the DEA allows data to speak for themselves, thus leading to wide application in efficiency measurement (Charnes et al., 1978; Charnes et al., 1991). To offer empirical evidence for improving sustainability performance, a large number of studies have focused on evaluating environmental efficiency, eco-efficiency, and eco-productivity through DEA (Caiado et al., 2017). In contrast to radial DEA methods, the DDF described in Section 2.1.2 could optimize inefficient DMUs to the efficiency frontier by non-radial projection (Chung et al., 1997). Accordingly, the DDF is regarded as a more practical and effective tool, especially when researchers pay additional attention to undesirable environmental outputs. Nevertheless, the proportion rates for efficiency improvement in the

DDF are uniform for all inputs or outputs, which fails to reflect more realistic and complex cases where non-proportional adjustments are needed. Given this drawback of the DDF, the flexibility of the SBM in non-proportional efficiency adjustments and decomposability of total factor efficiency makes it a popular choice for separating specific production factor efficiency (Tone, 2001). Since zoning strategies are designed based on the comparison of economic and environmental performance in Study 1, the SBM is chosen as the foundational methodological framework to decompose overall sustainable efficiency into environmental and economic efficiency and further compare them. Following Tone (2001 & 2002), the production possibility set T is defined as

$$\mathrm{T} = \left\{(x, y) \middle| x \geq X\lambda,\ y \leq Y\lambda,\ \lambda \geq 0,\ \textstyle\sum_{j=1}^{n} \lambda_j = 1 \right\}, \tag{3.1.1}$$

where the input matrix $\mathrm{X} = (x_{ij}) \in R^{m \times n}$ and the output matrix $\mathrm{Y} = (y_{rj}) \in R^{s \times n}$ for n DMUs. λ is a non-negative vector to capture the variable returns-to-scale case (VRS) here (Tone, 2002). The efficiency score ρ of DMU(x_0, y_0) can be measured by the conventional setting of SBM as follows:

$$\rho = \min \frac{1 - \left(\frac{1}{m}\right) \sum_{i=1}^{m} \frac{s_i^-}{x_{i0}}}{1 + \left(\frac{1}{s}\right) \sum_{r=1}^{s} \frac{s_r^+}{y_{r0}}}$$

subject to

$$\begin{aligned} x_0 &= \mathrm{X}\lambda + s^- \\ y_0 &= \mathrm{Y}\lambda - s^+ \\ \lambda &\geq 0, \textstyle\sum_{j=1}^{n} \lambda_j = 1 \\ s^- &\geq 0, s^+ \geq 0. \end{aligned} \tag{3.1.2}$$

Theoretically, $\rho \in (0,\ 1]$, and when $\rho = 1$, the DMU(x_0, y_0) is SBM-efficient, which is equivalent to $s^- = 0$ and $s^+ = 0$. The vector $s^- \in R^m$ and vector $s^+ \in R^s$ represent input excess (i.e., input slacks) and output shortfall (i.e., output slacks), respectively. Moreover, ρ for DMU(x_0, y_0) can be decomposed into the inefficiency of input i (i.e., $\rho_i = (x_{i0} - s_i^-)/x_{i0}$) and the inefficiency of output r (i.e., $\rho_o = (y_{r0} + s_r^+)/y_{r0}$). In order to further estimate and rank the efficient DMUs (i.e., DMUs with $\rho = 1$) on frontiers, super-efficiency SBM proposed by Tone (2002) can be utilized to discriminate efficient DMUs after the optimization programming (3.1.2).

According to Coelli et al. (2005), efficiency scores are influenced by contextual factors that do not belong to traditional production factors. In such a case, it is recommended to employ a two-stage approach where the second step aims to regress the impact of contextual variables on efficiency scores obtained in the first step. However, this two-stage approach is limited to evaluating how these contextual variables affect efficiency scores and is not sufficient for us to obtain pure efficiency independent of such influence. To overcome this issue, Fried et al. (2002) propose a three-stage DEA model incorporating SFA to provide real efficiency scores that are not disturbed by contextual variables. Based on this method, Zhao et al. (2017) develop a three-stage parametric SBM to evaluate actual production performance by correcting the efficiency bias arising from overestimated/underestimated inputs and outputs. This parametric SBM incorporating three stages can be formulated as follows:

$$\min \rho = (1-k)\frac{1-(1/m)\sum_{i=1}^{m} s_i^{-}/x_{i0}}{1+(1/s)\sum_{r=1}^{s} s_r^{+}/y_{r0}} + k\frac{1-(1/m)\sum_{i=1}^{m} s_i^{M-}/x_{i0}^{a}}{1+(1/s)\sum_{r=1}^{s} s_r^{M+}/y_{r0}^{a}}$$

subject to

$$\begin{gathered}
\sum_{j=1}^{n} \lambda_j\left[(1-k)x_{ij} + kx_{ij}^{a}\right] + \left[(1-k)s_i^{-} + ks_i^{M-}\right] = (1-k)x_{i0} + kx_{i0}^{a}, i = 1, \dots, m \\
\sum_{j=1}^{n} \lambda_j\left[(1-k)y_{rj} + ky_{rj}^{a}\right] - \left[(1-k)s_r^{+} + ks_r^{M+}\right] = (1-k)y_{r0} + ky_{r0}^{a}, r = 1, \dots, s \\
ks_i^{-} = k(z_j\hat{\beta}_i + \hat{u}_{ij} + \hat{v}_{ij}) \\
ks_r^{+} = k(z_j\hat{\beta}_r + \hat{u}_{rj} + \hat{v}_{rj}) \\
\lambda_j, s_i^{-}, s_r^{+}, s_i^{M-}, s_r^{M+} \geq 0, \mathrm{j} = 1, \dots, \mathrm{n}, k = \{0,1\},
\end{gathered} \qquad (3.1.3)$$

where x_{i0}^{a} and y_{r0}^{a} indicate adjusted inputs and adjusted outputs estimated in the second step, separately. In this step, Zhao et al. (2017) originally propose an impact factor and an error factor to eliminate the overestimated/underestimated bias generated by contextual variables and error terms on inputs and outputs via SFA (see Zhao et al. (2017) for more estimation details). Furthermore, when $k = 0$, the conventional SBM efficiency scores are obtained in the first stage. When $k = 1$, the third stage is possessed to compute adjusted SBM efficiency scores. $s_i^{M-}$and $s_r^{M+}$are slacks from the third stage. As shown in Figure 5, the measurements at each stage serve different research goals. In the first stage, the economic and environmental efficiency estimates affected by contextual variables support the design of zoning strategies. After isolating the impacts of contextual variables in the second step, the third step provides access to actual economic and environmental efficiency estimates, thereby informing local governments of their actual efforts on sustainable development and further guiding future governance.

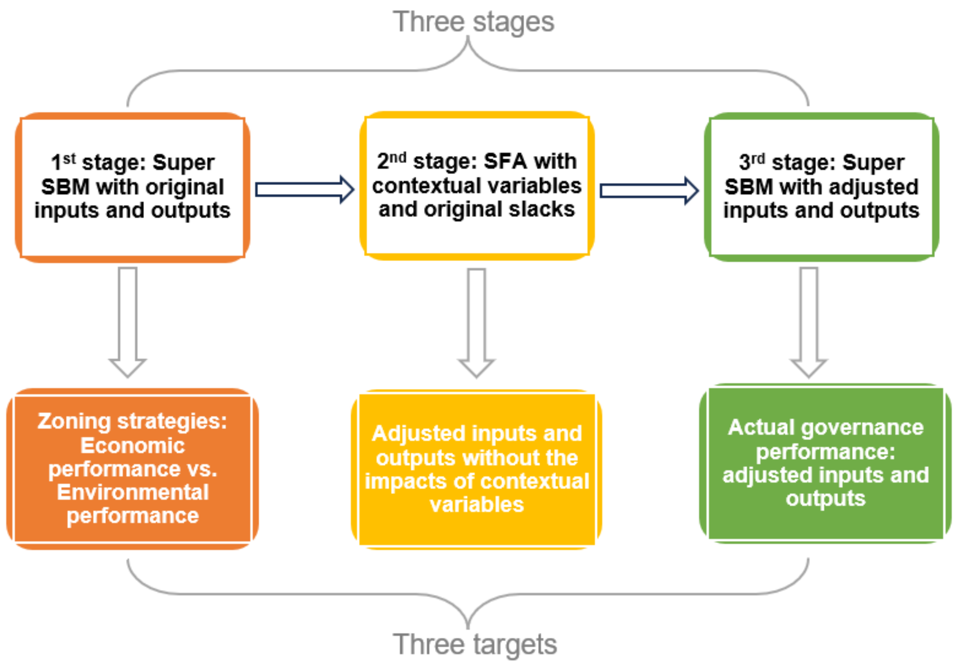

Figure 5 Methodological framework based on an enhanced parametric SBM.

(Source: own depiction)

3.2 Directional distance function with convex expectile regression

Shadow prices and abatement costs are among the key tools for estimating the economic value of environmental resources and the potential costs of reducing environmental pollution. A novel estimation methodology applied in Study 2 integrates DDF and SFA into a unified production frontier estimation for the full consideration of the inefficiency and noise term (Kuosmanen & Johnson, 2010). Accordingly, researchers define this type of method as a stochastic non-smooth envelopment of data (StoNED), which is generally expressed as follows (Kuosmanen & Kortelainen, 2012; Kuosmanen et al., 2015):

$$y = f(x) \cdot \exp(\varepsilon)\,. \tag{3.2.1}$$

In function (3.2.1), $f(x)$ refers to the frontier production function, consisting of the possible maximum outputs without the perturbation of the composite error term ε.

Combined with a given quantile τ, the corresponding conditional quantile function can be defined by the following:

$$F_y[\tau|(x,b)] = f(x,b) \cdot F^{-1}_{\exp(\varepsilon)}(\tau). \tag{3.2.2}$$

In the above function, $\tau \in (0, 1]$. When $\tau = 1$, the function is equivalent to the conventional DEA estimation. $F_{\exp(\varepsilon)}$ denotes the distribution function of ε. Outputs y in this function can be estimated locally given the quantile τ with the realization of ε. Figure 6 illustrates how DMUs can be projected locally under a convex quantile frontier. According to this figure, DMU A is projected by its single nearest quantile (i.e., 95% quantile frontier), while the efficiency score of DMU D is estimated based on a 5% quantile frontier. DMU C is projected by the weighted average of the nearest quantiles (i.e., 75% and 85% quantiles). Additionally, DMU B is fully efficient on 85% quantile frontier.

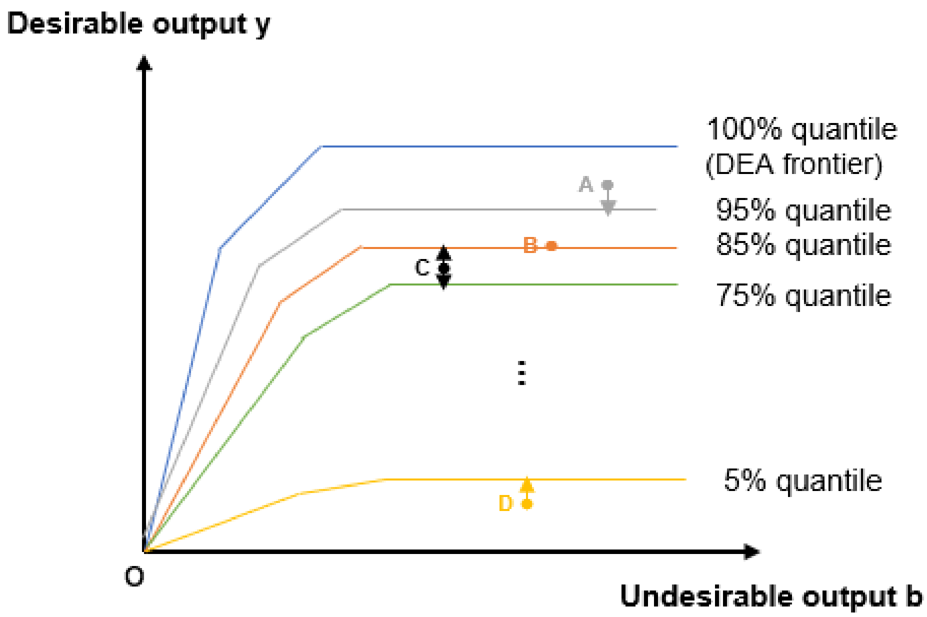

Figure 6 Graphic illustration of efficiency estimation with convex quantile regression.
(Source: adapted from Dai et al. (2020))

According to Kuosmanen et al. (2020) and Kuosmanen and Zhou (2021), a joint production technology of DDF with a given quantile τ can be written as function (3.2.3) and further estimated by a nonlinear programming problem with expectile $\tilde{\tau}$ (3.2.4).

$$\overrightarrow{D_\tau}(x_i, y_i, b_i, g^x, g^y, g^b) = sup\{\theta | \Pr.(x_i - \theta g^x, y_i + \theta g^y, b_i - \theta g^b) \geq 1 - \tau\} \tag{3.2.3}$$

$$\min_{\alpha,\beta,\gamma,\delta,\varepsilon^-,\varepsilon^+} (1-\tilde{\tau}) \sum_{i=1}^{n} (\varepsilon_i^-)^2 + \tilde{\tau} \sum_{i=1}^{n} (\varepsilon_i^+)^2$$

subject to

$$\gamma_i' y_i = \alpha_i + \beta_i' x_i + \delta_i' b_i - \varepsilon_i^- + \varepsilon_i^+, \forall i$$

$$\alpha_i + \beta_i' x_i + \delta_i' b_i - \gamma_i' y_i \leq \alpha_h + \beta_h' x_i + \delta_h' b_i - \gamma_h' y_i, \forall i, h \tag{3.2.4}$$

$$\beta_i' g^x + \delta_i' g^b + \gamma_i' g^y = 1, \forall i$$

$$\beta_i \geq 0, \gamma_i \geq 0, \delta_i \geq 0, \forall i$$

$$\varepsilon_i^- \geq 0, \varepsilon_i^+ \geq 0, \forall i.$$

The nonlinear programming (3.2.4) is the convex expectile regression with DDF, which differs from convex quantile regression with DDF only in the objective function (see Dai et al. (2020), Kuosmanen and Zhou (2021), and Wang et al. (2014) for more details). The main advantage of the convex expectile regression is that it guarantees a unique solution. Specifically, the notation of $\tilde{\tau}$ for expectiles is used to distinguish from the quantiles τ. The error term ε_i^- and the error term ε_i^+ refer to the negative deviation and positive deviation, respectively. As for the ith DMU on the expectile $\tilde{\tau}$, there must be $\varepsilon_i^- \cdot \varepsilon_i^+ = 0$. This method can project inefficient DMUs to the nearest expectile frontier instead of the conventional production frontier, which makes the estimation more robust to stochastic noise and heteroscedasticity. Given this, the estimates are less sensitive to the choice of the directional vector (Dai et al., 2021). Correspondingly, shadow prices and marginal abatement costs (MAC) can be further computed by the following function (3.2.5) based on the convex expectile approach (Kuosmanen et al., 2020).

$$\frac{\partial F_y[\tilde{\tau}|(x,b)]}{\partial b} = \frac{\partial f[\tilde{\tau}|(x,b)]}{\partial b} \cdot \exp(\varepsilon) \tag{3.2.5}$$

3.3 Spatial econometrics and a spatial binary probit model

To date, spatial econometrics has become a promising subject since it extends conventional econometric research into space-related scenarios. Generally, spatial econometrics can capture the spatial dependence behind geospatial networks. From an econometric perspective, the assumption of independence between observations required in traditional econometrics has been relaxed in spatial econometrics to consider spatial autocorrelation between observations (Cliff & Ord, 1970; Legendre, 1993). One fundamental theory underlying spatial econometrics is the first law of geography, suggesting that “everything is related to everything else, but near things are more related than distant things” (Tobler, 1970). Meanwhile, the closer the observations, the stronger their spatial association. Miller (2004) states that Tobler’s First

Law is at the center of spatial autocorrelation analysis and can be applied to study the correlations associated with distance or connectivity. To capture the distance and connectivity, spatial econometrics requires spatial data that contain geographic information (e.g., coordinates, distances between the units, boundaries, etc.) (Haining, 2003).

With the development of spatial modeling techniques, not only linear models but also discrete choices and limited dependent variables models can be employed in spatial structures, thus making spatial models widely used in various research fields (Billé & Arbia, 2019). For instance, Abdul Mumin et al. (2023) use a spatial autoregressive multinomial probit model to analyze how farmers' decisions to adopt new technologies are influenced by their neighbors' decisions. Wang et al. (2021) reveal a positive spillover effect of public attention on wastewater treatment performance by a spatial Durbin model. A Bayesian multinomial logit model has been proposed by Krisztin et al. (2022) to explore spatial patterns of urban expansion. In order to detect spatial patterns of pro-environmental waste disposal behavior in rural China, Study 3 adopts a spatial autoregressive probit model, which is described in detail below.

According to LeSage and Pace (2009), the model specification of the spatial binary probit model takes the following form:

$$y^* = \rho W y^* + X\beta + \epsilon, \qquad \epsilon \sim \mathrm{N}(0, \sigma_\epsilon^2 \mathrm{I_n}) \tag{3.3.1}$$

where y^* indicates a $n \times 1$ vector of the latent unobserved variable reflecting the binary outcomes y. Specifically, $y_i = 1,\ \mathrm{if}\, \mathrm{y}_i^* \geq 0$, while $y_i = 0, \mathrm{if}\, \mathrm{y}_i^* < 0$. The matrix X with parameters β is a $n \times k$ matrix of explanatory variables. More distribution information can be found in LeSage et al. (2011). W is the $n \times n$ spatial distance weight matrix, which is used to capture spatial relationships (i.e., geographic networks discussed in Study 3) between observations. ρ is a scaler notation to reflect the strength of spatial lag Wy^*, ranging from -1 to 1. Notably, a traditional probit model without spatial trends is described when $\rho = 0$. Figure 7 shows that weight distance determines the neighbors of one specific sample point. For this sample point, its neighbors are only those points that lie within a circle with a radius of the reference weight distance. Additionally, the weight distance can be adjusted based on specific research purposes.

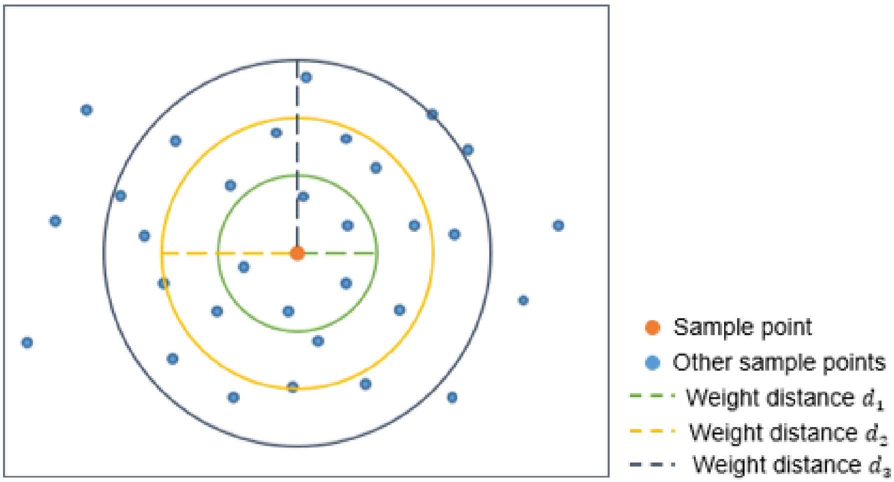

Figure 7 Identification of neighbors under the reference weight distance.
(Source: own depiction)

Equation (3.3.1) can be further organized as

$$y^* = (I_n - \rho W)^{-1} X\beta + (I_n - \rho W)^{-1}\epsilon = S(\rho)X\beta + S(\rho)\epsilon. \tag{3.3.2}$$

The relevant expectation form of equation (3.3.2) is as follows:

$$\mathrm{E}(y = 1|X, W) = \Pr(y = 1|X, W) = F\{S(\rho)\, X\beta\} = F(\phi). \tag{3.3.3}$$

In equations (3.3.2) and (3.3.3), I_n is an identity matrix of size n. $F(\cdot)$ is a nonlinear probability function. Like the traditional probit model, the estimated parameters $\hat{\beta}$ cannot be used to measure the marginal effects. Following LeSage and Pace (2009) and Lacombe and LeSage (2018), the marginal effect of explanatory variable x_r at mean $\bar{x}_r$ in the spatial probit model can be expressed by equation (3.3.4) based on equation (3.3.3).

$$\frac{\partial \mathrm{E}(y = 1|x_r)}{\partial x_r'} = \phi(\mathrm{S}(\rho) I_n \bar{x}_r \beta_r) \odot \mathrm{S}(\rho) I_n \beta_r \tag{3.3.4}$$

3.4 Regime switching models and threshold analysis

From a methodological perspective, researchers often use regime-switching models (like the Markov switching model (Goldfeld & Quandt, 1973)) and threshold models (such as the threshold autoregressive model (Tong, 2012; Tsay, 1989) and the panel threshold models (Hansen, 1999)) to detect the switching regimes for dynamic correlations. According to Chan et al. (2017), Markov switching models emphasize the identification of potential nonlinear dynamics over time in certain systems. In contrast, threshold models focus on examining how shifts between different regimes occur according to specified triggers and how these triggers affect regime-dependent variables in different regimes. These triggers mentioned here act as threshold variables in threshold analysis. In general, both approaches can identify significant changes in the parameters of the systematical structure across regimes (Chan et al., 2017). The main difference between these two approaches lies in the conditions under which these regimes are switched. In Markov switching models, regime switching is latent and can happen due to unknown time-varying conditions without specifying a specific threshold variable (Kim, 1994). However, in threshold models, regime switching describes fundamental changes in the parameters for the systematical structure only after a particular threshold variable crosses its corresponding threshold value. Therefore, Study 4 takes advantage of the different strengths of these two approaches to provide a more thorough examination of the regime-switching structure in an agricultural system.

First, Study 4 conducts an exploratory analysis using a Markov switching model to investigate whether there are different regimes in which agricultural vulnerability affects crop yields differently. Assuming that there are two different regimes (i.e., Regime 1 and Regime 2) regarding the influence of agricultural vulnerability VUL on crop yields $CROP$, the model can be expressed as follows:

$$CROP_{it} = \alpha_0 + \alpha_1 VUL_{it} + \alpha_2 AIS_{it} + u_{1i} \tag{3.4.1}$$

and

$$CROP_{it} = \beta_0 + \beta_1 VUL_{it} + \beta_2 AIS_{it} + u_{2i}, \tag{3.4.2}$$

where i denotes the ith observation and t represents different time periods. AIS_{it} is one important contextual variable representing the agricultural industrial structure of i th observation at time t. According to Goldfeld and Quandt (1973), there are two different regimes when the condition $(\alpha_1, \sigma_1^2) \neq (\beta_1, \sigma_2^2)$ holds. More details of the specifications can be found in Hamilton (1989 & 1996).

Once different regimes are identified, threshold analysis can further examine how these switching regimes occur based on threshold variables z_{it} and estimate specific threshold values δ above which the regime switches to another different regime (Chan et al., 2017). The general single-threshold model is specified as (Hansen, 1999; Wang, 2015):

$$y_{CROP_{it}} = \gamma_0 + \gamma_1 x_{VUL_{it}} I(z_{it} \leq \delta) + \gamma_2 x_{VUL_{it}} I(z_{it} > \delta) + \gamma_3 x_{AIS_{it}} + \mu_i + e_{it}, \quad (3.4.3)$$

where γ_0 is the intercept. The notations μ_i and e_{it} denote individual heterogeneity and disturbance terms, respectively. Importantly, additional control variables can be included in the study as needed. In this model, the corresponding null hypothesis and the alternative hypothesis are shown below.

$$H_0: \gamma_1 = \gamma_2$$

$$H_a: \gamma_1 \neq \gamma_2$$

To test the above hypotheses, F statistic is constructed to assess the statistical significance of the threshold effect (Hansen, 1996) as follows:

$$F = \frac{(S_0 - S_1)}{\hat{\sigma}^2}, \quad (3.4.4)$$

where S_0 is the residual sum of squares (RSS) obtained from the linear model and S_1 is the RSS generated by the threshold model. Besides, $\hat{\sigma}^2$ is the residual variance and is estimated by the least squares estimator of δ. In addition, the model (3.4.3) can be extended to a double or triple-threshold model, which is determined by the optimal number of thresholds based on the F statistic test (Hansen, 1999). Figure 8 graphically depicts two regimes underlying the relationship between elements A and B in one system. Based on the equation (3.4.3), these two regimes in the figure imply two different parameters to characterize the different states of the relationship between A and B.

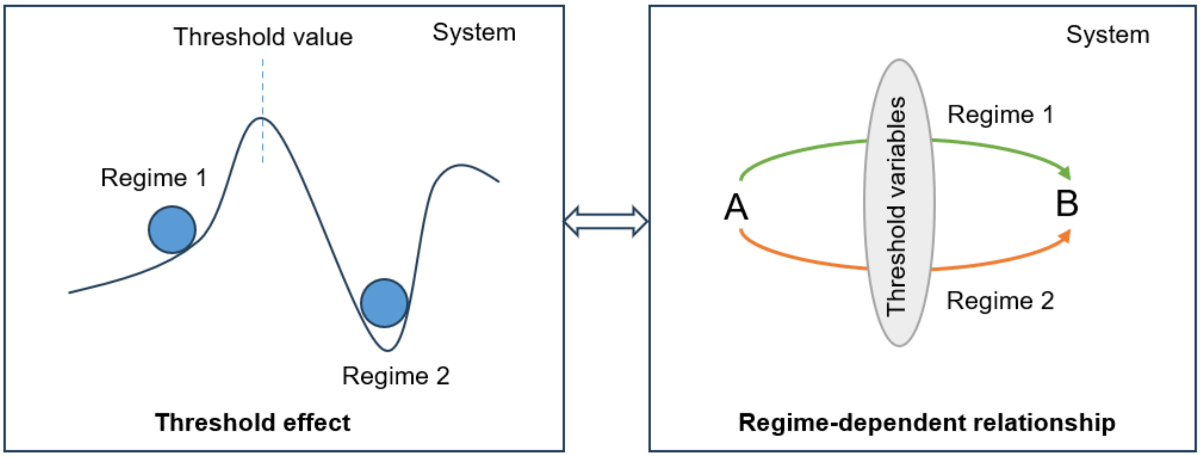

Figure 8 Graphic illustration of regime switching and threshold analysis.

(Source: own depiction)

Table 3 Summary of the conceptual framework and methodology of four empirical studies related to sustainability policy development.

Policy process	Conceptual framework	Methodology
Policy design in Study 1: formulating zoning strategies for sustainable development	Production theory and efficiency measurement	A three-stage parametric slacks-based measure of efficiency approach
Policy assessment in Study 2: optimizing pathways to effectively implement the SLCP	Production theory and shadow prices	Directional distance function with convex expectile regression
Policy implementation in Study 3: identifying key factors affecting the effectiveness of waste disposal-related policy	Behavioral contagion theory and geographic networks	Spatial probit models
Policy innovation in Study 4: improving more effective climate mitigation measures for sustainable agricultural production	Agricultural vulnerability and regime switching	A Markov switching model and panel threshold regression

4. Empirical studies

Based on the conceptual framework and methods introduced in previous sections, this section aims to present how the challenges of sustainable development policies mentioned in Table 1 are addressed in specific empirical studies. In addition to an extended abstract of each study, publication status and the authors' contributions are also provided in this section.

4.1 Evaluation of sustainable development considering natural conditions: A parametric slacks-based measure of efficiency approach[7]

Abstract

To attain sustainable development, a national strategy of "Ecological Conservation and High-quality Development of the Yellow River Basin" was proposed in China in 2019. Given the specific characteristics of a particular location or context, this strategy aims to reposition economic growth and environmental conservation to suit regional development priorities and needs for sustainable development. Using data for the years 2005, 2010, and 2015, this paper offers empirical evidence for classifying the 326 counties within the basin into different function zones through a three-stage parametric slacks-based measure of efficiency approach. By comparing the economic and environmental efficiency in the first step, trade-offs between economic growth and environmental improvement can be verified, which further confirms the necessity and feasibility of zoning strategies for the entire basin. Meanwhile, since local development patterns are closely associated with land use, assessing land use performance (including farmland, forest, and construction land) can help local governments allocate and utilize land resources efficiently, thus promoting the implementation of zoning strategies. Taking into account natural heterogeneity, the second stage examines how natural conditions (including temperature, precipitation, elevation, and slope) influence sustainability performance by improving/impairing the functioning of production factors (e.g., capital, land, etc.). Following this step, results suggest that natural conditions can be catalysts to help production factors play their best role for economic growth and environmental protection in some regions, whereas in other regions, unfavorable natural conditions may hinder production factors from functioning as intended. Due to the interference of natural conditions, the efficiency scores estimated in the first step may not serve as fair criteria for assessing

[7] The full publication is not embedded in this dissertation to avoid plagiarism or dual publication. However, the full version was sent to the examiners for grading.

government achievements in sustainable development. In order to evaluate actual governmental performance in sustainable development, the third stage excludes the impacts of natural conditions and objectively assesses actual sustainability performance without the help/disturbance from natural conditions. In summary, the three stages involved in this study target multiple research goals, which can not only contribute to develop zoning strategies in the Yellow River Basin but also provide a reference to efficiently promote governmental performance in sustainable development.

Publication:

Wen, X., Yao, S., & Sauer, J. (2022). Evaluation of sustainable development considering natural conditions: A parametric slacks-based measure of efficiency approach. *Journal of Cleaner Production*, *340*, 130788. https://doi.org/10.1016/j.jclepro.2022.130788

Authors' contribution:

Xiaojie Wen: Formulated the research questions, established the conceptual framework, designed the methodology, collected the data, conducted the formal analysis, and wrote the original manuscript.

Shunbo Yao: Assisted in the data collection process.

Johannes Sauer: Provided supervisory support.

4.2 Shadow prices and abatement cost of soil erosion in Shaanxi Province, China: Convex expectile regression approach[8]

Abstract

The Chinese central government pays increasing attention to soil conservation and has launched the Sloping Land Conversion Program (SLCP) since 1999 to alleviate soil loss by converting inefficient or ecologically vulnerable farmland to forest and grassland. However, the vast amount of converted farmland coupled with a fixed compensation rate per unit of converted farmland has made the cost-effectiveness of the SLCP controversial, as it fails to adequately consider heterogeneous natural conditions and opportunity costs of land conversion. In response to this debate, this study seeks to examine whether the SLCP was always the most cost-efficient solution for soil loss control compared to the other two abatement alternatives (i.e., downscaling the primary industry and downscaling the non-primary industries) in terms of shadow prices. Since Shaanxi Province is the first demonstration area to implement the SLCP, this study chooses 83 counties in this province as case study areas and accurately estimates the shadow prices of soil erosion for the years 2000, 2005, 2010, and 2015 by a directional distance function with convex expectile regression. By comparing the shadow prices of three abatement solutions, it is demonstrated that the SLCP was not the least-cost abatement option for all counties during the study period. Meanwhile, controlling the scale of agricultural production has gradually become the least-cost alternative to soil conservation. Moreover, significant geographic heterogeneity requires further investigation of its impacts on abatement costs. Results show that wind speed and vegetation quality can influence abatement costs significantly. In terms of shadow prices and abatement cost of soil erosion, this study brings more evidence for the debate on the cost-effectiveness of the SLCP and recommends a more nuanced implementation scheme of the SLCP in the future.

Publication:

Wen, X., Yao, S., & Sauer, J. (2022). Shadow prices and abatement cost of soil erosion in Shaanxi Province, China: Convex expectile regression approach. *Ecological Economics*, *201*, 107569. https://doi.org/10.1016/j.ecolecon.2022.107569

Authors' contribution:

[8] The full publication is not embedded in this dissertation to avoid plagiarism or dual publication. However, the full version was sent to the examiners for grading.

Xiaojie Wen: Formulated the research questions, established the conceptual framework, designed the methodology, collected the data, conducted the formal analysis, and wrote the original manuscript.
Shunbo Yao: Assisted in the data collection process.
Johannes Sauer: Provided supervisory support.

4.3 Geographic networks matter for pro-environmental waste disposal behavior in Rural China: Bayesian estimation of a spatial probit model[9]

Abstract

Promoting pro-environmental waste treatment plays a critical role in achieving broader economic, environmental, and social sustainability goals. As China has become the world's largest waste producer, the central and local governments, industries, and academia have placed great emphasis on addressing waste treatment issues, especially in more ecologically fragile rural areas. The "Three-year Action Plan for Rural Living Environment" implemented in 2018 aims at an overall improvement of domestic waste disposal, domestic sewage treatment, agricultural waste disposal, as well as toilet retrofitting. Against this policy background, a household survey entitled "Ecological Conservation and High-Quality Rural Development in the Yellow River Basin" was carried out in 2020 to better understand the status quo of waste management in rural China. In order to assess the achievement of this action plan, this study investigates the current status of four types of waste treatment behavior (including domestic waste disposal, domestic sewage collection, agricultural waste disposal, and toilet retrofitting) and further examines the influencing mechanisms behind different waste disposal behavior. A novelty of this study is the application of the behavioral contagion theory in waste treatment behavior analysis by measuring the role of geographic networks (i.e., physical distances) on spreading waste disposal behavior. Under shared geographic networks, waste treatment behavior can be mimicked by observing others' behavior directly, even in the absence of social networks (i.e., psychological distances). This finding highlights the significance of geographic networks in enhancing citizen participation in proper waste disposal practices, thereby motivating local governments to establish exemplary communities and populations as good examples for sustainable waste management. Additionally, socio-economic conditions (e.g., accessibility of public services, settlement density, etc.) and household characteristics (e.g., family size, education experience, annual income, etc.) can impact waste treatment behavior in various ways, which requires policymakers to develop context-specific waste management programs.

Authors' contribution:

Xiaojie Wen: Formulated the research question, established the conceptual framework,

[9] This section is based on a working paper that is currently under review for publication. In order to avoid plagiarism or dual publication, the full version of this paper is only included in the examiners' copies of this dissertation for grading. The working paper was accepted for presentation at the 97th Annual Conference of the Agricultural Economics Society (AES) in 2023.

designed the methodology, collected the data, conducted the formal analysis, and wrote the original manuscript.

Philipp Mennig: Assisted in developing the conceptual framework and reviewing/editing the manuscript.

Hua Li: Assisted in the data collection process.

Johannes Sauer: Provided supervisory support.

4.4 Assessing the regime-switching role of risk mitigation measures on agricultural vulnerability: A threshold analysis[10]

Abstract

In order to mitigate agricultural vulnerability and achieve sustainable agricultural production under climate change, Chinese authorities have implemented a series of risk mitigation measures throughout the country, such as soil loss control and reservoir construction. However, a systematic understanding of how mitigation practices contribute to reducing agricultural vulnerability and sustaining crop yields is still lacking. Based on Chinese provincial-level data on farmland areas affected by agrometeorological disasters (including drought, flood, hail, low temperatures, and frost) from 2000 to 2021, the agricultural vulnerability is constructed in this study. This indicator not only reflects the intensity of the aforementioned disasters but also captures the ability of the farming system to recover from these disasters. After analyzing the spatial-temporal characteristics of agricultural vulnerability, it is found that there is an urgent need to reduce agricultural vulnerability in underdeveloped areas, especially those dependent on agricultural production. Taking into account sectoral structures, a Markov switching model is applied to detect different regimes of the relationship between crop yields and agricultural vulnerability. Results indicate that there are two different regimes in this regard. In one regime, agricultural vulnerability would not significantly impair crop yields for economically developed areas. In the other regime, it could negatively affect crop yields for less-developed regions where agricultural production is predominant. To further explore the nexus between agricultural vulnerability, risk mitigation measures, and crop yields, four risk mitigation measures (involving irrigation systems, reservoir capacity, soil loss control, and drainage systems) act as threshold variables to examine whether and how these mitigation measures affect the negative influence of agricultural vulnerability on crop yields. By quantifying the threshold levels of mitigation measures beyond which agricultural vulnerability cannot significantly reduce crop yields, this study contributes to formulating and developing policies and strategies for effective risk mitigation management and sustainable agricultural production.

Authors' contribution:

Xiaojie Wen: Formulated the research question, established the conceptual framework, designed the methodology, collected the data, conducted the formal analysis, and wrote the

[10] This section is based on a working paper that is currently under review for publication. In order to avoid plagiarism or dual publication, the full version of this paper is only included in the examiners' copies of this dissertation for grading.

original manuscript.

Philipp Mennig: Assisted in developing the conceptual framework and reviewing/editing the manuscript.

Johannes Sauer: Provided mentoring support.

5 Discussion and conclusions

In response to global sustainable development goals, a series of national strategies, policies, and action plans taken in China have been introduced in this thesis, including “Ecological Conservation and High-quality Development of the Yellow River Basin” (Study 1), “Sloping Land Conversion Program” (Study 2), “Rural Vitalization Strategic Plan (2018-2022)”, “Three-Year Action Plan for Improving Rural Living Environment” (Study 3), “National Climate Change Program of China”, and “National Climate Change Adaptation Strategy” (Study 4). These action plans and policies consider multiple sustainable development stakeholders (e.g., rural households, county governments, and provincial governments) and aim to address diverse sustainability challenges, such as trade-offs between economic growth and environmental conservation (Study 1), soil erosion control (Study 2), waste treatment management (Study 3), and climate adaptation for sustainable agriculture (Study 4). In order to provide empirical evidence on sustainable development in China, this thesis is dedicated to detecting potential issues behind policy design and implementation (such as Study 1 and Study 2), assessing the impact mechanisms of sustainability concerns (like Study 3), and investigating the driving factors of economic, environmental, and social sustainability (such as Study 3 and Study 4). To conclude this thesis, the following sections provide more detailed key findings and related discussions in Section 5.1, as well as limitations and future research avenues in Section 5.2.

5.1 Main findings and discussion of the studies

Given the heterogenous local context, development priority zoning provides a macro perspective for optimizing regional planning and is widely accepted as a fundamental strategy for sustainable development (Wang et al., 2017). Due to complex sustainability challenges in the Yellow River Basin (such as poverty and ecological vulnerability), a greater emphasis has been placed on sustainable development in this basin after the “Ecological Conservation and High-quality Development of the Yellow River Basin” was launched in 2019. Although “The National Plan for Functional Areas (2010)” has proposed a major function zoning scheme (see Wang et al. (2020) for details), this high-quality development strategy for the Yellow River Basin elevates zoning plans to a significant level in this region.

In order to achieve high-quality development and improve resource use efficiency in the Yellow River Basin, Study 1 provides a reference for county-level zoning planning by revealing trade-offs between economic and environmental performance. The logic behind this development priority zoning is to assess comparative advantage. Similarly, based on the regional comparative advantage, Xu et al. (2006) carry out the zoning of sustainable agricultural development, and Sun et al. (2021) have identified key ecological function zones. For Study 1, after assessing the comparative advantages in terms of economic and environmental efficiency, counties located in upper reaches are more suitable to be designated as ecological function zones because of their better environmental performance. This finding is consistent with ecological security strategic patterns mentioned in “The National Plan for Functional Areas (2010)” (Wang et al., 2020). In contrast, relatively higher economic performance in lower reaches implies that it makes more sense to zone counties in this region as core economic areas. This outcome is in agreement with the identification of economic function zones in China by Fan et al. (2019). As for the counties in the middle reaches, there is no uniform conclusion for their zoning strategies due to the complex situations, which further calls for a more specific and flexible zoning plan. Similar results can also be found in Fan et al. (2019). Apart from these, considering that local development patterns are closely related to land space utilization efficiency (Liu et al., 2019), Study 1 evaluates different land use efficiency (including construction land, farmland, and forest) as a complementary analysis and further provides valuable insights into specific zoning strategies. Additionally, it is found that the zoning classification has subtle differences among the zoning-related studies according to different research purposes. Some examples are given in Table 4.

Table 4 Different zoning criteria among the zoning-related studies in China.

Study	Study area	Zoning criteria
Fan et al. (2019)	China	Urbanization zones; Food security zones; Ecological security zones; Heritage protection zones
Liu et al. (2022)	Sichuan Province	Dual pressure zones; Economic backward zones; Ecological crisis zones; Coordinated development zones
Liu et al. (2019)	Eastern China	Socio-economic development system; Agricultural production guarantee system; Ecological safety maintenance system
Sun et al. (2021)	Southwest China	Key ecological function zones; Non-key ecological function zones
Wang et al. (2017)	Zhejiang Province	Development-type areas; Protection-type areas
Wen et al. (2022) (**Study 1**)	Yellow River Basin	Ecological function zones; Core economic zones; Agricultural function zones

From a methodological perspective, one novel aspect of Study 1 is to consider the impacts of natural conditions (including temperature, precipitation, elevation, and slope) on actual efficiency estimates. On the one hand, favorable natural conditions positively affect production factors and outcomes, which further improves sustainability performance. However, it may induce the authorities to overestimate their achievements in sustainable development and neglect some potential issues (e.g., mismanagement and inefficient investment). On the other hand, unfavorable natural conditions can impair the functioning of production inputs (e.g., farmland) and damage economic and environmental outcomes. As a result, the authorities may be misled into underestimating their efforts, neglecting resource-based constraints on regional development, and further pursuing overly ambitious targets for efficiency improvement. Consequently, to gain a clearer understanding of the actual contribution to sustainable development, one of the objectives of this study is to assess actual economic and environmental performance independent of natural conditions. This can provide empirical evidence for policymakers to set well-founded and reasonable goals for enhancing efficiency.

Recall that Study 2 applies the DDF with convex expectile regression to estimate the shadow prices and abatement costs of soil erosion. The technically inefficient DMUs under this approach are projected to their nearest quantile frontiers instead of the full production frontier. Therefore, the estimates obtained by this method are robust to inefficiency and noise terms and are insensitive to the choice of the direction vector. To better identify the least-cost abatement solution and evaluate the optimal abatement cost of soil erosion, this study compares the shadow prices of soil erosion from input-side abatement option (i.e., the SLCP investment) and the output-side abatement alternatives (i.e., downsizing the primary sector and downsizing the non-primary sectors). By measuring the economic cost of soil loss control at the county level in Shaanxi Province, this study formally answers whether it is practical to continue the SCLP and how to reduce soil loss in a cost-effective manner. According to the results, the abatement potential of the SLCP was diminishing for most studied counties after 2005. It is advisable to halt the SLCP investments in counties where the economic costs of the SLCP are no longer the lowest among abatement options. This finding corroborates the ideas of Wang and Maclaren (2012), who argue that the SLCP is inefficient in terms of productivity and environmental heterogeneity in northeastern China. By 2015, controlling the scale of agricultural production was the most economical abatement option for over half of the counties in Shaanxi Province. Moreover, Wang et al. (2007) and Wang and Maclaren (2012) emphasize the importance of wisely choosing retirement plots for the SLCP, which has also been mentioned in Study 2. In addition, some counties were invested excessively, which matches that observed by Ding and Yao (2021). It is therefore important to identify the optimal abatement solution with the lowest shadow price, avoid over-paid incentives, and encourage authorities to put more efforts into soil loss control.

Nevertheless, some studies conclude that it is essential to continue the implementation of the SLCP for other economic and social benefits. For example, Komarek et al. (2014) recommend increasing the SLCP investments to prevent households from reconverting their land to farmland. Besides, considering that ecosystems take a long time to recover, Bennett (2008) suggests extending the subsidy lengths. Meanwhile, the positive impact of the SLCP subsidy on rural households' livelihoods was considered as one reason to extend the SLCP implementation (Liao & Zhang, 2008). But so far, this argument has been much criticized because continued subsidy assistance could undermine the sustainability of this program (Bullock & King, 2011), and improvements in rural livelihoods are fundamentally dependent on local economic development. Moreover, it has been argued that the positive impact of the SLCP on household income results from labor transfer and off-farm employment instead of subsidies (Lin & Yao, 2014). In general, one of the main reasons for the debate on the SLCP is that different studies focus on different environmental, economic, and social purposes. At last, given the significance of environmental heterogeneity (Song et al., 2014; Zhang & Paudel, 2019), this study calls for more flexibility in the SLCP implementation in terms of targeted areas and compensation standards.

Based on a household survey of "Ecological Conservation and High-Quality Rural Development in the Yellow River Basin", Study 3 comprehensively evaluates four key waste management practices (including domestic waste sorting, domestic sewage process, agricultural waste disposal, and toilet retrofitting). Since the number of valid questionnaires varies depending on specific waste disposal behavior, the sample size used in the empirical analysis ranges from 800 to 1400 households. According to statistical results, although there is a strong willingness to engage in domestic waste sorting, more than 30% of the surveyed households do not do any form of domestic waste sorting. The gaps between willingness and actual practices are also founded in agricultural waste disposal. The discrepancy between intention and behavior in terms of waste separation and recycling has also been observed in Ran and Zhang (2022), Wang et al. (2020), and Zhang et al. (2023). Furthermore, one-third of the surveyed households dump their domestic sewage improperly, and more than half of households still use pit toilets. This poses a severe threat to the living environment and human health in rural areas. Therefore, this study highlights the importance of enhancing citizen engagement and self-regulation for sustainable waste treatment management.

More importantly, considering the different roles of social networks (i.e., psychological distances) and geographic networks (i.e., physical distances among households) in shaping behavior, Study 3 differentiates the impacts of social and geographic networks on pro-environmental waste disposal behavior. By revealing the significantly positive spillover effects of geographic networks on pro-environmental waste disposal behavior, the study demonstrates the waste disposal behavior contagion. This finding encourages policymakers to establish exemplary waste disposal practices and leverage the role of communities in spreading sustainable waste treatment behavior. In turn, individuals and local community groups can become more powerful and influential in their involvement in environmental protection. Moreover, due to the uneven waste treatment development across regions in China (Zhang et al., 2022), people may need to adapt different waste disposal standards as population mobility increases. In this context, acquiring waste disposal knowledge from others living nearby can efficiently accelerate the learning process. Apart from these, because of the unique properties inherent in waste disposal practices, different waste disposal practices respond to household characteristics and socio-economic conditions differently. It is also observed that the capital-intensive waste disposal practices, such as sewage collection and toilet retrofitting discussed in this study, exhibit similarities in their impact mechanisms. This finding reflects the potential synergy between different waste treatment behaviors, which further inspires policymakers to develop corresponding synergistic sustainable solutions for more efficient waste management.

In a changing climate, exploring a pathway to sustainable agricultural production has received increased attention from academia, businesses, and governments. To better understand the threat of climate change on crop production in China over the past decades, a number of recent studies have investigated the spatial-temporal impacts of agrometeorological disasters on crop production (e.g., maize, wheat, rice, etc.) (Shi et al., 2021; Zhang et al., 2014). These studies are mainly based on provincial-level data regarding the cropland damaged by agrometeorological disasters (including drought, flood, hail, low temperatures, and frost) (Zhou et al., 2015). This dataset is annually updated by the National Bureau of Statistics in China in accordance with the “Statistical Survey System of Large-Scale Natural Disasters”. In this dataset, the indicator “covered area” measures the sown area with at least 10% yield losses caused by the abovementioned hazards. Meanwhile, the other relevant indicator “affected area” represents the sown area with more than 30% (including 30%) yield losses. Previous studies usually assess these two indicators separately and mostly connect them with farmland area to reflect the climate risk of agriculture (Wang et al., 2017; Xu & Tang, 2021). However, very little was found in the literature on the link between these two indicators. To fill this gap, Study 4 measures the ratio of the affected area to the covered area and defines it as agricultural vulnerability. By analyzing the agricultural vulnerability from 2000 to 2021, the results not only reflect the intensity of the disasters but also indicate the ability to absorb the shocks from extreme weather events. More importantly, the regional discrepancy in agricultural vulnerability provokes reflections on the different economic structures. By examining the relationships between crop yields and agricultural vulnerability, it has been proved that agricultural vulnerability has a significantly negative effect on crop yields, especially in underdeveloped areas that are highly dependent on agriculture. In contrast, agricultural vulnerability brings less economic losses in developed regions. These findings help the authorities to identify priority areas for reducing agricultural vulnerability.

At the same time, particular attention in Study 4 has been placed on the regime-switching role of risk mitigation measures (including irrigation systems, reservoir capacity, soil loss control, and drainage systems) on the relationship between agricultural vulnerability and crop yields. The most important finding is that agricultural vulnerability exerts varying effects on crop yields under different scales of mitigation measures. By enhancing irrigation scales, reservoir capacity, and soil loss control to certain levels, the negative consequences of agricultural vulnerability on crop yields become insignificant. The specific scales for these mitigation measures to achieve this regime switching have been explicitly estimated in Study 4, which provides practical guidance for mitigating agricultural vulnerability and its harmful effects on crop yields. A similar finding is also reported by Troy et al. (2015), who confirm that irrigation plays an important role in decoupling crop yields from climate. In addition, this study also demonstrates the nonlinear relationships between mitigation measures and crop yields. Accordingly, it is important to bear in mind that decision makers cannot blindly scale up mitigation measures.

Drawing upon the findings from empirical studies covered in this thesis, some conclusions regarding the domestic policy process toward sustainable development can be summarized as follows:

In terms of policy making process, it is necessary to fully understand the development status of target regions in the early stage of policy design (Xue et al., 2018). China is the largest developing country with a vast territory and intricate natural, social, and economic dynamics (Zhang & Wen, 2008). In this context, the path towards sustainable development shows obvious regional discrepancies. Therefore, this step would ensure policy goals to be implementable and adaptable to varying conditions. Meanwhile, understanding the development status helps to uncover obstacles to the achievement of the SDGs and to identify policy needs (Guo et al., 2018). Importantly, as the current status in achieving SDGs changes dynamically, it is required to monitor the development status on a regular basis for planners, which contributes to improving future policy design and optimizing a new round of policy implementation.

Apart from these, the trade-offs between sustainability targets encourage policymakers to make good use of zoning strategy in policy design. Taking into account the resource constraints, regional comparative advantages, and development demands, it is unrealistic and inefficient to achieve the long-term complex SDGs simultaneously. As a result, it is essential to identify priorities across different regions and suggest local governments tailor their own context-based policies instead of a 'one-size-fits-all' regional policy (Zhang & Wen, 2008). Nevertheless, in order to provide overarching guidelines for policy-making process, some related frameworks have been proposed and widely discussed in the existing literature (Meyar-Naimi & Vaez-Zadeh, 2012), such as the "Pressure-State-Response framework" for environmental sustainability and the "Driving Force-State-Response framework" for a sustainable energy future. Boulanger and Bréchet (2005) also suggest some fundamental criteria in sustainable development policy planning, including interdisciplinary perspective, long-term perspective, global-local perspective, and stakeholders' participation.

From the perspective of policy evaluation, there is no uniform standard or framework for assessing the performance of policy implementation due to the varying research objectives and contexts (Guo et al., 2018). Despite this fact, researchers have provided valuable references regarding the forces that impact policy implementation and diverse assessment methodologies (Boulanger & Bréchet, 2005; Roberts, 2006). As Roberts (2006) points out, the policy assessment focuses on the efficiency and effectiveness of policies designed to deliver the SDGs. This evaluation is essential to be undertaken by multiple evaluation stages, including preliminary assessments at the ex-ante evaluation stage, progress checks at the mid-term evaluation stage, and feedback reviews at the ex-post evaluation stage. An effective policy assessment requires appropriate tools, such as macro-econometric models, computable general equilibrium models, optimization programming (e.g., DEA), multi-agent simulation, Bayesian-based assessment models, etc.. At the same time, particular care should be taken to avoid some modeling issues in policy assessment. First of all, sustainable development emphasizes the coordination of economic, environmental, and social systems, which implies that single trajectory modeling is insufficient and biased for relevant policy assessment. Moreover, the interaction between different systems is more likely to exhibit non-linear patterns instead of simple linear relationships. Besides, static modeling without the consideration of dynamic trends of different systems can lead to less reliable conclusions in policy assessments. Finally, the carrying capacity constraints and development boundaries of different systems should be considered.

5.2 Limitations and implications for future research

Generally, empirical studies frequently confront various limitations stemming from factors such as data availability, methodological constraints, and existing knowledge gaps. Some of these limitations can be mitigated and addressed by conducting additional surveys, increasing the number of observations, updating datasets, using advanced methodological techniques, and so forth. However, some limitations can be more challenging and complicated to overcome, which points the way to future research.

Following the national strategy of “Ecological Conservation and High-quality Development of the Yellow River Basin”, Study 1 provides differentiated regional development plans for counties by identifying local priorities and measuring comparative advantages. The function zoning plans proposed by this study are based on efficiency measurements and determined by economic, environmental, and land use performance. Accordingly, the results can only speak for themselves from the perspective of efficiency performance. In order to improve the consistency and viability of zoning strategies, it is beneficial for policymakers and practitioners to consider multi-criteria assessment and find compromises. Besides, zoning strategies are designed for the holistic sustainable development of the entire basin. In this context, counties within the basin are assigned to different function zones and play different roles in enhancing economic, environmental, and social sustainability. However, the balance between economic growth, environmental protection, and social improvement within counties may be neglected, thus exacerbating regional disparities. Regarding this potential issue, a global-local perspective would help to understand how macro-level policy frameworks constrain micro-level policy planning, thereby contributing to overcome the challenge of integrated policy planning (Boulanger & Bréchet, 2005). Meanwhile, a room to integrate different stakeholders’ objectives in policy planning is required to facilitate comprehensive public participation. Additionally, this study reveals that some counties have similar economic or environmental outcomes to other nearby counties. The potential spatial clustered pattern requires further dynamic spatial-temporal investigation from a long-term perspective in future research.

From a policy-planning point of view, Study 2 aims to improve the SLCP implementation in terms of the cost-benefit aspect and further contributes to reducing the economic costs of soil loss control. However, without considering the indirect benefits brought by the SLCP (e.g., income growth and non-farming employment), it is challenging to reach comprehensive and rigorous conclusions about the future implementation of the SLCP (Lu & Yin, 2020). Therefore, a promising research topic is to comprehensively conduct policy assessment under wider economic, environmental, and social sustainable goals and achievements. Another concern is the data availability. Specifically, the observable data regarding river sediment volume and soil loss are collected by the hydrological stations. They are confidential data and are not disclosed to the public. To remedy this limitation, this study uses the estimated amount of soil loss as a proxy indicator via the Revised Universal Soil Loss Equation (RUSLE) in ArcGIS. Even though this method is widely applied in academia to evaluate soil erosion (Eder et al., 2021), the results may be more convincing if observable data were available. Additionally, due to the data unavailability, what I use in this study are four years with gaps: 2000, 2005, 2010, and 2015, rather than consecutive years from 2000 to 2015. It causes certain difficulties in investigating the dynamic time trend behind abatement costs of soil erosion.

Waste management remains challenging in rural China due to lagging waste disposal equipment and services, insufficient financial investment, and inactive citizen participation. Less attention has been paid to rural waste disposal research compared to urban waste disposal research. In this context, one of the major challenges in rural research is the lack of well-established data collection systems. To date, data collection for rural waste treatment research largely relies on questionnaire surveys, which demand significant labor and financial inputs. From a long-term perspective, the data from this process is hard to track and inadequate for dynamic analysis. The data used in Study 3 also face this limitation, which restricts the study to the cross-sectional modeling. Other challenges are related to methodological aspects. In this study, geographic networks and social networks in waste treatment behavior analysis are captured by different pathways. Specifically, geographic networks are measured by spatial distance weights that are used to weigh the influence of others' waste treatment behaviors. In contrast, the indicator reflecting the closeness of social networks is set as an explanatory variable, similar to other explanatory variables affecting waste disposal behaviors. While this approach helps to disentangle the impacts of geographic and social networks on shaping behavior, it does not allow to examine whether additional synergy exists when households share both close geographic and social networks. At last, agricultural waste has its special features compared to domestic waste. In detail, agricultural waste, such as fertilizer packaging, is more likely to contaminate soil and water quality and threaten human health if it cannot be handled properly. To avoid this undesirable situation, farmers need to have more specialized waste disposal knowledge, improve production conditions, and put more effort into disposing of agricultural waste. Since the current research only discusses the basic characteristics of households, conclusions regarding agricultural waste disposal are limited. Therefore, future research needs more agricultural production-related indicators to analyze agricultural waste disposal behavior.

Study 4 demonstrates that ex-ante risk mitigation measures (including irrigation systems, reservoir capacity, and soil loss control) contribute to moderating the negative impacts of agricultural vulnerability on crop yields. Unexpectedly, no such mitigating effect of drainage systems is found. One possible reason for this statistically insignificant result is the relatively small scale of drainage systems. However, this claim requires more evidence to support it. Besides, due to the heterogeneous natural and socio-economic conditions, the mitigation measures implemented in different regions may differ even within the unified national policy framework. The context-specific mitigation practices further cause difficulties in generalizing the empirical results. Finally, this study lays the foundation for future exploration of the dynamic effects of mitigation measures under changing climatic conditions.

Overall, this policy-oriented thesis centers around sustainability concerns and provides evidence-based recommendations to improve policy planning, implementation, monitoring, and evaluation. The limitations mentioned in this section are mainly related to the consideration of multiple stakeholders and their different values, periodic goal setting for dynamic sustainability status, and data limitation, which point out future research directions at the same time.

6. References

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