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The need for and feasibility of diversification in agriculture

Knowledge production, farming practices, and decision-making

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Abstract

Diversification has become a critical strategy in farming systems for mitigating risks, while also providing socio-economic benefits and ecological resilience. However, the dominant conceptualization of diversification in land use science focuses primarily on crops or farm-level practices, overlooking its relevance across interdependent components namely science, policy, and practice, that are determinants of agricultural diversification. This narrow framing limits understanding of the benefits, challenges, and constraints of diversification, thereby restricting its potential to support sustainability. This thesis addresses this gap by examining the need for and feasibility of diversification across three domains: (i) knowledge production, (ii) farming systems, and (iii) decision evaluation processes.

A scientometric analysis of 161,909 peer-reviewed land-related research articles (2000-2021) reveals a lack of diversification in knowledge production, with women underrepresented (27%), and authorship dominated by White (62%) and Asian (30%), while Hispanic (6%), and Black (2%) women remain significantly marginalized. Intersectional inequalities are particularly stark, with Black and Hispanic women significantly underrepresented in lead authorship positions. These structural patterns of exclusion highlight the need for diversity of targeted efforts to diversify who produces land-related knowledge and to expand the epistemic basis of land-related science.

In terms of feasibility of scaling diversified farming systems based on niche modeling approach using maximum entropy (MaxEnt) with socio-economic variables and observed locations of profitable diversified farming systems, the analysis identified infrastructure as a key impediment. Globally, 47% of the land was suitable for profitable diversified farming systems, with higher suitability in the Global North and in areas close to cities in the Global South. These findings suggest targeted investments in infrastructure, especially in the Global South, could enhance the scalability and adoption of diversified farming systems.

In evaluating the decision to consolidate land among smallholder farmers through decision analysis approach, stakeholder diversification including different groups of smallholder farmers emerged as essential in capturing the full impacts of land consolidation. Engagements with stakeholders revealed that conventional land consolidation models inadequately address farmers' needs. Consequently, stakeholders co-developed alternative model that better aligned with their realities, offering potential for more responsive land consolidation policies and models. Probabilistic modeling of financial viability of land consolidation for smallholder farmers indicated that land consolidation was less preferable (27%) than maintaining small farms (72%), with maize and land prices as key determinants. This participatory modeling approach demonstrates the value of stakeholders under uncertainty and data scarcity.

Together, these studies demonstrate that diversification must be expanded beyond a narrow agronomic scope to include representation in knowledge production, context-sensitive decision-making, and enabling socio-economic conditions for diversified farming systems adoption. This broader conceptualization is not only necessary to reduce systemic risks associated with simplification but also feasible across key domains. The findings underscore diversification's central role in advancing agricultural sustainability and provide methodological and policy-relevant contributions for future interventions.

Kurzfassung

Diversifizierung ist zu einer entscheidenden Strategie in landwirtschaftlichen Systemen geworden, um Risiken zu mindern und gleichzeitig sozioökonomische Vorteile und ökologische Widerstandsfähigkeit zu erzielen. Die vorherrschende Konzeption von Diversifizierung in der Landnutzungswissenschaft konzentriert sich jedoch in erster Linie auf Nutzpflanzen oder Praktiken auf Betriebsebene und übersieht dabei ihre Relevanz für die miteinander verflochtenen Komponenten Wissenschaft, Politik und Praxis, die für die Diversifizierung in der Landwirtschaft entscheidend sind. Diese enge Sichtweise schränkt das Verständnis der Vorteile, Herausforderungen und Hindernisse der Diversifizierung ein und begrenzt damit ihr Potenzial, die Nachhaltigkeit zu fördern. Diese Arbeit befasst sich mit dieser Lücke, indem sie die Notwendigkeit und Durchführbarkeit der Diversifizierung in drei Bereichen untersucht: (i) Wissensproduktion, (ii) Landwirtschaftssysteme und (iii) Entscheidungsbewertungsprozesse.

Eine scientometrische Analyse von 161.909 begutachteten Forschungsartikeln zum Thema Land (2000–2021) zeigt einen Mangel an Diversifizierung in der Wissensproduktion, wobei Frauen unterrepräsentiert sind (27 %) und die Autorschaft von Weißen (62 %) und Asiaten (30 %) dominiert wird, während hispanische (6 %) und schwarze (2 %) Frauen weiterhin deutlich marginalisiert sind. Die intersektionalen Ungleichheiten sind besonders ausgeprägt, da schwarze und hispanische Frauen in leitenden Autorenpositionen deutlich unterrepräsentiert sind. Diese strukturellen Muster der Ausgrenzung unterstreichen die Notwendigkeit gezielter Maßnahmen zur Diversifizierung derjenigen, die Wissen im Zusammenhang mit Land produzieren, und zur Erweiterung der epistemischen Grundlage der Landwissenschaft.

In Bezug auf die Machbarkeit der Skalierung diversifizierter Anbausysteme auf der Grundlage eines Nischenmodellierungsansatzes unter Verwendung der maximalen Entropie (MaxEnt) mit sozioökonomischen Variablen und beobachteten Standorten profitabler diversifizierter Anbausysteme identifizierte die Analyse die Infrastruktur als ein wesentliches Hindernis. Weltweit waren 47 % der Flächen für profitable diversifizierte Anbausysteme geeignet, wobei die Eignung im Globalen Norden und in stadtnahen Gebieten im Globalen Süden höher war. Diese Ergebnisse deuten darauf hin, dass gezielte Investitionen in die Infrastruktur, insbesondere im globalen Süden, die Skalierbarkeit und Einführung diversifizierter Anbausysteme verbessern könnten.

Bei der Bewertung der Entscheidung, Land unter Kleinbauern durch einen Entscheidungsanalyseansatz zu konsolidieren, erwies sich die Diversifizierung der Interessengruppen, einschließlich verschiedener Gruppen von Kleinbauern, als wesentlich, um die vollständigen Auswirkungen der Landkonsolidierung zu erfassen. Die Zusammenarbeit mit den Interessengruppen ergab, dass herkömmliche Landkonsolidierungsmodelle den Bedürfnissen der Landwirte nicht ausreichend gerecht werden. Infolgedessen entwickelten die Interessengruppen gemeinsam ein alternatives Modell, das besser auf ihre Realitäten abgestimmt ist und das Potenzial für reaktionsfähigere Landkonsolidierungspolitiken und -modelle bietet. Die probabilistische Modellierung der finanziellen Rentabilität der Landkonsolidierung für Kleinbauern ergab, dass die Landkonsolidierung weniger bevorzugt wurde (27 %) als die Beibehaltung kleiner Betriebe (72 %), wobei Mais- und Landpreise die wichtigsten Determinanten waren. Dieser partizipative Modellierungsansatz zeigt den Wert der Interessengruppen unter Unsicherheit und Datenknappheit.

Zusammen zeigen diese Studien, dass Diversifizierung über einen engen agronomischen Rahmen hinaus erweitert werden muss, um die Wissensproduktion, kontextsensitive Entscheidungsfindung und die Schaffung sozioökonomischer Bedingungen für die Einführung diversifizierter Anbausysteme einzubeziehen. Diese breitere Konzeption ist nicht nur notwendig, um die mit der Vereinfachung verbundenen systemischen Risiken zu verringern, sondern auch in allen wichtigen Bereichen realisierbar. Die Ergebnisse unterstreichen die zentrale Rolle der Diversifizierung für die Förderung der Nachhaltigkeit in der Landwirtschaft und liefern methodische und politikrelevante Beiträge für künftige Maßnahmen.

Contents

List of abbreviations

AIC	Akaike Information Criterion
AUC	Area Under the Curve
BvAT	Biovision Africa Trust
CIDP	County Integrated Development Plan
COVID-19	Coronavirus Disease 2019
DA	Decision Analysis
DFS	Diversified farming systems
EU	European Union
EVPI	Expected Value of Perfect Information
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
ICT	Information and Communication Technology
KES	Kenya shilling
LANUSYNCON	At the Science-policy Interface: Land Use Synergies and Conflicts within the framework of the 2030 Agenda
MaxEnt	Maximum Entropy
NPV	Net Present Value
PICOC	Population, Intervention, Comparator, Outcomes, Context
PLS	Projection to Latent Structure
REML	Restricted Maximum-Likelihood
ROC	Receiver Operating Characteristic
SDG	Sustainable Development Goals
SDM	Standardized Mean Difference
SI	Sustainable Intensification
SSA	Sub–Saharan Africa
UN	United nations
VIP	Variable Importance in the Projection
VoI	Value of Information
WoS	Web of Science

1. Introduction

Agriculture in the 21st century faces a myriad of challenges, including increasing food demand from a growing population, climate change and biodiversity loss (Foley et al. 2011). To date, research and policy have largely promoted intensification strategies to close yield gaps (Tilman et al. 2011), which has led to the simplification of farming (Alletto et al. 2022). This simplification of farms and landscapes has contributed to global loss of biodiversity (Leclère et al. 2020), increased the number of vulnerable individuals to climate change impacts (Doan et al. 2023), and weakened the resilience of agricultural systems (Aleksandrova et al. 2016). Despite these issues, agriculture continues to be a vital contributor to the Gross Domestic Product (20–30%) in many low-income countries over the past five years (2019–2023) (World Bank 2024a). Agriculture serves as the primary livelihood option and resilience strategy for over two billion smallholder farmers (FAO 2013) and is crucial to achieving several Sustainable Development Goals (SDGs), including "zero hunger", "life on land", and "climate action" (Blesh et al. 2023).

Collectively, these observations underscore the need for a shift away from agriculture practices that undermine ecosystem services, especially cultural and regulating functions (Newbold et al. 2016), toward long-term, sustainability-oriented solutions (Godfray et al. 2010) that restore and stabilize the integrity of agricultural systems and landscapes (Kremen and Merenlender 2018; Chivasa 2019). This transition also necessitates changes in research and policy, as implemented farming practices are influenced by produced knowledge, institutional dynamics, global forces and decision-making structures (von Braun and Díaz-Bonilla 2008; Jackson-Smith 2010).

In recent years, diversification has been positioned as counter-strategy to conventional agriculture–characterized by monocultures and input-intensive practices–offering ecological, economic, and social benefits (Rosa-Schleich et al. 2019; Tamburini et al. 2020; Beillouin et al. 2021). Although often narrowly conceptualized in terms of crop or farm-level diversification, research in this area is on the rise (Hufnagel et al. 2020; Alletto et al. 2022), addressing both demand for change from conventional agriculture and supply of alternative farming methods across various scales. For instance, studies have examined diversification at regional and national scales (Nelson and Burchfield 2021) and at the farm level (Tamburini et al. 2020). The ecological benefits of diversification have been shown to enhance ecosystem functioning, processes, and services through ecological interactions (Rosa-Schleich et al. 2019; Tamburini et al. 2020; Beillouin et al. 2021) and support biodiversity conservation (Jones et al. 2021). Economically, diversification has been shown to increase farm profits and dietary options (Powell et al. 2015; Mburu et al. 2016; Waha et al. 2018). At landscape level, benefits include provision of habitats for other species, improved pollination, and enhanced water quality (Kremen and Merenlender 2018). However, structural forces such as market incentives for largescale monocultures, global initiatives like "one country, one priority product", and subsidy programs that mainly support cash crops continue to favor simplified farming practices such as monocropping in many countries (Mortensen and Smith 2020), possibly due to limited knowledge about the enabling conditions for profitable diversified farming systems (DFS).

Diversification may also be considered at broader system and structural levels. For example, Reckling et al. (2023) identified diversification opportunities across cropping, grassland, farming, landscape, governance, and food systems. Moreover, diversification can extend into other domains such as science and policy level, and specifically, who produces agricultural knowledge and who participates in land use decision making. These are critical socio-technical structures that influence the implementation of agriculture practices. A narrow focus on farm-level diversification risks obscuring systemic levers for transformation. Diversity in knowledge production, for instance, remains under-researched despite its importance in shaping research agendas and contributing to inter- and transdisciplinary solutions to sustainability challenges (Jackson-Smith 2010). From the perspective of epistemic diversity, the inclusion of multiple knowledge systems spanning disciplinary, cultural, and experiential domains enhances the robustness, legitimacy, and contextual relevance of scientific inquiry, particularly in addressing complex socio-ecological issues (Sikimić 2023). Male dominance in research (Vaughan et al. 2019; Dawson et al. 2021) is likely to skew both problem framing and solutions generated. Agricultural data and innovations are disproportionately drawn from or tailored to men (Sperber et al. 2023), even though women, who make up 49.7 % of the global population (World Bank 2023), play a significant role in farming, conservation, and land management (Villamor et al. 2014). Underrepresentation of some ethnic groups (Hopkins et al. 2013; AlShebli et al. 2018; Riegle-Crumb et al. 2019) is likely to devalue innovations and contributions produced by some groups (Hofstra et al. 2020), yet ethnic diversity is crucial for varied perspectives, experiences and innovations. Intersection of gender and ethnicity further marginalizes certain groups (Crenshaw 1989), leading to persistent solution gaps and constraining innovation in agriculture.

Similarly, decision-making processes in agriculture are often exclusionary. Land use policy evaluations frequently prioritize the interests of select stakeholder groups, thereby undermining the salience, legitimacy, and credibility of the resulting information and decisions (Cash et al. 2003). Exclusion of key stakeholders, particularly those from marginalized groups, weakens implementation efforts and increases the likelihood of policy failure (Dick-Sagoe et al. 2023). Given that the impacts of any agricultural decision are inherently interrelated across economic, environmental, social, political, and governance factors (Whitney et al. 2018), it is essential to examine how stakeholder diversity can enhance the evaluation of agricultural decision-making processes. Moreover, interventions often affect diverse stakeholders differently including different groups of farmers, warranting inclusion of different perspectives.

This thesis aims to expand the conceptualization of diversification in agriculture examining three interrelated dimensions: farming systems, knowledge production, and decision-making. It specifically explores: (i) who produces agricultural knowledge and the relation between diversity and research outputs; (ii) the socio-economic determinants of profitable diversified farming systems and includes the spatial predictions suitable areas for profitable diversified farming; and (iii) the integration of diverse stakeholder perspectives in evaluating land-use decisions to support decision-making.

1.1 Research problem and justification

The transition to sustainable agriculture is impeded by entrenched simplifications: the dominance of male researchers in knowledge production (Vaughan et al. 2019; Kamau et al. 2021), the exclusion of diverse stakeholders from decision-making structures (Rossi et al. 2003, p. 18), and the widespread overreliance on simplified farming practices such as monocropping (Hendrickson 2015). While these simplifications may offer short-term benefits in terms of yields (Pretty 2008; Ramankutty et al. 2018), they contribute to long-term soil degradation (Kopittke et al. 2019), biodiversity loss, and increase vulnerabilities exposure among marginalized groups of people (Benton et al. 2021). Furthermore, they reinforce a narrow framing of agriculture as merely a food production sector, neglecting its broader socio-ecological and governance roles.

Although diversification has recently re-emerged as a promising pathway toward sustainable agriculture, its dominant conceptualization, focused primarily on crop or farm-level diversification (Birthal et al. 2015; Waha et al. 2018; Smith 2022; Blesh et al. 2023), fails to capture its systemic potential. Diversification is seldom applied to domains such as knowledge production and decision-making, where limited epistemic and participatory engagement constrains innovation. Even within farm-level diversification, there is limited understanding of the socio-economic conditions that surround profitable diversified farming practices or how these conditions vary spatially. This knowledge gap may hinder the adoption of DFS, as farmers, donors, and practitioners often base investment decisions on expected returns (Michler et al. 2019).

The implementation of sustainable agricultural practices fundamentally depend on who produces knowledge and how decisions are made. Since knowledge is a primary driver of innovation (Ayoub 2023), diversity of knowledge producers is critical to designing inclusive and effective solutions (Sperber et al. 2023). However, evidence indicates that disciplines such as ecology, soil science, political, and archaeology remain male-dominated (Schucan Bird 2011; Tushingham et al. 2017; Vaughan et al. 2019; Maas et al. 2021). This skew towards male perspectives affects the types of innovations produced, despite women comprising nearly half of the global population (World Bank 2023) and playing critical roles in farming and land stewardship. In research areas relevant to land and land systems including agriculture, environmental science, biodiversity and conservation, forestry, water resources, and energy and fuels, the extent of diversity of among knowledge producers remains unclear. Yet, addressing complex land-related interactions could benefit significantly from diverse perspectives and knowledge approaches.

Similarly, decision-making spaces often exclude those most affected by agricultural interventions and do not often include the full diversity of all stakeholders affected, undermining procedural legitimacy and resulting in flawed evaluations (Curșeu and Schruijer 2017). Decisions based on the input of only a few stakeholders' risk failure due to social resistance and marginalization of key actors. In contexts such as land consolidation for smallholder farmers for example, incorporating diverse stakeholder perspectives is crucial for capturing localized impacts and ensuring social legitimacy. Conventional evaluations processes that have been used to support decisions in the past and focus solely on economic feasibility such as typical cost-benefit analysis, may fail to capture the socio-environmental impacts that are equally crucial when making decisions (Luedeling et al. 2015).

1.2 Research objectives

The study aims to contribute to a more comprehensive understanding of the different dimensions of diversification in agriculture and how they can advance sustainability in agriculture. The specific research objectives are to:

i. Assess diversity among knowledge producers in land science-related fields and analyze how academic productivity varies with gender, ethnicity, and their intersection.
ii. Determine the spatial distribution of financially viable diversified farming systems based on socio-economic conditions and identify areas where these systems can support sustainable intensification.
iii. Evaluate a land use decision on land consolidation for smallholder farmers by incorporating diverse stakeholder perspectives.

1.3 Structure of the thesis

This thesis is structured into six chapters. Chapter 1 provides the background context, outlines the research problem, and presents the study objectives. Chapter 2 reviews literature on the relevance of diversification at different system levels and identifies key barriers to its adoption. It also introduces the conceptual framework guiding this study. Chapter 3 analyses the representation of knowledge producers publishing in land science research areas from 2000 to 2021. It investigates whether gender and ethnicity influence scholarly productivity and identifies groups marginalized by intersecting inequalities. Chapter 4 predicts the spatial suitability distribution of profitable DFS based on socio-economic conditions and addresses where these practices can contribute to sustainable intensification. Chapter 5 evaluates a land use decision on whether smallholder farmers in Kenya should or should not consolidate their land, offering a detailed cost-benefit analysis to support decision-making. Chapter 6 provides synthesis of the key findings, policy implications, limitations, and suggests directions for future research. Chapters 3 and 4 have been published in peer-reviewed journals and included with minimal adjustments while Chapter 5 is currently under review at *Land Use Policy*. Data used in Chapter 4 is linked to another publication published in peer-review journal. The publications are as follows:

i. **Kamau, H.**, Uyen T., & Biber-Freudenberger, L. A long way to go: gender and ethnic diversity in land use science. Journal of Land Use Science, 2022, 17(1): 262-280. DOI: https://doi.org/10.1080/1747423X.2021.2015001

ii. **Kamau, H.**, Roman, S., & Biber-Freudenberger, L. Nearly half of the world is suitable for diversified farming for sustainable intensification. Communications Earth & Environment, 2023, 4(1): 446. DOI: https://doi.org/10.1038/s43247-023-01062-3

iii. Sánchez A.C., **Kamau H**., Grazioli F., Jones S.K. Financial profitability of diversified farming systems: A global meta-analysis. Ecological Economics, 2022, 201:107595. DOI: https://doi.org/10.1016/j.ecolecon.2022.107595

2. Diversification

The definition of "diversification" in agriculture is ambiguous and context-dependent (Hufnagel et al. 2020). In agribusiness and other broader economic landscape, diversification refers to the development of investment portfolios with varied characteristics aimed at minimizing exposure to risks and market volatility (Reed and Luffman 1986). Business organizations adopt diversification for multiple reasons, including for survival, expansion, profitability (Cannon and Hillebrandt 1989; Su and Tsang 2015), efficient utilization of resources, the creation of new opportunities, the achieve comparative advantages (Kang 2013), or as a turnaround strategy from previous business models (Harrigan 2012).

In agriculture, "diversification" is most commonly defined through the lens of crop or farm-level diversification (McCord et al. 2015; Hernández-Ochoa et al. 2022; Rissing and Burchfield 2024; Keller et al. 2024). Crop diversification enhances adaptation and resilience by reducing vulnerability to climate-related shocks and hazards (McCord et al. 2015). According to the Intergovernmental Panel for Climate Change (IPCC), agricultural diversification includes a range of practices and products aimed at improving farmers' resilience to climate variability and the economic risks associated with fluctuating market (Smith 2022). Like in business, agricultural diversification serves multiple purposes: it helps mitigate risks and uncertainties linked to climate variability (Ebi et al. 2011), broadens the product base, optimizes resource use (Below et al. 2012; Bryan et al. 2013; Waha et al. 2013; McCord et al. 2015), and can facilitate agricultural development by freeing up agricultural labor (Schuh and Barghouti 1988).

In political and social contexts, "diversification" is often framed as a mechanism for inclusion (Gans 2018) and may affect democratic processes depending on the type of diversity involved (Gerring et al. 2018). A key motivation in these settings is to leverage creativity by bringing together individuals with varied expertise, skills, and preferences (Mershon and Walsh 2016). Other motivations include countering implicit biases, such as those perpetuated by "old boys" networks in academia (Massen et al. 2017) and addressing discrimination and marginalization (Monroe et al. 2008). However, increased inclusion can also lead to conflicts (Curșeu and Schruijer 2017) and higher operation costs (King and Ehlert 2008).

Across these varying definitions, a common theme is the intention to reduce dependency on a single product, technology, perspective, stakeholder, or actor conditions that often lead to simplification. Accordingly, in this thesis, "diversification" is defined as a strategy designed to generate benefits by maintaining a broader base of technologies, stakeholders, perspectives, and actors across disciplines. This approach aims to mitigate risks and dependencies associated with reliance on any single element.

2.1 Relevance of diversification in agriculture

Achieving the SDGs remains a global priority. SDG 2 ("Zero hunger"), SDG 13 ("Climate action"), and SDG 15 ("Life on land") are intrinsically linked to land, yet often represent competing objectives. Agriculture significantly contributes to climate change, land degradation (Mulinge et al. 2016), biodiversity loss (Potts et al. 2010; Rhodes 2018), and greenhouse gas emissions (Ramankutty et al. 2018). The IPCC projects more than a 50% chance of global temperatures reaching or exceeding 1.5°C between 2021 and 2040. Pereira et al. (2024) anticipate widespread biodiversity loss due to climate change and land use changes from 2015 to 2050. Declines in regulating ecosystem services such as crop pest control, pollination, soil protection, and nitrogen retention are likely to impact agriculture severely. Meanwhile, global demand for agricultural commodities is projected to rise by 35–56% between 2010 and 2050 (Van Dijk et al. 2021), necessitating urgent transitions to sustainability systems.

Conventional agriculture has increased food production but led to landscape homogenization (Hazell and Wood 2008), reducing adaptability and biodiversity, and heightening vulnerability to climate and biological shocks (Potts et al. 2010; Ramankutty et al. 2018; Rhodes 2018). Diversification via crops or farming practices can enhance system resilience by mitigating such risks (Rosa-Schleich et al. 2019; Tamburini et al. 2020), improving yields (Beillouin et al. 2021), and soil fertility and structure. It also supports nitrogen cycling, carbon sequestration (Burney et al. 2010; Liu et al. 2016; Tamburini et al. 2020), groundwater recharge (Yang et al. 2021; Wang et al. 2023), and on-farm biodiversity (Jones et al. 2021). Moreover, diversification can support both extensive and intensive systems in transitioning toward sustainable intensification (Kamau et al. 2023) (Figure 2.1).

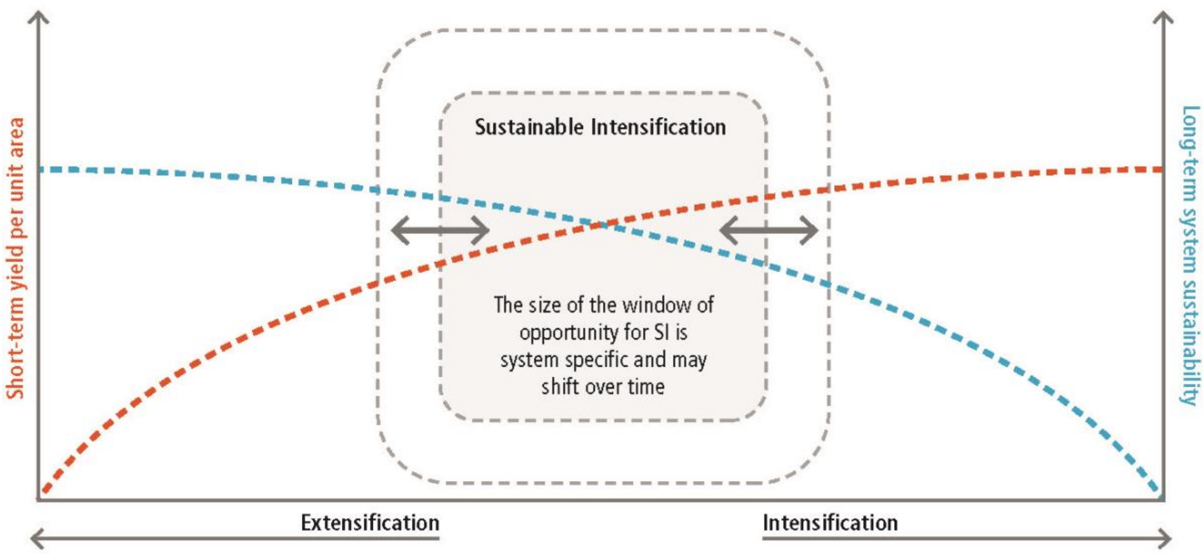

Figure 2.1: Diversification as a "window of opportunity" for minimizing land use trade-offs. It acts as a "pull" for intensive systems and a "push" for extensive systems towards sustainable intensification. Source (IPCC 2022)

Historically, male researchers and scientists have dominated agricultural sciences. They have then shaped the agricultural knowledge systems as agriculture depends on accumulated knowledge (von Braun and Díaz-Bonilla 2008). Despite the advancements in agricultural science, significant perspectives and epistemic diversity has been constrained due to the underrepresentation of women in scientific disciplines (Abramo et al. 2009; van Arensbergen et al. 2012; Helmer et al. 2017; Vaughan et al. 2019; Dawson et al. 2021). Evidence suggests that diverse knowledge producers can enhance problem solving capabilities in complex systems (Kamau et al. 2021) and drive innovations (AlShebli et al. 2018; Hofstra et al. 2020).

The SDG principle of "leaving no one behind" by 2030 requires decisions aligned with SDG 16.7: "Ensure responsive, inclusive, participatory, and representative decision-making at all levels". Yet, land use decisions often lack inclusivity. For example, in Malawi, household heads may make farming decisions that other members have to implement, despite being excluded from the decision-making process (Meijer et al. 2015; Msofi Mgalamadzi et al. 2024). Exclusion can result in resistance, reduced effectiveness, and missed opportunities (Villamor et al. 2014). Stakeholder diversity can enhance decision quality by incorporating a broader spectrum of values, experiences, and impacts (Curșeu and Schruijer 2017; Ely and Thomas 2020). Stakeholders encompass groups or individuals who are impacted by have influence over, or hold vested interests in an issue at hand (Luu et al. 2022).

2.2 Barriers of diversification adoption

Despite diversification's potential to achieve multiple goals, it faces systemic barriers. In knowledge production, gender gaps persist besides preferential hiring and funding programs. Institutional biases, retrogressive stereotypes, and gender roles (Kamau et al. 2021; Velander et al. 2022; Liu et al. 2024) limits women's participation. Similar biases exist for racial, ethnic, and socioeconomically marginalized groups (Graves et al. 2022).

In decision-making, stakeholder diversity introduces coordination challenges and uncertainty. Emotions, loyalties, and competing interests can impede consensus (Celino and Concilio 2011), elevate costs (King and Ehlert 2008; Su and Tsang 2015), or generate false consensus (Curșeu and Schruijer 2017). In weak institutional settings vulnerable to corruption and manipulation, diversification can be regressive if stakeholder involvement is not adequately planned or executed (Oladimeji and Udosen 2019).

In farming systems, while meta-analyses affirm that diversification boosts productivity (Tamburini et al. 2020; Beillouin et al. 2021), it is criticized for lacking concentration which reduces crop yield (Himmelstein et al. 2016) and increase labor demands (Kotir et al. 2022). These criticisms can potentially deter farmers from adopting diversification. However, Sánchez et al. (2022) argued that income gains from superior yields can offset labor costs. Kotir et al. (2022) recommended aligning crop choices with staggered labor demands rather than crops whose labor demands peak simultaneously. Other recommendations include using shade plants or cover crops to reduce the effort required for weed maintenance (van Zonneveld et al. 2020).

Farm diversification is knowledge intensive for farmers, particularly in determining the best crop combinations or farming practices to apply (Keller et al. 2024). Blesh et al. (2023) demonstrated that agency is a key asset in adopting diversification, as it relates to the capacity of changing narratives, attitudes, and general know-how. Most farmers lack this agency, despite its importance. Diversified farming practices, such as agroforestry, require long-term investment and secure land tenure. Where farmers have insecure tenure rights, adopting diversification practices may become challenging (Sánchez Bogado et al. 2023, 2024).

Another critical barrier is the presence of simplification forces that incentivize and reward farmers within conventional farming systems (Mortensen and Smith 2020). These forces are linked to markets where certain crops have increasing demand and complementary benefits. For instance, volume discounts are often associated with farm inputs (Magdoff et al. 2000). Infrastructural inadequacies related to farming, transportation, and storage can limit the types of farming practices and crops a farmer can utilize based on the region, climate, and demand (Meynard et al. 2018). Policies at any level can impede the adoption of diversification. For example, policies designed to offer preferential incentives and subsidies prioritize specific crops or value chains (Roesch-McNally et al. 2018), inadvertently encouraging monocultures. Similarly, global programs and initiatives that promote priority crops such as "One Country One Priority Product" threatens diversification.

2.3 Conceptual framework

This study adopts a conceptual framework that views agriculture as a complex, interdependent system shaped by various actors and processes such as institutions, economic processes, governance, socio-cultural dynamics, and environmental interactions. Understanding these interconnections is critical for designing targeted interventions that leverage causal relationships and feedback loops to foster sustainability.

Building from socio-ecological systems (Wittman et al. 2017) and systems thinking (Meadows 2009), the framework positions diversification as a central mechanism linking knowledge production, farming practices and decision-making (Figure 2.2). The socio-ecological framework emphasize that agriculture outcomes are influenced by numerous variables, but some variables have more influence than others in driving the outcomes (Wittman et al. 2017; Blesh et al. 2023). From a systems thinking perspective, agriculture is more than the sum of its parts. A system is seen as a whole, despite comprising various elements, relationships, and functions. While agriculture comprises numerous elements and relationships, agriculture's overall behavior emerges from interactions forming feedback loops that either reinforce or stabilize the system. Identifying leverage points, where small changes can have large impacts, is crucial to improving efficiency without overburdening the system (Meadows 2009).

One of the primary drivers of knowledge production is the need for solutions that address societal challenges, paired with the curiosity of researchers. However, knowledge produced within academic institutions is often compartmentalized into specific scientific disciplines which can limit cross-disciplinary understanding. Such knowledge is usually considered objective and independent of researcher or societal influence. This is because the knowledge produced undergoes formal validation processes, such as peer review, which aim to ensure rigor and credibility. In such contexts, science is presumed to inform policy, which then informs practice. Characteristics such as author composition and researchers background (e.g., gender, race) are presumed to bear little or no influence for the knowledge produced or its applicability to diverse societal needs.

For several reasons that are described in Chapter 2 and 3, men dominate in academia and science institutions, with implications for the direction and inclusivity of research. The accumulated knowledge we possess today is a testament to the scholarly productivity of researchers. While scientific productivity in terms of publications has increased over time, critiques highlight misalignment between science and societal needs, overly technical language, and weak engagements with non-scientific stakeholders (Magnuszewski et al. 2010). These criticisms point to science often failing to address the diverse needs of society and diversifying research teams can provide a much-needed shift. For example, contrary to the earlier assumption that research traits bear little or no implications for solutions and recommendation, research has shown that a researchers' background including gender, age, sexual orientation, class, religion, race, and the intersection of the traits, shapes the science we produce (Thorp 2023). Without such diversity, science risks perpetuating narrow perspectives, often leading to solutions that fail to meet the needs of all groups (Sperber et al. 2023), one-sided narratives (Adichie 2009; Sturmberg et al. 2022), limited applicability of results, or overgeneralizations such as one-size-fits-all approaches (Alegria et al. 2010), and hindrances to the expansion of scientific knowledge (Meadows 2009, p. 160; Kozlowski et al. 2022).

Disciplines such as archaeology and ecology continue to reflect stark disparities in gender and ethnicity representation (Tushingham et al. 2017; Maas et al. 2021). Within land-related fields, data on diversity is limited to research areas like ecology and soil science (Vaughan et al. 2019; Maas et al. 2021; Dawson et al. 2021), though land-related research spans broader areas including agriculture, forestry, water, and energy, and environment. Understanding the baseline representation across these research areas is essential for designing effective interventions.

Developmental interventions require holistic evaluation, as many past investments based on conventional evaluations have yielded limited success (Yet et al. 2020). Evaluating these interventions is crucial, given that they are often costly and have unintended consequences (Shepherd et al. 2015). Moreover, such evaluations are often challenging due to lack of robust empirical evidence coupled with inherent complexities of agricultural systems. Consequently, most evaluation processes used are often marked by concerns such as heavy dependence on economic feasibility (World Bank 2010), a lack of consideration of social and ecological impacts (Luedeling et al. 2015), and tokenistic participation to legitimize an intervention (Luyet et al. 2012). Effective responses to societal challenges require context-specific understanding, co-designed solution options, participatory evaluation processes, and autonomy in deciding on the best solution where possible. Perceptions of societal challenges may vary among different stakeholders (Hall et al. 2014), as they may be impacted differently. Inclusive evaluations can harness stakeholder diversity and generate actionable alternative solutions.

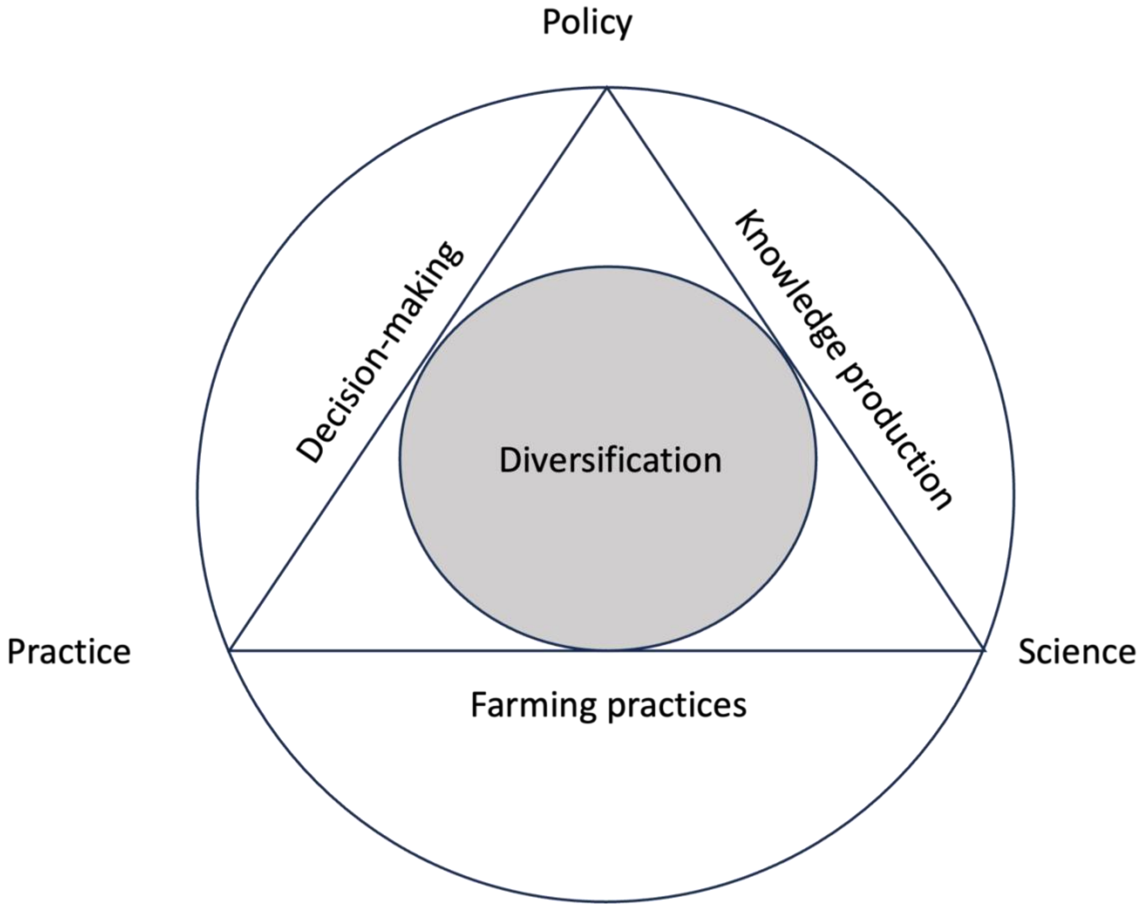

Figure 2.2: Conceptual framework applied in this thesis. The key components–decision-making, knowledge production, and farming practices–are interlinked and anchored by diversification (center), which acts as a leverage point to generate novel solutions, promote holistic evaluations for agriculture solutions, and yield co-benefits.

Diversified farming practices can enhance biodiversity, ecosystem functioning, and services in which multiple benefits can result (Tamburini et al. 2020; Jones et al. 2021; Yang et al. 2021; Kamau et al. 2021; Sánchez et al. 2022; Wang et al. 2023). Yet, profitability of DFS remains uncertain and context-dependent, influenced by the specific practices adopted and the contextual social, economic, governance, and environmental conditions.

Focusing diversification solely on farming systems often reinforces siloed approach, limiting broader systemic transformation. For example, attempts to scale up DFS have faced challenges due to policy biases favoring conventional agriculture, limited infrastructure like in Global South countries (Kamau et al. 2023), and weak institutional support (Blesh et al. 2023). A more integrated approach targeting simultaneous diversification in knowledge production, decision-making, and farming systems is needed. Engaging diverse stakeholders in agricultural decision-making enhances decision quality and legitimacy, which inclusive knowledge production can challenge dominant assumptions and foster innovation. While this integrative approach is complex, it holds significant potential for transformative, sustainable agriculture.

3. A long way to go: gender and diversity in land use science

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3.1 Abstract

Female scientists and researchers with diverse cultural backgrounds, especially of the Global South, are underrepresented in scientific systems. This is also the case for land use science and even for research teams researching in Global South countries. To assess trends in gender parity, ethnic diversity, and intersectionality in this field, we conducted a meta- analysis based on systematic literature review that included 316,390 peer-reviewed journal articles. We found that 27% of all authors between 2000–2021 represented women. Ethnicity representation was biased towards White researchers (62%) followed by Asian (30%), Hispanic (6%) and Black (2%) researchers. Intersection of inequalities further underrepresented Black and Hispanic women when author positions were considered, giving Black women 0.6% chance of becoming first authors in land use science in comparison to 19.3% chance of White women. Supportive actions to empower women are needed to reduce intersectional inequalities and to achieve the sustainable development goals.

Keywords: Women; global south; sdg; gender balanced assessment tool; intersectionality

3.2 Introduction

Land access, use, management and planning are key for achieving the Sustainable Development Goals (SDGs). While several SDGs such as zero hunger (SDG 2), affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life on land and below water (SDG 14 and 15), are directly linked to land and its use, others are indirectly influenced. In particular, land use research in the Global South is highly relevant, considering projections of doubling populations by 2050, which would further accelerate existing challenges linked to food insecurity, biodiversity threats and land degradation (Leclère et al. 2020).

It has been argued that the puzzles to unlocking the SDGs accelerators lie in the complex interactions, causal relationships, and feedback loops of the different SGD targets (Gao and Bryan 2017; Fu et al. 2019). Consideration of diverse academic disciplines, perceptions, knowledge, and approaches are crucial to understanding these complex interactions of land use systems and to solve challenges in their sustainable management. Studies have shown that, for example, interventions and decisions made by women are often more effective in conserving biodiversity (Cook et al. 2019) or reducing greenhouse gas emissions (Villamor et al. 2014).

Unfortunately, land use decisions made at household and community levels are often biased against women primarily due to land tenure rights that favor men, in particular, in many countries of the Global South (Fonjong et al. 2013; Villamor et al. 2014). Women, however, execute land-related decisions and have equally been placed at the heart of land matters including farming, conservation, and management regardless of limited tenure (Fonjong et al. 2013). In the Global South, where land related issues are highly topical and relevant, unravelling and understanding the complexity of land use systems would highly benefit from diverse perspectives and decision making from women at all levels of management.

Similar to other sectors and parts of society, academic systems have been found to favor male scientists (van Arensbergen et al. 2012; Helmer et al. 2017). Studies found for example, a general underrepresentation of female scientists in research (Abramo et al. 2009), academic tenure positions (Sheltzer and Smith 2014) and scientific publications (Larivière et al. 2013; Lerback and Hanson 2017; Helmer et al. 2017). Peer-reviewed publications in scientific journals are considered as an indicator for the experience and status of a researcher. Gender disparities in terms of publication outputs, academic positions, editorial boards, and society memberships were found for example, in ecology (Maas et al. 2021), political science, economics, psychology, and social policy (Schucan Bird 2011), soil science (Vaughan et al. 2019; Dawson et al. 2021) or archaeology (Tushingham et al. 2017).

At the same time, gender disparities in scientific systems and publications are also likely to be shaped by geographical and ethnic biases (Hopkins et al. 2013). Women's participation and representation in science differ between countries. For example, Abramo et al. (2021) found a larger gender gap in Italy than in Norway, which the authors attributed to stronger societal engagement of women in family and domestic responsibilities in Italy than in Norway. Tao et al. (2017) found that women in the US published more than men in engineering and less in science while in China they found no differences between men and women in science publications but only in engineering, where women published more. These differences in China and the US were amplified by variables like family obligations (marriage and children). For example, a married female researcher in China on average has a better productivity compared to a single woman. They also found that in China, children negatively affect productivity, in contrast to the US where neither being married nor having children did affect productivity. Across sub-Sahara African countries, Fisher et al. (2020) found that women (single and married) on average had about 26% less articles accepted for publication in journals in comparison to men in any given year. One of the attributed factors to the above trend was family obligations, where, if doctoral students got married during their studies, it reduced female students' productivity but had an opposite effect on the male doctoral students. Besides the number of authorships of scientific publications, other indicators for academic performance, for example academic rank, have also been used to analyze disparities between different ethnic groups (Hopkins et al. 2013; Vaughan et al. 2019). While disparities have previously been observed for isolated factors, when these factors interact, intersect, and overlap one another they result in an effect known as intersectionality, which amplifies the underrepresentation of women within certain societal groups (Crenshaw 1989). For example, there is disproportionate bias against women when both geographical and ethnic factors are considered (van Arensbergen et al. 2012; Vaughan et al. 2019). If more factors are taken into account such as different career stages, the underrepresentation of female scientists becomes even more striking (Hopkins et al. 2013; Vaughan et al. 2019). Hopkins et al. (2013), for example, found that “Black” and “Hispanic” women are more marginalized and underrepresented when gender, race, geographical location, discipline, and career variables are combined.

Different studies have found a consistent underrepresentation of female scientists in publications (Helmer et al. 2017). Scholarly productivity is, however, often also measured by other indicators including the number of citations, the h-index (h = high impact) and the position in the order of authors (Wren et al. 2007; Hopkins et al. 2013; Huang et al. 2020; Fisher et al. 2020). According to Huang et al. (2020) and Andersen et al. (2019), the disparity between men and women in scientific publications is further worsened when disaggregated by gender, age, and author position. The position of an author often indicates different levels of scientific careers, with the last position being commonly reserved for a senior author and the first position frequently being held by early career scientists (e.g., during doctoral studies). These mutually reinforcing disparities result in fewer publications authored by women, in particular, from specific ethnic groups and are often dominated by researchers from US and Europe. This phenomenon of intersectionality is leading to the disregard of diverse and valuable perspectives from researchers with different backgrounds and ideas. In particular, land use research, one of the biggest research priorities to solve sustainability challenges of the Global South, would highly benefit from diverse research teams (Whelan and Schimel 2019; Maas et al. 2021).

Despite the general consensus on gender, ethnicity, and intersection of inequalities in science, variations of gender representation are likely to appear in different scientific disciplines. For example, in fields like ecology only 11% account for top publishing authors and are majority from Global North (Maas et al. 2021), and in archaeology–a female rich discipline–had 32% female authors between 1974 and 2016 (Tushingham et al. 2017). However, until now, there exists no study that has focused on publications within the field of land use science encompassing different associated disciplines such as agriculture, environmental sciences and ecology, biodiversity, forestry, water resources, energy, and fuels. Moreover, from the available studies, it is rather difficult to reconcile these variations across disciplines because of limited inference space, which is as a result of sampling limitations in previous studies considering gender disparity in general science or based on specific journals, countries, or institutions. Therefore, here we evaluate gender disparities in land use science by assessing the gender and ethnic diversity of authors within the field of land science and their scholarly productivity indicated by the annual citations and authorship positions. We look at intersectionality of gender, ethnicity and scholarly productivity focusing on an in-depth study that covers more than 20 years of scientific research in land use to show the progress towards gender parity and ethnic diversity in land use research. We hypothesize that (1) authorship position is associated with gender and ethnicity and (2) that there are differences in average citation rates between gender groups and among ethnicities.

3.3 Materials and Methods

3.3.1 Collection of data

The Clarivate's Web of Science (WoS) database was sourced for articles published from 2000 to 2021 using an all-inclusive search term for land-related publications on 25 May 2021. The search query was "topic = land, AND document type = Article, AND language = English, AND time span = 2000–2021". We obtained a total of 316,390 articles.

A strict inclusion-exclusion screening scheme with four steps was applied in R (R Core Team 2020), R-Studio (RStudio Team 2019), and Excel (Microsoft-Corporation). In the first step, we maintained only journal articles and excluded all other forms of publications (e.g., book in series), resulting in 315,611 studies. In the second step, based on the research area variable classified by WoS and embedded in the extracted dataset, we kept only articles with research areas relevant to land use science such as Agriculture; Environmental sciences and Ecology; Biodiversity & Conservation; Forestry; Water resources; and Energy & Fuels leaving 162,902 studies in the sample.

The third and last step of the screening scheme were to exclude studies with more than 20 authors to facilitate the memory usage of R and the duplicated studies. As a result, 719 studies (0.4% of the original sample) with 21–515 authors were excluded. We removed further 274 duplicated studies, resulting in 161,909 studies for further analysis. From the 161,909 studies, we obtained 702,788 individual author names for analysis (Figure 3.1)

3.3.2 Gender and ethnicity balance assessments

Gender and ethnic diversity assessments were performed using two R packages, namely, `genderizeR` (Wais 2016) and `predictrace` (Kaplan 2021). While the package `genderizeR` is used only for predicting the authors' gender, the package `predictrace` has two separate functions to determine both gender and ethnicity of authors.

Both R packages `genderizeR` and `predictrace` predict the authors' gender by matching their first names with the corresponding names in the data sources of each package. The package `genderizeR` is accessing the genderize.io database via its API. The database contains 114.5 million unique names from 242 countries (Genderize.io 2021) and is constantly being updated from social network profiles since 2013 (Wais 2016). The US Social Security Administration (SSA) database in package `predictrace` contains more than 92,600 unique names from annual Social Security card applications for births that occurred in the United States between 1880–2019 (Wais 2016; Kaplan 2021). Both approaches have been applied in previous literature (e.g., for SSA database: (West et al. 2013; Larivière et al. 2013); for genderize.io API: (Teele and Thelen 2017; Dion et al. 2018; Fortin et al. 2021)) to obtain information about gender and ethnic diversity of large datasets.

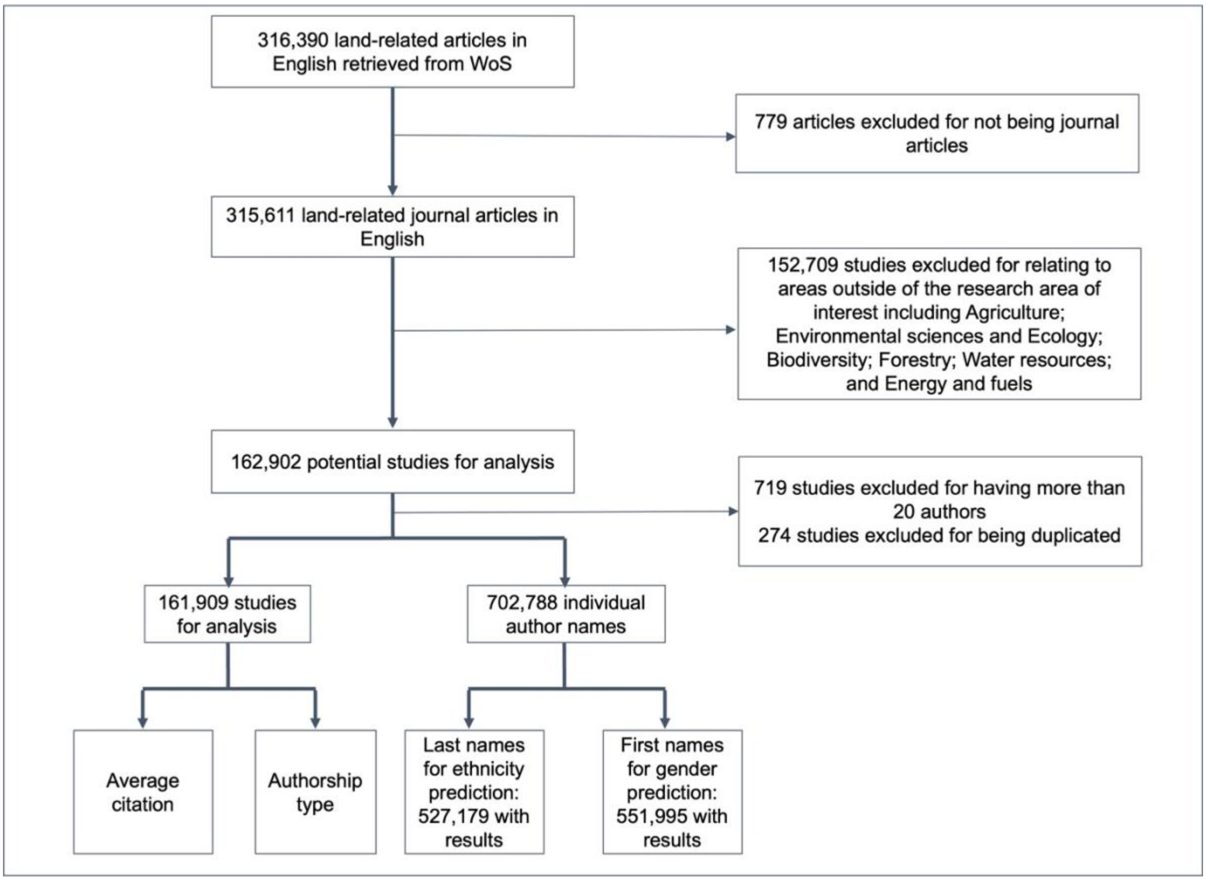

Figure 3.1: Selection scheme resulting in 702,788 author names from 161,909 studies included in the assessment of gender and ethnic diversity in land use science following a strict inclusion/exclusion criterion of a search conducted in May 2021 for journal articles.

The `genderizeR` package allows splitting the first names into single strings, which are matched with entries of the database by its API to return the most likely gender of the associated name along with a matching probability (i.e., the proportion of male and female profiles for each name). Meanwhile the `predictrace` package links the non-formatted names (i.e., without spaces and hyphens) with the SSA database for the corresponding gender and accuracy probability. Therefore, to optimize the prediction process, we split the first names with more than one string (i.e., "Marrie Anne") into single strings (i.e., "Marrie" and "Anne"). Then, they separately underwent the gender prediction process. First names that were initialized in the sample were not excluded; however, they would result in being undetermined in the gender assessment processes. If both databases predicted different gender to be most likely, the result with the highest probability was considered for further analysis.

Both packages are characterized by a number of limitations. Package `genderizeR` was reported to have an inherent error rate of 2–5% (Teele and Thelen 2017; Santamaría and Mihaljević 2018). For package `predictrace`, West et al. (2013) reported that there might be a tendency of excluding or misrepresenting uncommon and androgynous names in the SSA database. By combining both databases in a complementary way, we minimized these limitations.

Using the package `predictrace`, authors' ethnicity was determined based on last names. The package utilizes the SSA database with 167,000 stored last names and their equivalent most likely ethnicity ("Asian", "Black", "Hispanic", "White", "American-Indian", "Asian-Black", "Black-White" and "Two ethnicities") (Kaplan 2021). Similar to the gender prediction process, the last names were split into single strings to predict the most probable ethnicity of each author.

3.3.3 Determination of scholarly output

Scholarly output was determined by authorship position and average citations per year. Authorship position was classified by the sequence of the authors' names in an author order as "Sole", "First", "Last", or "Middle" author. If an article had only two authors, we classified the first as "First" and the latter as "Last".

We used the average number of citations per year per article as another indicator for scholarly output calculated based on all citations in all databases within WoS products (including Web of Science Core Collection, KCI-Korean Journal Database, Russian Science Citation Index, SciELO Citation Index) up to May 2021, and the years since its publication.

3.3.4 Descriptive and statistical analysis

Trends of gender disparity are reflected via the proportion of male and female authors of the whole sample, each ethnic group, and each authorship position, respectively. We analyzed and visualized all data in R Studio (Wickham 2007, 2021; Wickham et al. 2019, 2021; Morales et al. 2020; R Core Team 2020; Dowle and Srinivasan 2021). The annual growth rate of each ethnicity group was calculated based on the difference in absolute numbers of authors between two consecutive years divided by the number of authors in the former year.

To analyze the impact of ethnicity and gender on scholarly output, we used authorship position as a nominal response variable with four levels (sole, first, last and middle), and gender (two levels male, female), and ethnicity (four levels "White", "Asian", "Hispanic" and "Black") as independent variables. In order to explore how the intersection of gender-ethnicity might affect the authorship position, we tested for their association by conducting Pearson's chi-squared tests of independence (McHugh 2013), where the null hypothesis implies that the variables of interest are independent (Franke et al. 2012). We also visualized data over time. We tested whether scholarly output measured by average citations is affected by the first authors' traits such as gender and ethnicity based on a subsample including only first and sole author names and omitting last and middle author names. This enabled each observation to reflect one unique article and its corresponding number of citations. First, we used the Anderson-Darling normality test to assess whether the average number of citations per year follows a normal distribution (Nelson 1998; Gross and Ligges 2015). Subsequently, we conducted non-parametric methods including the Wilcoxon–Mann–Whitney test (or also known as Mann–Whitney U test or Wilcoxon rank sum test) to test for the differences in the average number of citations between gender groups and the Kruskal–Wallis test (Kassambara 2021) for ethnicity groups. Both methods are useful in those cases where the normal distribution assumption of their parametric analogs (t-test and ANOVA) is violated, as they transform data from two or more independent samples to ranks before applying the usual parametric procedures (Conover and Iman 1981). For the Kruskal–Wallis test, we found significant differences for at least one group. We conducted the Bonferroni method of post-hoc multiple pairwise comparisons to identify which samples differed significantly from each other (de Mendiburu 2020). Using both Wilcoxon rank sum and Kruskal–Wallis tests, we also tested for significant differences in citation rate between different gender-ethnicity subsamples.

3.4 Results

3.4.1 Gender diversity in land use science publication

The gender prediction tools successfully determined 382,477 male and 166,745 female authors out of 702,788 authors in the sample (78.1%). However, the success rate varied among publication years in the study period. We noticed that many authors' first names were only recorded as initials in WoS database for the years before 2007, which led to the relatively low success rate of these years (25.6% on average). For the successfully-determined cases, the mean accuracy probability of the gender outcomes was 95.6%. There were 2773 cases in the total sample where the name was considered as gender-neutral (probability of 50% for each gender).

Trend analysis showed that the proportion of female authors in land use science has increased from 19.8% in 2000 to 32.3% of total authors in 2021 (Figure 3.2). Although the gap between the number of female and male authors in land use science literature has slightly decreased at the average rate of 1.2% per year, the number of male authors remains twice as high as the number of female authors by 2021.

3.4.2 Ethnicity diversity in land use publication

We were able to determine the most probable ethnicity from 75% of all authors in our sample. Besides the four main categories "Asian", "Black", "White" and "Hispanic", we subsumed 165 authors predicted as "American–Indian", "Asian–Black", "Black–White" or "Two ethnicities" as "Two ethnicities". Trend analysis showed that the share of "Asian" authors has gradually grown over the years to become the largest group in 2020, accounting for 49.1% of all authors in our sample (Figure 3.3). During the same time, the share of "White" authors has been halved and decreased from 80.2% in 2000 to 42.5% in 2020. The share of "Black" and "Hispanic" authors remained more or less stable over the years, accounting for on average 1.9% and 5.8% of all authors, respectively. The share of the group with "Two ethnicities" only accounted for 0.03% of all authors on average with no particular trend. Annual growth rates of the total number of authors calculated for each ethnic group indicates that the "Asian" ethnic group had by far the highest average annual growth rate of 21.6% over the period

2007–2020, followed by 15.4% and 14.5% of the "Black" and "Hispanic" groups, respectively. The "White" group had the lowest average annual growth rate at 10.3%.

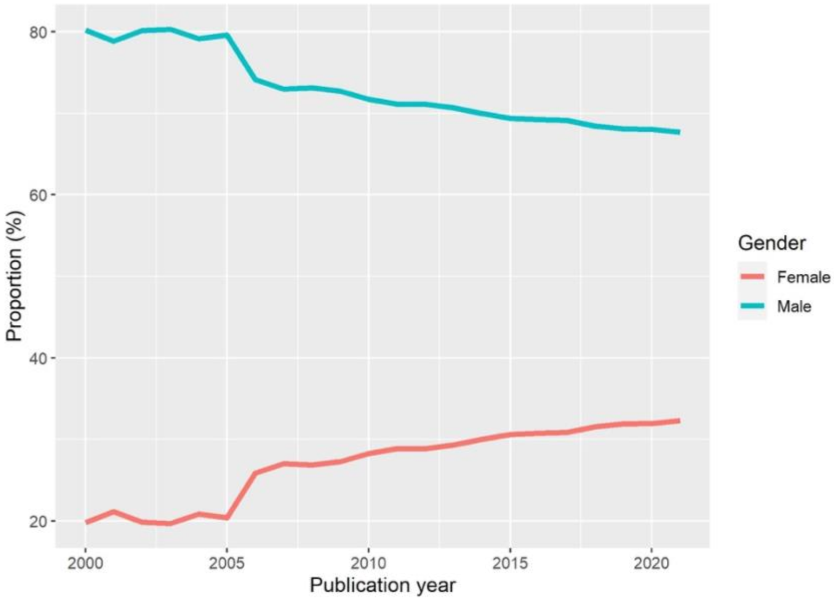

Figure 3.2: Proportion of female and male publishing authors in research areas of Agriculture; Environmental sciences and Ecology; Biodiversity; Forestry; Water resources; and Energy & Fuels. These proportions represent 382,477 male and 166,745 female authors from 161,909 studies

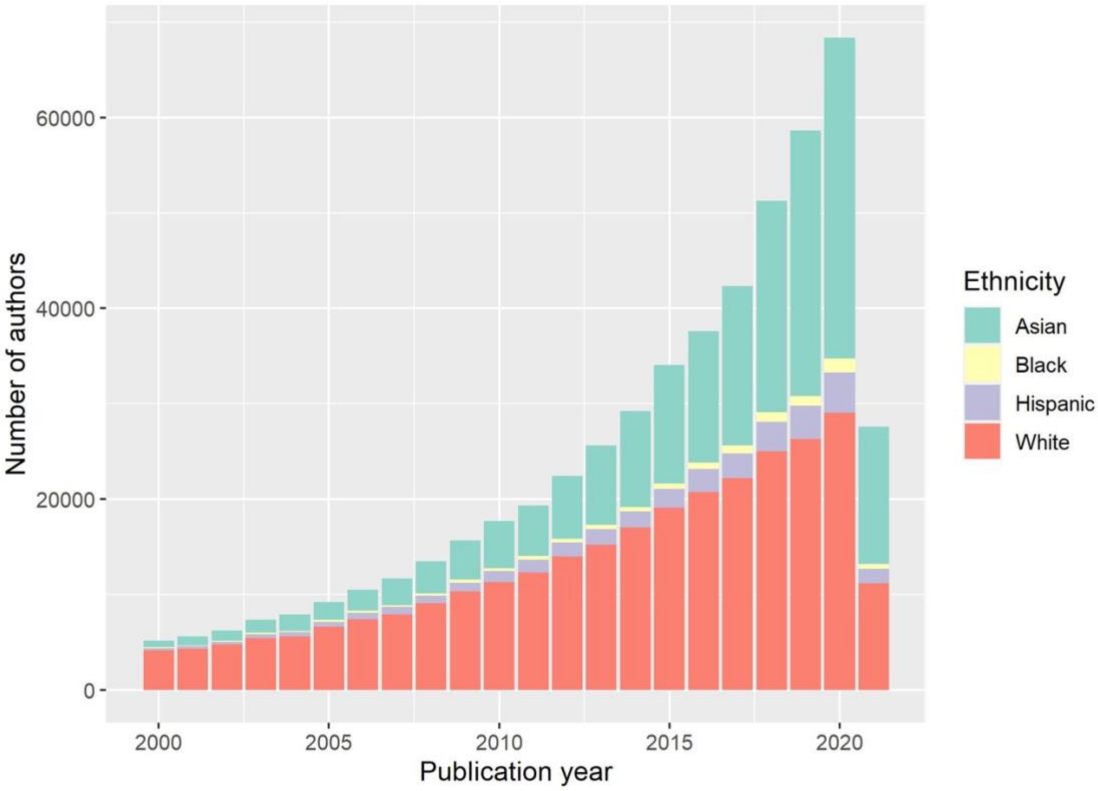

Figure 3.3: Total numbers of authors in land use science journal articles belonging to 5 ethnicity groups "Asian", "Black", "Hispanic", "White", and "Two ethnicities" in

2000-2021. The "Two ethnicities" group consists of "American-Indian", "Asian-Black", "Black-White", or "Two ethnicities (without further specification)". As this group only comprises an average of 0.03% of the total sample, it was not included in the graph. The last bar included publications within the first five months of 2021.

3.4.3 Intersection of gender and ethnicity

Looking at intersectionality, we analyzed gender gaps for each of the four main ethnic groups (Figure 3.4). For each group, we found a similar trend to the gender overview, where the share of female authors annually rose at the average rate of 0.8%, 0.9%, 1.2% and 1.5%, of Black, Hispanic, White, and Asian authors, respectively. Nevertheless, the gender gap in the "Black" ethnic group had the lowest closing rate and remained almost unchanged over the years at 25% female vs. 75% male authors by 2021. In the year 2002, female "Black" authors briefly accounted for a higher share than male "Black" authors. Since the total number of "Black" authors in the years 2000 to 2005 was overall relatively low (on average 144 authors accounting for only 2% of all authors), we would attribute this effect to the prediction error rate of the used algorithms rather than an actual brief closing of the gender gap, in particular since the gap widened afterwards immediately again.

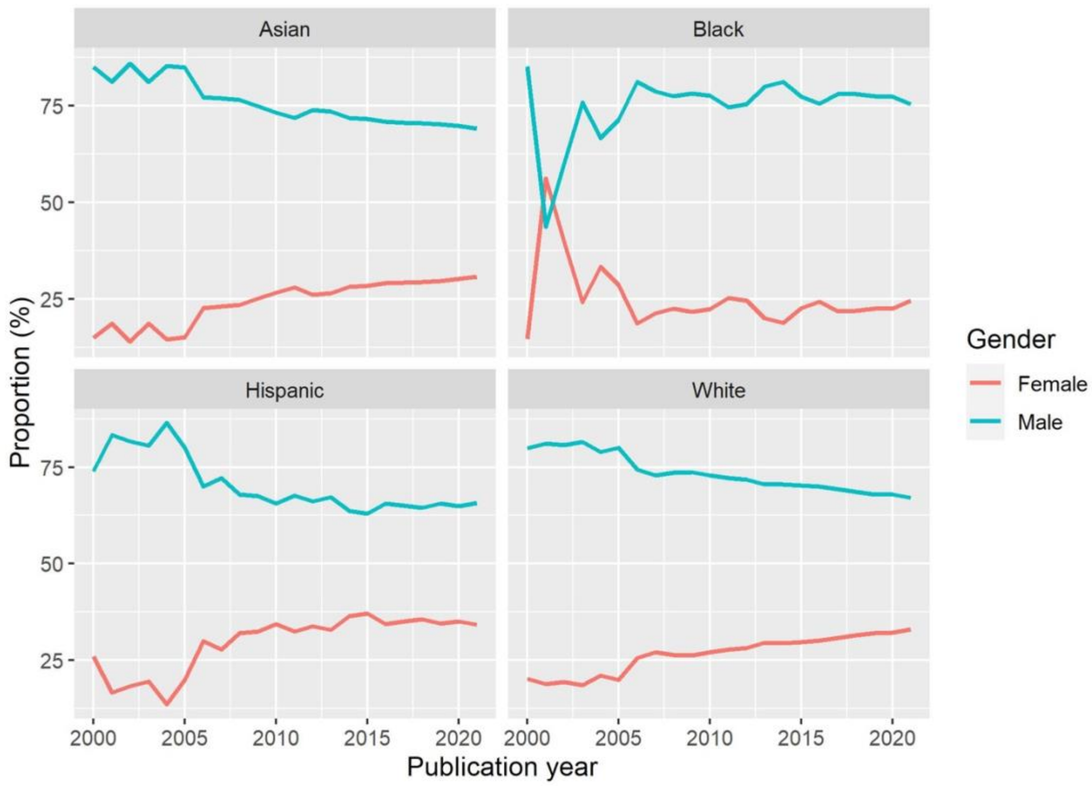

Figure 3.4: Proportion of female and male authors for each of the main ethnic groups (“Asian”, “Black”, “Hispanic”, “White”) in land use science in 2000-2021 representing 289,320 “White”, 195,981 “Asian”, 31,795 “Hispanic”, and 9,918 “Black” authors.

3.4.4 Author position in land use science publication

The average size of the author teams considered in this analysis was 5.8 authors, with a standard deviation of 3.2. For the whole sample, we recorded 11,120 “Sole” authorships from the same number of individually authored studies (6.9% of total article sample and 1.6% of total author sample), and 150,783 “First” and “Last” authorships each from the same number of jointly-authored studies (21.5% of total author sample each). Furthermore, we classified 390,102 authorships under the “Middle” authors category (55.5% of total author sample).

We found persisting but closing gender gaps for all four categories of authorship positions (Figure 3.5). This trend was however most pronounced for first (1.8% per year) and much less pronounced for last authorship positions (0.8% per year), both middle and sole authorship observed the average closing rate of 1.1% per year. The difference between the share of male and female authorships was around 60% for all four groups at the beginning of the study period and decreased to 25.4% for the first, 35.7% for the middle, 36.7% for the sole and 44.5% for the last author group. Since in academia author positions can be linked to the status and experience of an author, we would argue that this indicates a closing gender gap in the early stages of academic careers, but a largely persistent gender gap in the later stages such as professorships and senior academic positions.

Pearson’s chi-squared tests indicated that authorship position was significantly associated with both gender (χ2 ¼ 1591:8, $p < 0.05$) and ethnicity (χ2 ¼ 1970:8, $p < 0.05$). “Black–Female” and “Black–Male” authors had the lowest probability to become first authors with 0.6% and 1.6% respectively (Figure 3.6). These two pairs of intersectionality are also least likely to be either sole, last, or middle authors, followed by “Hispanic” females and “Hispanic” males. “White” men are found to dominate all four groups of authorship positions with a probability of 34.2% to become first author or of 44.6% to become last author.

Figure 3.5: Proportion of female and male authors by authorship position in land use science literature in 2000 - 2021. These proportions represent 150,783 first, 390,102 middle, 150,783 last, and 11,120 sole authorships.

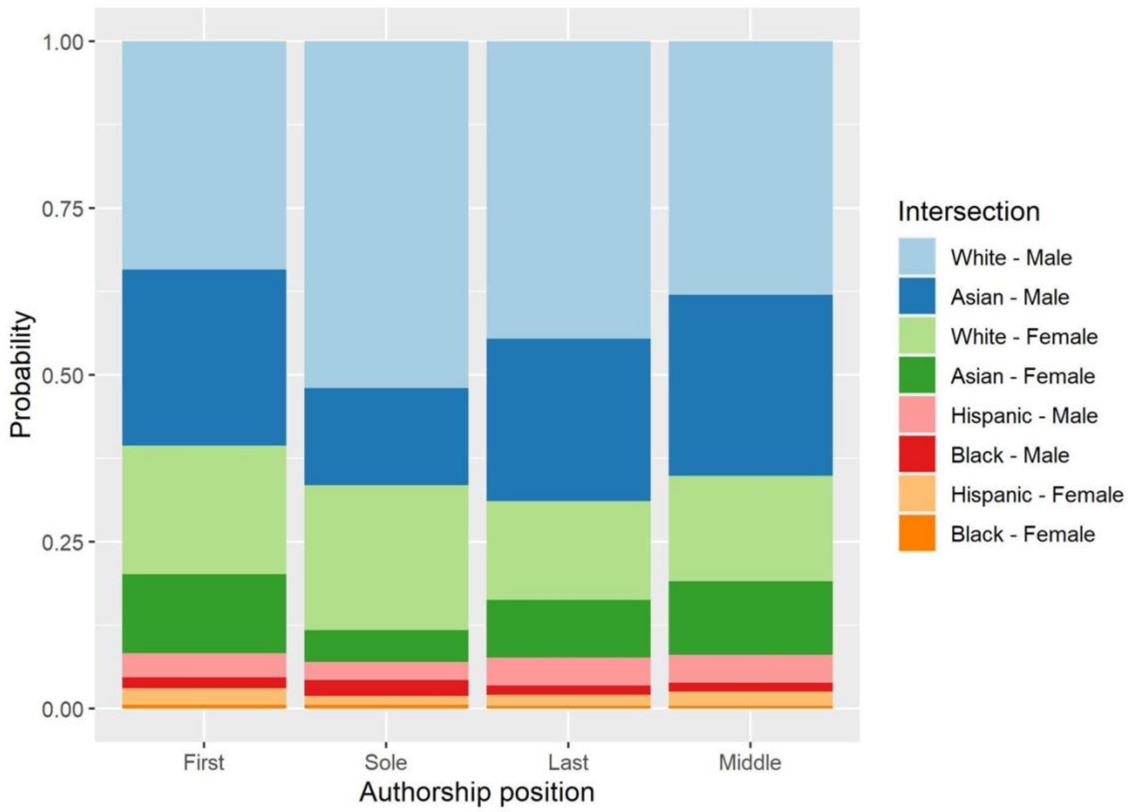

Figure 3.6: Probability of an author from a certain ethnicity and gender being in either of the four authorship positions. The probability ranges from 0 to 1, and is measured by the proportion of each pair of intersectionality within one group of authorship positions. This figure represents 87,377 first, 23,4620 middle, 87,569 last, and 5,804 sole authorships in the study period. The number of observations of each group is smaller than the original number due to missing information on either gender or ethnicity.

Table 3.1: Statistical results from Wilcoxon rank-sum test with continuity correction

First and sole authors	Average citation rate						Wilcoxon rank-sum test
	Female			Male			
	N	Mean	SD	N	Mean	SD	p-value
All	31478	3.28	4.66	61703	3.6	6.04	1.8e-09*
White	18122	3.27	4.7	32898	3.58	6.26	8.3e-05*
Asian	10608	3.41	4.82	23910	3.86	6.02	1.2e-05*
Hispanic	2204	2.85	3.6	3304	3.11	4.68	0.91
Black	544	2.76	3.67	1591	2.7	3.67	0.15

*Note: * signifies statistical differences at significance level 0.05*

3.4.5 Average citation rates in land use science publication

Based on a sample of 93,181 observations containing 87,377 first and 5,804 sole authors and excluding all observations without information on gender and ethnicity, the average citation rate per paper has a mean of 3.5 times per year and a standard deviation of 5.6. The Anderson–Darling normality test resulted in a goodness-of-fit statistic of 9,702 ($p < 0.05$) indicating that the average citation rate does not follow a normal distribution. Results from Wilcoxon rank sum tests indicate that the average citation rates of articles firstly authored by males were significantly higher than those by female authors ($p < 0.05$, Table 3.1). We also observed significant differences in citation rates between male and female first authors belonging to White and Asian groups, while the differences between male and female first authors in Black and Hispanic groups are not significant. The Kruskal- Wallis tests and post-hoc multiple pairwise comparisons of data ranks reveal significantly different citation rates amongst the four ethnic groups ($p < 0.0001$), with “Asian” authors being cited more frequently ($X_{asi} = 3.7$) followed by “White” ($X_{whi} = 3.5$), “Hispanic” ($X_{his} = 3.0$) and “Black” authors ($X_{bla} = 2.7$) (Table 3.2a). The difference in citation rates between “Asian” and “White” authors however are not significant. Trends for the average citation rates are similar to the trend of total first and sole authorships even when we broke them down to separate male and female subsets (Table 3.2(b, c) and Figure 3.7). Regardless of their gender, the “White” and “Asian” authors are significantly more likely to be cited than “Hispanic” and “Black” authors. While there is a significant difference between male- “Hispanic” and male- “Black”, the citation rates between female- “Hispanic” and female- “Black” are similar.

Table 3.2: The summary results from Kruskal-Wallis tests and the post-hoc multiple pairwise-comparison of three models. Models' a-c show the association between average citation and ethnicity of first and sole authors as a whole (a), first and sole male authors (b), first and sole female authors (c). These models stand for 93,181 articles which were firstly-authored by 51,020 "White", 34,518 "Asian", 5,508 "Hispanic", and 2,135 "Black" authors, respectively. In pairwise comparisons, groups sharing the same letter are not significantly different by data ranks at the alpha level of 0.05.

First and sole authors			All	Male			Female		
Average citation rate	Mean (a)	SD	Pairwise comparison	Mean (b)	SD	Pairwise comparison	Mean (c)	SD	Pairwise comparison
White	3.5	5.8	a	3.6	6.3	d	3.3	4.7	g
Asian	3.7	5.7	a	3.8	6.0	d	3.4	4.8	g
Hispanic	3.0	4.3	b	3.1	4.7	e	2.8	3.6	h
Black	2.7	3.7	c	2.7	3.7	f	2.8	3.7	h

Kruskal-Wallis, chisq(3) = 117.61, p=<0.0001, n = 93,181
Kruskal-Wallis, chisq(3) = 90.47, p=<0.0001, n = 61,703
Kruskal-Wallis, chisq(3) = 28.41, p=<0.0001, n = 31,478

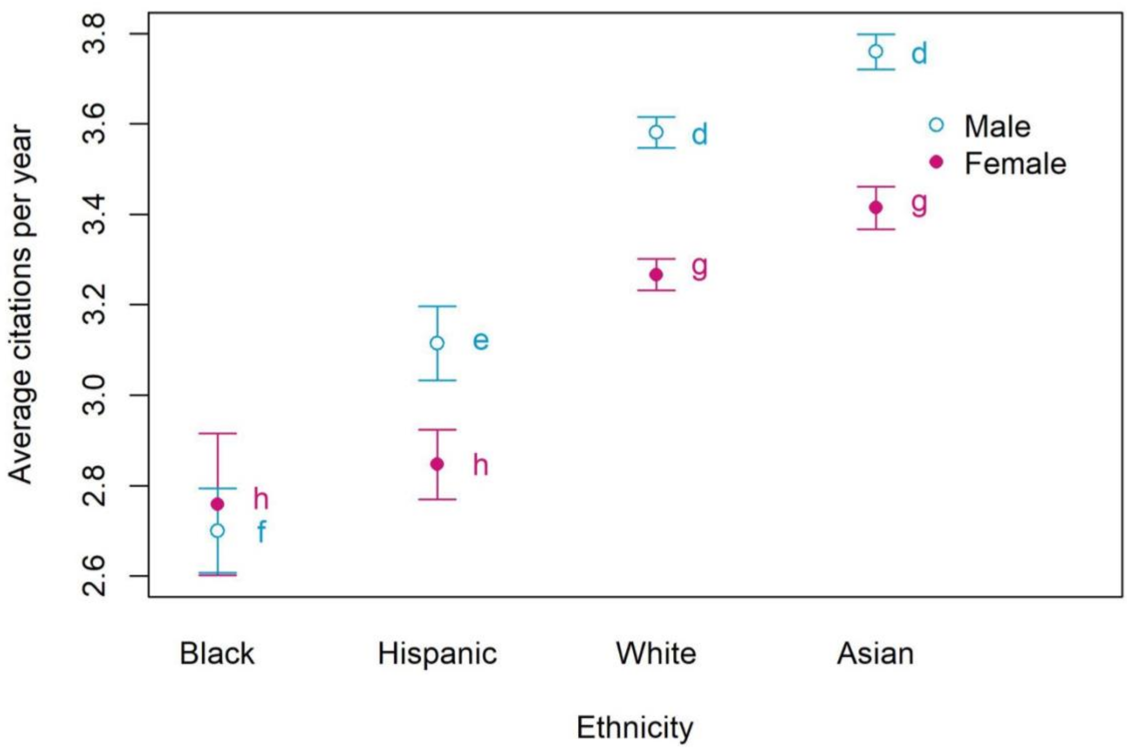

Figure 3.7: Mean of average annual citations rates by gender and ethnicity intersection of first and sole authors. The whiskers represent mean +/-1 standard error, with NA values removed. The letter designations represent the significant difference resulting from

post-hoc multiple pairwise comparisons by data ranks. This figure reflects the average citation rate of 91,181 articles authored by 1,591 “Black” males, 544 “Black” females, 3,304 “Hispanic” males, 2,204 “Hispanic” females, 32,898 “White” males, 18,122 “White” females, 23,910 “Asian” males, and 10,608 “Asian” females as first or sole authors.

3.5 Discussion

3.5.1 Gender disparity

Our findings support earlier studies indicating an ongoing underrepresentation of women in science and as publishing authors. While no previous study has been done specifically on women representation in land use science, these results are in line with findings from other science disciplines like ecology (Maas et al. 2021), soil science (Vaughan et al. 2019) and archaeology (Tushingham et al. 2017). Similar trends were also observed in the British ecology journals (Schucan Bird 2011), and in journals listed in Nature Index (Bendels et al. 2018) and JSTOR corpus (West et al. 2013). Despite a persistent gender gap in terms of journal articles published by men and women, our findings show that the gender gap is closing at a very slow rate of 1.2% annually. This relatively slow increase was also noted for top publishing ecologists by Maas et al. (2021), who found that the number of women had increased from 3% (1945 to 1959) to 13% (1990 to 2004) and 18% (2005 to 2019). There is a knowledge gap when comparing the total female population in academia to the total female publishing population within academia. While that is the case, studies like Fuchs et al. (1998) show us that the total female population in academia is increasing over the years. However, the increase found by other researchers and in this study pales in comparison to the global share of the female population (~47% in 2020) (UN DESA 2019). From the results of this study, we cannot determine any causal relationship, why women are underrepresented among land use scientists. However, the low publication share by women could be attributed to the fact that women submit fewer papers than men (Fisher et al. 2020) or that men have a double chance of being invited by journals to submit papers (Holman et al. 2018). In contrast, Lerback and Hanson (2017) observed that journals of American Geophysical Union accepted papers with women as first authors at a higher rate than their counterparts and a similar observation was made when disaggregated by age of the first author.

Other studies have found that the lower representation of women among authors might be a consequence of women being more likely to leave academic careers due to persistent traditional gender roles (Ledin et al. 2007; van Arensbergen et al. 2012; Holman et al. 2018; Abramo et al. 2021; Shamseer et al. 2021), in particular, in many African societies or since women are more likely to get caught up in intermediate employment levels like administrative and or teaching commitments (Sheltzer and Smith 2014). However, this effect is also noticeable in other parts of the world including Europe and the US, where women are more likely to reduce time devoted for research under increasingly challenging situations such as the COVID-19 pandemic (Vincent-Lamarre et al. 2020; Viglione 2020; Squazzoni et al. 2020).

Authorship position relates to seniority and establishment of the author (Wren et al. 2007). Although the gap between male and female first authorships is closing, the rate is very slow with only 1.8% per year. This gap is even bigger for the last authorship position or those publications with single author. This implies that the share of female graduates, PhD students, postdocs, and early career scientists in land use science, who in many instances make up the first authors, is increasing with time. However, the low number of women as last authors also indicates a leaky pipeline in the female's progressive science career. The same was also observed by Larivière et al. (2013) and West et al. (2013) where the number of women as last authors even decreased over time. Women likely abandon academia upon completion of graduate or postdoctoral training which is likely related to biological constraints when it comes to childbearing at a higher age and a tendency of women to take over a bigger share of care-taking tasks (Fisher et al. 2020). Of the 6.9% of the single-authored articles that we found, the share of men as authors was higher than that of women. This gap between men and women single authors is closing, however, its presently still wide. We argue that women publishing comparatively less than their male counterparts could signify (1) their inability to take up responsibilities for leadership roles in science and (2) it could indicate that they are challenging the dominant styles and pressures of publishing single-authored articles by preferring collaborative science as evidenced by the high numbers of articles authored by two or more (93.1%) authors (Schucan Bird 2011). However, Fox (2001) found that women were likely not to collaborate in author teams because they feel uncomfortable contributing and speaking in group meetings and within departments, they are less likely to be respected or taken seriously than men. Notwithstanding, Wren et al. (2007) observed an increasing trend of the number of authors per journal article in 2006 in comparison to a conservatively more single–authored era from 1966 to 1996, which could explain the high number of women as middle authors as well as the average number of authors per study. The increasing numbers of women as middle authors but not as last authors might also indicate women's reluctance to take on senior positions and a tendency to execute rather supporting roles in science (Vaughan et al. 2019). Moreover, it could signify the existing structural bottlenecks, e.g., conscious and unconscious discrimination of women. Whatever the reasons might be, we are convinced that the low number of women as last and sole authors indicates their underrepresentation especially in leadership positions (Maas et al. 2021).

Similarly, the average citation of journal articles that are authored by women either as first or as sole authors is significantly lower than that of men. Similar results in sole authored papers were observed by Larivière et al. (2013), where the average relative citation of female authors was <1. Furthermore, average citations of papers with female authors as first or last authors disaggregated by collaboration level (national or international) were also cited less than those with male authors (Larivière et al. 2013; Bendels et al. 2018). These results might indicate that women shy away from self-promotion of their work unlike men, a general lower level of acceptance of studies authored by women or their preference for other forms of publications like in grey literature (Tushingham et al. 2017). We would argue that this might also be a result of a lower share of publications in high-ranking journals. Bendels et al. (2018) found that out of 54 journals only 5 had equal chances for women being able to secure authorships while men had higher odds to be last authors in all journals. Furthermore, a presence of old-boy networks and subsequent citation behavior could explain the underrepresentation of women (Massen et al. 2017).

3.5.2 Ethnic disparity

Our findings show that the share of “Asian” authors is increasing more significantly over time compared to other ethnic groups, while the share of contributions from “White” authors is decreasing. From our data, we cannot derive reasons for this phenomenon. We would however, argue that population increase coupled with increasing investments in education, research and development in many Asian countries could be potential drivers of the seen trend. For instance, according to UNESCO data on research and development (UNESCO 2021), there is a general increase in expenditure on research and development in (in descending order) North America, Asia (Eastern), Oceania and Europe, with all of them being above 1.5% gross expenditure of their GDP. The share of “White” authors is observed to decline (Figure 3.3), which we attribute to the increasing numbers of other ethnicities, in particular, “Asian” authors. Based on a survey of the publishing authors, Hopkins et al. (2013) found that “White” authors represented 81%, “Asian” 10%, “Hispanic” 5% and “Black” <1%. Our results indicate that “White” authors dominated land use science up to 2018 and since then, the share of “Asian” authors started increasing with a proportion of 47.3% versus 44.9% of “White” authors in 2019. Regardless of the change in proportion of “White” authors, they are still more likely to head research teams and are likely to be cited more than other ethnic groups. Hofstra et al. (2020) working in US found that contribution from minority groups (majorly non-white) despite being novel and innovative, was less likely to be acknowledged. Shares of “Hispanic” and “Black” authors have consistently remained very low regardless of increasing population in continents where these ethnic groups represent the population majority. For example, the population in Africa reached 1.3 billion in 2019 and is projected to increase up to 1.6 billion by 2030, a growth rate of almost 30% (UN DESA 2019). Despite their significant share in the world population of 16.9% in 2019 (UN DESA 2019), in particular, “Black” authors continue to be underrepresented in scientific studies focusing on land use. Although we might underestimate the share of authorships of “Hispanic” and “Black” scientists by excluding journal articles published in languages like Spanish and French, which are predominantly spoken in several countries of the Global South, we are convinced that their viewpoints are often underrepresented in author teams.

The increasing population size in many countries in Latin America, Africa and Asia coupled with accelerating pressures from global change and increasing resource demands from countries of the global North will continue to amplify existing land use pressures and conflicts. At the same time, research and development expenditure in the Global South continues to remain below 1% of the GDP for gross expenditures on research and development in Latin America, Africa, and Asia (Central). This, under allocation of budgetary resources, increases dependency on research funding through projects sponsored by scientists from the global north, which in most cases turns into a “helicopter research” (Minasny and Fiantis 2018; Pettorelli et al. 2021). Published outputs of such funded projects are done by scientists of the global north either taking first, last or both author positions (Nuñez et al. 2019; Hazlett et al. 2020). Subsequently, complains from global south scientists show that their involvement in the research activities are reduced to logistical roles and where their input is considered in the journal articles, they do not take the first positions (Minasny and Fiantis 2018). Such opportunistic collaboration can foster mistrust, resentment, inadequate research approaches leading to misinterpretation of research outputs (Pettorelli et al. 2021) and compromising management of land, land use and systems in places that would benefit the most. Whilst the investing in research in the global south by the global north scientists is not necessarily problematic per se (Hulme 2011; Mammides et al. 2016; Nuñez et al. 2019), there is an urgent need to increase the ethnic diversity in land use science not only a matter of political correctness but also as a way to integrate different viewpoints, norms and values, which might not be as well captured by researchers from the Global North but highly relevant for the development of sustainable land use practices.

3.5.3 Intersection of gender and ethnicity

In our study, we found a gap between the proportion of female publishing authors in all ethnicities. This is an indication of an enduring worldwide underrepresentation of female scientists, irrespective of their ethnic groups. However, while the gap is slowly closing in “Hispanic”, “White” and “Asian” ethnicities, there seems to be no change in gender equality among “Black” authors (Figure 3.4). These results are in line with findings by Nelson and Rogers (2003) on diversity in doctoral studies of science and engineering, who found a gap between female and male students in all classified ethnicities, which was more pronounced for “Black” authors and doctoral students. In terms of author positions, first, last, and sole authorship positions are also more likely to be taken by “White” female authors, followed by “Asian” female authors. “Black” women’s representation in either position is low and slightly higher in sole authorship positions relative to other positions.

These results show that in particular “Black” women are underrepresented in the scientific land use community. One reason might be that they are consciously choosing other fields or altogether other career paths (Archer et al. 2015; Riegle-Crumb et al. 2019). Riegle-Crumb et al. (2019) showed that the rate of black students switching or leaving STEM field was 19% higher than for white students, instigated by social classes, persistent stereotypes of presumption of inferiority in STEM majors and possibly their alignment of success to giving back to community in which they consider non-STEM majors like business and humanities to be more compatible with. Coming back to land use science, “Black” women are likely to be engaged in roles that give them more satisfaction in the posit of value for community/society. These roles may range from supervision and mentoring of students to field data collection.

When gender and ethnicity intersect, our findings reveal severe underrepresentation by share of female authors, position of the author and citation of “Hispanic” and “Black” women in land science. The underrepresentation continues to persist in the 21st century. Hofstra et al.

(2020) working with longitudinal data of 38 years found that science produced by gender and ethnic minority groups is highly likely to be devalued and consequently accrue lower citations, which might explain the low share of female senior authorship positions. In addition, Archer et al. (2015) found that the aspirations of “Black” women in science are shaped by the intersection of these inequalities and when social class is included their science aspirations are further lessened.

Furthermore, the intersection of these inequalities limits the diversity not only of leadership but of innovations that are necessary in addressing the SDGs. These inequalities elicit concerns in the context of an increasing population, accelerating land use pressures from domestic and non-domestic land use needs, and the eminent risk for biodiversity rich areas in the Global South (Leclère et al. 2020). Inclusion of gender and ethnic minorities would highly benefit land use systems and the importance of a diverse research community could not be any greater at this point.

3.5.4 Limitations

The conclusions of this study are limited in different ways. One bias might be due to the potential of the used gender and ethnicity assessment tools of introducing biases (see Methods), which might lead to an over- or under-representation of certain groups. However, as error margins are relatively low (between 2%-5% according to Teele and Thelen (2017) and Santamaría and Mihaljević (2018)), we would argue that the results are still valid and robust.

Another bias of our study might be the result of including English articles exclusively. While other languages are certainly the exception rather than the rule and even most articles written in other languages provide English abstracts, this limitation has the potential to cause a certain bias. In particular in Latin America, many authors publish in Spanish journals, which we did not consider in this study. At the same time, this might also be the case for a certain share of articles being published in Chinese, French or German journals and we would argue that this bias is likely to be more or less consistent across all ethnic groups. We also only included journal articles and excluded all other forms of publications such as book chapters, reports, conference proceedings, among others. While we do not want to deprive these publications of their scientific merit, we chose to focus on peer-reviewed journal articles to assure a certain scientific standard and since a comprehensive inclusion of other publication formats would have required the coverage of other databases such as Google Scholar, which has a much better coverage of grey literature and other formats, but was outside of the scope of this study.

For academic hierarchy and application of research grants, scholarly productivity in terms of peer reviewed journal articles and its attributes plays a key role. While we are aware of other metrics like the use of new format curriculum vitae inspired by the San Francisco Declaration of Research Assessment (DORA) (Hatch and Curry 2020), we focused on authorship positions and citations as attributes of scholarly productivity. Academic careers are driven by a more diverse set of activities than publishing. In such, women may not be as productive in terms of publications as their male counterparts, as evidenced by the results, yet contribute significantly to the scientific debate e.g., through public outreach or supervision of students. In addition, the found gender imbalance in authorship positions may be influenced by some publications following the approach of some studies listing authors in alphabetical order instead of their contributions.

3.6 Conclusions and implications

Our analysis indicates that women are underrepresented in land use science as other authors have found for different scientific disciplines. While we found a positive trend in terms of a closing gender gap over time, we argue that it comes at a very slow pace. Ethnicity, similar to gender, plays a key role in land use science, and “Black” and “Hispanic” authors remain marginalized in this discipline. Intersection of gender and ethnicity marginalizes, in particular, “Hispanic” and “Black” women as publishing authors, as senior authors and in terms of citation rates. “White” men continue to dominate land use science. Disregarding diverse viewpoints from women of all ethnicities in land use science will diminish our chances to reach the SDGs and to manage land sustainably in the future.

So, what can be done to level the playfield? Supportive actions to empower women are needed to further reduce the gap between men and women as well as between different ethnic groups in scholarly output. Such actions might include an active encouragement and support of scientists from minority groups to write and submit papers to journals. To encourage more submissions, journals should also have favorable terms, for example, Mammides et al. (2016) found a general significant lower rate of acceptance of manuscripts of authors from non-high income countries in comparison to authors of higher income countries in both high and low impact factor conservation journals. Most importantly, efforts should target the sealing of the leaks in the pipeline of academic careers through provisioning of better working conditions for women. The establishment of women’s quota in senior academic positions, the financial and organizational support of male and female researchers during parental leave, mentoring programs for young female researchers or equal opportunities for grants are just a few examples of measures that would support women to continue their career in academic research. Moreover, a long-term solution would be to develop stronger institutional capacity for researchers in the global south to ultimately bridge the gap. Furthermore, stricter ethical considerations should be outlaid and adhered to especially where research collaboration between researchers of global south and north is happening to devoid it of parachute research while also increasing the visibility of global south researchers. Furthermore, it is necessary to support careers of female researchers from the Global South to reduce systemic stereotypes and discrimination of “Black” and “Hispanic” female scientists. Predominantly patriarchal societies are more pronounced in many countries of the Global South, but can also still be found in the Global North. Overcoming patterns of systemic discrimination will be much more likely if there is an active process of creating and supporting role models and future female land use research champions for future generations.

4. Nearly half of the world is suitable for diversified farming systems for sustainable intensification

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4.1 Abstract

Sustainable intensification, defined as increasing production per unit without harming the environment, has potential to transform agricultural systems. While questions persist about which practices and conditions lead to sustainable intensification, diversification has gained prominence as a proposed solution. Here we apply niche modelling using maximum entropy modelling approach to predict the global spatial distribution of profitable diversified farming systems under different socio-economic conditions. We found about 47% of the world is suitable for profitable diversified systems with a larger area in the global North. When we combined our findings with knowledge about biophysical potential for cropland expansion and intensification, we found that different areas could benefit from diversification to achieve sustainable intensification through cropland expansion (e.g., Europe), intensification (e.g., sub-tropics and tropics), or both (e.g., West Africa). With these results, we provide insights in which way diversification can support sustainable intensification and contribute to the debate on land sharing vs sparing.

Keywords: MaxEnt; intensification; suitability; simplified farming; financial profitability; agricultural transformation

4.2 Introduction

Current agricultural systems are not well designed to meet food demands and conserve biodiversity at the same time. While predominant agricultural practices are often vulnerable to multiple risks, including climate change and market shocks, they are also drivers of land degradation (Mulinge et al. 2016), biodiversity loss (Potts et al. 2010; Rhodes 2018), poor household diets (Snapp 2020) greenhouse gas emissions (Ramankutty et al. 2018), and limited long term sustainability (Crowder and Reganold 2015). As the demand for agricultural commodities is expected to increase tremendously (35-56 % between 2010-2050) (Van Dijk et al. 2021), pressure is increasing to either further intensify farming systems or to expand cropland. While these events might increase food production, they will also lead to further biodiversity loss and higher vulnerability of poor and marginalized communities (Ramankutty et al. 2018).

The abundance of scientific evidence pointing out the unsustainability of agricultural practices has led to a growing demand for a system transformation of agriculture by policy makers, NGOs, and governmental bodies. However, the exact nature and structure of this transformation remains a subject of highly controversial debates. It has been argued that agricultural intensification can increase food production thereby limiting the need to increase agricultural area. At the same time, agricultural intensification might lead to reduced levels of biodiversity on the field e.g., due to heavy use of pesticides. Agricultural extensification might improve biodiversity by providing suitable conditions and space for diverse habitats and ecosystems, which in turn can attract a wider range of plant and animal species. At the same time, extensification may also trigger additional deforestation and biodiversity loss through agricultural expansion. In the conservation community, this dilemma has been discussed in the context of the land-sharing vs. land sparing debate, with one side arguing for further intensification to save as much land as possible from conversion to agricultural land and the other side supporting extensification to conserve on-farm biodiversity (Van Grinsven et al. 2015; Isbell et al. 2017; Humann-Guilleminot et al. 2023). However, intensification is faced by criticism and concerns of whether spared land is put under conservation (Matson and Vitousek 2006) and extensification might not be as beneficial to farm biodiversity conservation if it contributes to deforestation (Van Zanten et al. 2016)) or mainly benefits generalists (Bateman and Balmford 2023). Other scholars have argued that there is an optimal window of sustainable intensification (SI), where tradeoffs between both approaches are minimized (Kremen 2015). Yet, although many different approaches for SI have been suggested, it remains unclear how agricultural practices would have to change under a system of SI and how this would depend on local context variables. In some areas SI most likely would require extensification as agricultural practices are already highly intensified to a degree which can be considered unsustainable while in other regions SI would require intensification as the major sustainability challenge is increasing natural habitat conversion (Pretty and Bharucha 2014; Angelo and Du Plesis 2017). As such, SI is not homogenous but rather highly context specific. In this study we borrow the definition by van Grinsven et al. (2015) on "sustainable intensification as increasing food production per unit hectare without compromising the environment and degrading natural resources and sustainable extensification as decreasing the depletion of natural resources and environmental impacts while limiting the decrease of food production per unit hectare".

In this study we argue that diversified farming systems (DFS) are a key element of SI as they can support both intensification as well as extensification, in different contexts and under different socioeconomic conditions. They have the potential to improve ecosystem services, processes, and functions (Kremen et al. 2012), including pest and disease control, water quality regulation and mitigation of ground water depletion by up to 19%, weed control, soil health improvement by increasing soil carbon content, pollination, and carbon sequestration and mitigation (Burney et al. 2010; Liu et al. 2016; Rosa-Schleich et al. 2019; Tamburini et al. 2020; Beillouin et al. 2021; Jones et al. 2021; Yang et al. 2021). At the same time, increasing diversity on farms has also been found to provide co-benefits in yield, yield quality and system resilience and stability as in accordance with ecological theory (Tilman et al. 2011; Isbell et al. 2017; Finn et al. 2018).

Management practices in diversified farming systems including crop rotation, agroforestry, inter cropping, embedding natural habitats (e.g., vegetation strips, hedgerows), and mixed crop and livestock farming can be used to shift farming systems towards a state of SI. In extensively managed systems, often characterized by low input agrochemicals, and high diversity croplands with low yields, crop production could be intensified through rotating mixed crops, increasing cropping density in mixed plantings, vegetation strips or through agroforestry systems. Intensively managed systems on the other hand, often signified by large tracts of monocultures managed with high agrochemicals (Liu et al. 2013a; Hendrickson 2015; Kopittke et al. 2019), could be diversified through mixed plantings, agroforestry systems including diversified home gardens (Duguma et al. 2019), boundary planting that involves use of hedgerows or tree breaks (Kremen 2020; San et al. 2023), embedding natural habitats e.g., vegetation strips (Kremen 2020), and diversifying landscapes surrounding croplands (Isbell et al. 2017).

In theory and in practice, there is increasing context dependent evidence about the benefits of DFS on food production by over 10% (Beillouin et al. 2021; Zhao et al. 2022), above 20% change in economic output (Himmelstein et al. 2016; Sánchez et al. 2022), reduce ground water depletion by 19% (Yang et al. 2021; Wang et al. 2023), carbon mitigation by 11% (Tamburini et al. 2020), and biodiversity conservation by over 20% (Bowman and Zilberman 2013; Mauser et al. 2015; Himmelstein et al. 2016; Rosa-Schleich et al. 2019; Tamburini et al. 2020; Beillouin et al. 2021; Jones et al. 2021; Zhao et al. 2022). Yet, DFS has also been criticized for producing lower yields and profits in comparison to simplified farming systems (Ponisio et al. 2015; Himmelstein et al. 2016) even though the yields are often of high quality and fetch higher prices in stratified markets (Asioli et al. 2020). This profitability, however, seems to be highly variable and little is known under which circumstances diversification is likely to improve profitability. Furthermore, it is unclear if DFS might trigger a shift towards extensification or intensification in order to reach SI. Although studies have shown cropland suitability distribution combining information on climate, edaphic, and crop specific requirements at different spatial scales (Teka and Haftu 2012; Zabel et al. 2014), little is known about the suitability of diversified farming systems and their profitability for farmers influenced by factors such as access to markets and infrastructure (Bowman and Zilberman 2013).

As there is evidence that farmers and other practitioners of agriculture (e.g., funders, donors) are making land use decisions based on the expected profitability (Clough et al. 2016; Michler et al. 2019), we predicted suitable locations for profitable DFS globally based on maximum entropy distribution modelling MaxEnt. Although, this methodology was originally developed for predicting species distributions based on species presence data and in combination with environmental predictors, we apply the method based on locations of profitable DFS in combination with socio-economic predictors. We use the term prediction in this study to refer to evaluation of grid-by-grid suitability based on a set of socio-economic constraints and identification of other areas with similar conditions. With our results, we contribute to the knowledge about factors influencing the distribution of the suitability of DFS, which is crucial for effective policies supporting diversified farming and agricultural system transformation. Moreover, we discuss the concept of diversification as a means to sustainable intensification in the context of land sharing and land sparing debate.

We found that suitable land for profitable diversification ranged from 29 to 93 million km^2 and locations in the global north are highly suitable and only areas in the global south with proximity to major towns/cities are profitable. About 20% (29 km^2) of the world has the highest suitability for profitable diversified farming systems and about 53% is not suitable. When we combined the map about the spatial distribution of profitable DFS sites with knowledge about the biophysical for expansion and intensification potential, to highlight areas that could benefit from DFS as a means of achieving SI, we found that areas in South America and Sub-Sahara are suitable for both profitable DFS and intensification, while in North America and Europe those areas were suitable for extensification.

4.3 Methods

4.3.1 Data collection

Occurrence data*:* Data on profitability of DFS were obtained from a meta-analysis by Sánchez et al. (2022; 2022). This meta-analysis summarized scientific findings about the profitability of DFS and simplified farming systems based on 119 peer-reviewed publications yielding 3192 comparisons of intervention versus control practices. Diversified farming practices included in the meta-analysis were crop rotation, intercropping, associated plants, combined practices, agroforestry and embedded natural systems while simplified farming practices included monoculture, and practices that when compared with diversified practices had comparatively lower number of varieties or species e.g., a crop rotation with a single crop compared with crop rotation in tandem with intercropping or with multiple crops, or simple agroforestry with a single tree species compared to a multi-strata agroforestry (Sánchez et al. 2022). Effect sizes based on the comparisons of profitability of diversified and simplified farming practices were summarized in the dataset by information on the study location and experiment design including treatment, methods, and measured indicators. Effect sizes were calculated as log response ratios for gross income, total costs, and benefit cost ratio and Standard Mean Difference (SDM) for gross margin and net incomes (Supplementary Figure 8.1).

We classified all positive effect sizes as profitable and negative as unprofitable DFS. We used presence locations of profitable DFS to model DFS suitability and excluded duplicated presence locations (some comparisons were from the same study area). We combined the remaining 114 presence and 93 absence records, with different predictor variables to model suitability of profitable DFS (Supplementary Figure 8.1).

Predictor variables: Different variables influence profitability of diversified farming practices at different scales including farm, country, region, and global scale. In this study, we use 14 variables (Supplementary Table 2), to predict the suitability of profitable DFS, which we selected based on past published literature (See supplementary Note 1). These variables included environmental (cropland area and soil organic carbon), social (population size and density), economic (electricity coverage, time taken to travel to nearest urban center, and Information and Communication Technology (ICT) coverage, human development index, and Gross Domestic Product), and political and governance factors (voice and accountability, rule of law, absence of political violence, government effectiveness, and regulatory quality). We rasterized and resampled all data to a spatial resolution of 2.5 arc minutes, the same projection, and the same geographic extent.

We excluded highly correlated variables (Pearson correlation coefficients > 0.8), which have been shown to affect the quality of the models and increase uncertainties in prediction (Feng et al. 2019), and used eight uncorrelated variables for modelling purposes (Supplementary Table 8.3, Supplementary Figure 8.2).

4.4 Modeling approach

We used a maximum entropy (MaxEnt) modeling approach to assess the spatial distribution of socio-economic suitability for profitable DFS. MaxEnt belongs to the family of machine learning approaches and builds models by evaluating the suitability of each grid cell to predict the species occurrence potential or probability as a function of a set constraints (Phillips et al. 2006). MaxEnt has been applied mainly to predict species richness, spread of invasive species, hotspots for endemism and impacts of climate change on species distribution (Franklin 2010) but increasingly, it is also used for other purposes e.g., to predict the distribution of fishing activities (Geronimo et al. 2018), renewable energy sites (Tekin et al. 2021), and cultural ecosystems (Arslan and Örücü 2021).

MaxEnt models suitability based on presence records (e.g., coordinates of profitable DFS) and a set of spatially explicit data representing constraints in the form of environmental or socioeconomic variables. Unlike other distribution models, which often require presence and absence records, MaxEnt is a presence only model. While our original data on profitability included absence records (those locations where diversified farming was not profitable under certain conditions), we did not consider them as true absences. This is because many studies included metadata analysis by Sánchez et al.(2022) found that profitability differed with crop choice and farm management conditions indicating that DFS might be profitable after all in the same locations under different assumptions.

Model creation, calibration, and evaluation: We used the `kuenm` package (Cobos et al. 2019) in R (R Core Team 2022) to develop, calibrate and select the best performing MaxEnt model. To this end, we created 155 candidate models through a combination of 8 variables, 5 regularization multipliers (0.5, 1, 2, 3, and 4) and 31 combinations of all feature classes (linear, quadratic, product, threshold, and hinge). Selection of the best model was based on 3 requirements, i.e., 1) statistical significance evaluated based on partial Receiver Operating Characteristic (ROC) with 500 iterations and 50 % of the data for bootstrapping, 2) predictive power indicated by the omission rate and an omission error rate ≤ 5%, and 3) model complexity calculated as maximum delta Akaike Information Criterion (AIC) ≤ 2. Models that met these criteria were remodeled using ten-fold cross validation. Based on the Area Under the Curve (AUC), we evaluated the models' goodness of fit.

We selected the model with the least omission rate to create binary (presence/absence) maps. Where omission rates of two models were the same, we chose the one with the least delta AIC, and if delta AIC was the same, we selected the model with the least feature classes (simple model). We used 4 suitability thresholds to create binary maps i.e., maximum training sensitivity plus specificity (mtss), balanced training omission (bto), equal training sensitivity and specificity (etss), and 10 percentile training presence (ptp). Through the selection of multiple thresholds and their comparisons, we were able to account for uncertainties inherent to modelling approaches with imperfect data.

We used MaxEnt output format cloglog (complementary log-log transformation), which ranges from 0 to 1 and argued to be a better predictor of the probability of presence than the logarithmic transformation commonly used before the cloglog option (Phillips 2017). Based on jackknife results of the initial model, we selected predictor variables (Supplementary Figure 8.3) using the top 5 predictor variables of the permutation importance estimate. These variables were accessibility, cropland area, voice and accountability, nighttime lights, and GDP per capita (Supplementary Table 8.2). Model development, calibration, evaluation, and creation of binary suitability maps were performed using the same procedure, regularization multipliers and feature classes as the initial model.

4.4.1 Towards sustainable intensification

Data on the integrated potential for cropland expansion and intensification were obtained from Zabel et al. (2019), who examined tradeoffs between agricultural impacts brought about by cropland expansion and intensification in the future and biodiversity. The authors in Zabel et al. (2019) combined information on biophysical with socio-economic conditions expected by 2030. In the case of cropland expansion potential, they included the aggregated biophysical potential of 17 crops and the land theoretically available for expansion. For intensification, the potential was derived based on the potential simulated yield of 17 crops under ideal conditions and validated on field trials. Comparing the potential yield against the statistical yield, the authors assessed the biophysical intensification ratio, which was then combined with marginal profitability of crops. The marginal profitability was predicted by reallocating crops iteratively while changing some dynamics like climate change, change in consumption patterns among others to achieve a stable allocation. Hence, in this study Zabel et al. (2019) data on a) integrated potential for cropland expansion (Supplementary Figure 8.4) and b) integrated potential for intensification (Supplementary Figure 8.5) were used to show areas where DFS could contribute to either extensification or intensification as a way to achieve SI. We created bivariate maps combining each of these two maps from Zabel et al. (2019) with the suitability map of profitable DFS that we created. These bivariate maps were created on R programming language (R Core Team 2022) using package `classInt` (Bivand et al. 2022).

4.5 Results

4.5.1 Model parameters and evaluation

From the initial 155 models we ran with different settings (combined 8 variables, 5 regularization multipliers and 31 feature class combinations), only one model satisfied all selection requirements except the omission rate, which was slightly above the acceptable level (Supplementary Table 8.4). Nevertheless, the model was comprised of simple feature classes (lq) and had a good predictive ability (AUC= 0.878). A rerun of the model using only the 5 most relevant predictors (31 feature classes and 5 regularization multipliers) led to a reduced omission rate of 0 and satisfied all selection criteria (Supplementary Table 8.4). Model features included classes of linear, quadratic, product, and hinge (lqpt).

4.5.2 Habitat suitability under current socio-economic conditions

We found high suitability of profitable DFS across the globe with higher coverage in North America, Europe, and South and East Asia. High suitability in the Global South was in particular around cities and along the coastline. This was also the case when we applied different thresholds (Supplementary Table 8.5, Supplementary Figure 8.6) to the aggregated suitability map (Figure 4.1). In terms of size, when we applied different thresholds (Supplementary Figure 8.6), we found that suitable areas ranged from 29 to 93 million km^2 (Supplementary Table 8.6) with the highest share taking balanced training omission rate as a threshold value for, predicted suitable area. When we combined the thresholds (Figure 4.1), we found that areas with high suitability accounted for 19.56% (Supplementary Table 8.7).

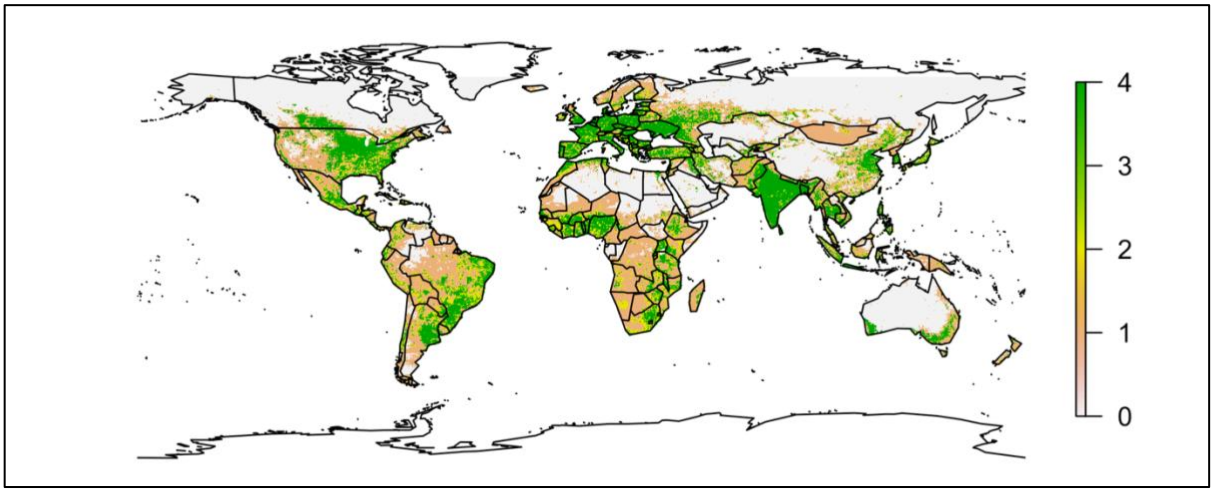

Figure 4.1: Suitability of profitable diversified farming systems. Number of models predicting high suitability of profitable diversified farming systems based on four different thresholds to distinguish high from low suitability including balanced training omission, maximum sensitivity plus specificity, equal training sensitivity and specificity and 10 percentile training presence thresholds. Models included 5 predictors variables, which were selected based on their permutation importance (Supplementary Table 8.8).

4.5.3 Socio-economic variable importance and their impact

Accessibility indicated by the distance to the nearest city, urban center, and market and cropland availability were the two most important variables driving profitability of DFS (Supplementary Table 8). Overall, we found that infrastructural variables (e.g., accessibility, electricity coverage, cell tower distance) together with land allocated for cultivation play a key role in the profit- ability of diversified farming systems. GDP per capita was not as relevant for the distribution for profitable diversified farming systems (4.8, 9.5). We predicted higher suitability for profitable DFS in areas with higher accessibility, closer to the urban centers, high electricity coverage (nighttime lights over 60 nW cm−2 sr−1, and higher values for governance and accountability (Supplementary Figure 8.7 and Supplementary Figure 8.8). We found high and increasing probability in areas with 30–60% of land being allocated to agriculture. Higher levels of agricultural area than 60% led to a small decrease in suitability. While we found that accountability, transparency, and openness of government measured by the index on voice was positively correlated with the suitability of profitable DFS, GDP per capita was negatively correlated. Above USD 60,000 of GDP per capita, the probability of suitability for profitable diversified farming systems was <60%.

4.5.4 Suitable areas for extensification and intensification

Areas with high levels of profitable DFS suitability and biophysical potential for cropland intensification can be found in sub-Saharan Africa, along the east coast of Brazil, parts of India and Tajikistan, Australia, and Canada (Figure 4.2). At the same time, we found, high suitability of diversified farming systems coinciding with high cropland expansion potential in western Europe, India, China, and some parts of Brazil and eastern Europe (Figure 4.3). Regions with pockets of land that is suitable for intensification and cropland expansion while also being suitable for high DFS probability include West Africa near the coast of Atlantic Ocean and parts stretching from eastern Africa to southern Africa.

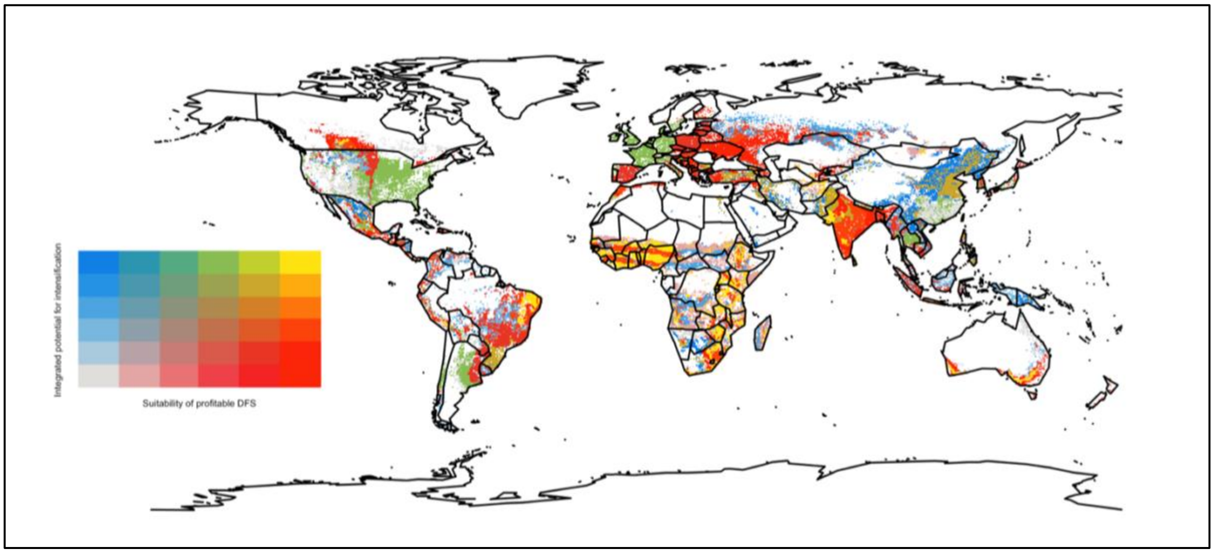

Figure 4.2: Suitable areas for intensification of profitable diversified farming systems. Bivariate map of integrated potential for intensification and profitability of diversified farming systems. Yellow indicates high potential for both profitable diversification and potential for intensification while grey indicates less of both. Blue indicates high potential for intensification and low suitability for profitable diversification while red, indicates high suitability for profitable diversification and low potential for intensification.

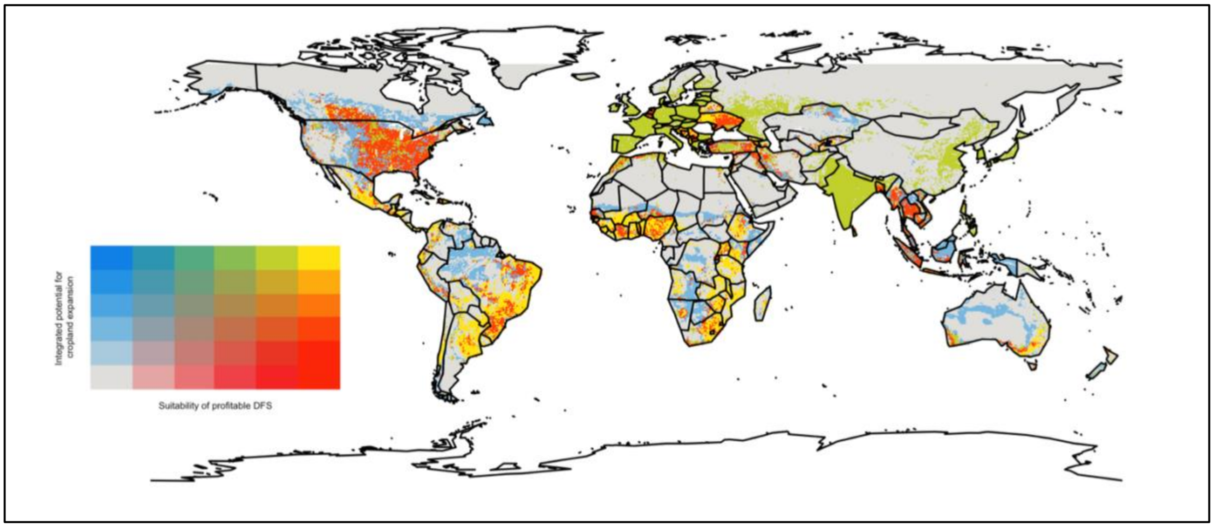

Figure 4.3: Suitable areas for cropland expansion and profitable diversified farming systems. Bivariate map of integrated potential for cropland expansion and suitability of profitable diversified farming systems. Yellow indicates high potential for both profitable diversification and potential for cropland expansion while grey indicates less of both. Blue indicates high potential for cropland expansion and low suitability for profitable diversification while red, indicates high suitability for profitable diversification and low potential for cropland expansion.

4.6 Discussion

We predicted the potential suitable habitat for profitable diversified farming systems using a set of socio-economic variables and known occurrences of profitable diversified farming systems. To our knowledge, no study has attempted to investigate spatial distribution of profitable diversified farming systems at either country, continent, or global levels nor integrated knowledge about suitability for diversification with potential for intensification and cropland expansion.

There is an increasing need for sustainable agricultural production that can satisfy the global demand for food, feed, and other agricultural products. Based on our analysis, we found that under current conditions the Global North is by tendency more suitable for profitable diversified farming systems compared to the Global South due to a well-developed infrastructure and established markets, offering premium prices for products from diversified farming systems e.g., with certificates like “sustainable” or “organic” (Li and Kallas 2021). In the Global south, we found that high suitability was by tendency higher within proximity to major cities supporting our assumption about the relevance of infrastructure for DFS profitability i.e., road connectivity, ICT, and electricity coverage to profitability. In addition, studies like Kumar et al. (2020), found that farmers are more likely to adopt new farming technologies when they are in proximity to urban centers or markets. Weiss et al. (2018) found that over 50% of the population in countries in sub-Saharan Africa live over one hour away from the city. Low infrastructure development in many countries in the Global South with limited ICT, and electricity coverage (~46% of the population was served by 2020 (Mukoro et al. 2022)) contributes to high costs of doing business, limited shelf life of produce and a lack of value addition (Bendinelli et al. 2020).

Our results are in line with these studies supporting the relevance of infrastructure for agricultural profitability, which has been found to be highly relevant by other studies. In line with other studies like Irungu et al. (2015) in Kenya, Jolex and Tufa (2022) in Malawi, we found that profitability of the agri-prenuers increased with the number of access to ICT tools. Similarly, our results indicate an important role of electricity coverage and market access in line with findings of other scholars (Warr 2010; Amador-Jimenez and Willis 2012; Bendinelli et al. 2020), who also support the relevancy of these variables for the profitability of farming systems, which are highly dependent on access to markets. In our study, voice and accountability increased suitability for profitable DFS. Some studies using the voice and transparency variable found a similar positive relationship between economic growth and governance in the global north (Zhuo et al. 2021) , while others found a negative correlation between voice and transparency and economic growth, e.g., (Samarasinghe 2018) in East Asia and Pacific regions. However, the latter study by Samarasinghe (2018) also found that control of corruption can result in an approximate positive change of up to 7% to economic growth. While other governance indicators like political stability, regulatory effectiveness, control of corruption, and governance effectiveness are likely to play an important role in economic growth and the profitability of diversified farming systems, we included only voice and accountability, as it was highly correlated to other variables. Overall, based on our findings we would argue that governance is important for profitable agriculture and most likely even more for diversified farming systems.

The differing results for the global north and south suggest that different strategies are likely to be necessary for the support of DFS and sustainable intensification. For example, suitability in the global north could be leveraged to increase extensification processes in many farms, which are currently heavily intensified. In the global south, on the other hand, effective policies for DFS would require efforts to increase the suitability of agricultural areas such as the development of new markets and transport routes of DFS products. As these measures might also trigger other negative feedback loops in terms of land use change, increasing land use prices, and opportunity costs for conservation, it should be carefully considered whether intensification actually compensates for these trade-offs.

In this study we modeled profitability of DFS based on socio-economic variables not considering other relevant factors including bioclimatic variables, land cover, crop choice and crop combination or adoption rates. Despite the relevance of these variables, we decided not to include them for different reasons. First of all, bioclimatic variables are crop specific and presence data used in this study considered a wide range of crop combinations as DFS. As different crops have different specific biophysical requirements, even though most of the major crops' requirements overlap, predicting the suitability of profitable DFS on a global scale would require separate models for different crop choices and combinations. Moreover, we combined our prediction with knowledge about the biophysical potential for cropland expansion and intensification thereby indirectly considering bioclimatic and land cover variables and their relevance for agricultural productivity. Specifically, the maps included crop requirements from FAO land evaluation hence spatially restricting regions that are suitable (Sys et al. 1993). In Zabel et al. (2019), the authors noted that land available for conversion was based on land cover classification and ultimately excluded classifications e.g., urbanized land that would not be available for conversion. Additionally, diversification may improve climate resilience outcomes through higher yields and improved yield stability compared to simplified farming systems (Vanino et al. 2022). Furthermore, diversification is likely to reduce emissions from farmland through soil organic carbon storage (Beillouin et al. 2023), the restoration of soil nutrients, atmospheric nitrogen fixation and improved availability of these nutrients to plants leading in turn to reduced leaching and mineralization losses (Isbell et al. 2017; Wang et al. 2023).

We found most areas with high DFS profitability in combination with high potential for intensification in Sub-Sahara Africa and South America. However, projection of crop expansion (10-25%) by 2050 are also mostly expected in these regions (Schmitz et al. 2014), threatening some of the most biodiverse areas in the world (Zabel et al. 2019; Leclère et al. 2020). In addition to this, these areas are often characterized by extensive production systems. Sustainable intensification on existing agricultural land could contribute to bridging the gap between current yields and production potential without converting additional natural habitats to agricultural land. This could be achieved for example through a better management of nutrients and water, which we find in many diversified farming systems including agroforestry, mixed planting on crop rotations, or combining livestock and crop production.

We found most areas with the highest cropland expansion potential while also having high suitability for profitable diversified farming mainly in Europe. Most agricultural areas in Europe are highly intensified in terms of nutrients, pesticides, and water use (Stoate et al. 2001). Intensification levels in many of these areas have led to a situation where agriculture is one of the key drivers of groundwater and surface water depletion and pollution (Pe'er et al. 2020). Biodiversity conservation in Europe is mainly in protected areas that are generally large in numbers (accounting for ~26% of the EU land according to the EU Biodiversity strategy) but are rather small in size (European Union 2020). Conservation in the agricultural landscapes is still limited within the member states of European union (European Court of Auditors 2020). To achieve the 30% EU biodiversity strategy target, it might be necessary to expand protected areas into agricultural lands thus promoting agricultural extensification. Beyond increasing cropland areas, other forms of extensifying agricultural production like mixed plantings, incorporating natural habitats e.g., vegetation and grass strips and hedgerows, and reducing the cropping density (e.g., number of harvests per year) (Wang et al. 2023) would play an important role in reaching SI levels. Cropland expansion might present a challenge due to the high demand for land for other uses including settlements, industries, and biodiversity conservation.

In line with Zabel et al. (2019), we found that areas suitable for cropland expansion are also often areas rich in biodiversity. Land use demand for cropland, in particular within these areas are likely to create conflicts. It would be extremely important to carefully balance these different needs on a smaller scale to assure additional land taken into production are not important biodiversity sites while maintaining high levels of on-farm biodiversity. A general reduction of demand for agricultural non-food products, e.g., for fodder or bioenergy, would be a key measure to generally reduce increasing pressure on and demand for agricultural land (Van Zanten et al. 2016). We would argue that a shift to more sustainable levels of intensification and increased levels of biodiversity on agricultural land without an unacceptable loss of yields or biodiversity can be achieved through a simultaneous introduction of DFS and, where possible, a significantly reduced demand for agricultural land.

Like other modeling approaches, estimating suitability in particular of DFS profitability are prone to uncertainties due to input data quality, complex system interactions and simplified assumptions. We also caution readers that issues of scale play a significant role in predicting DFS profitability and the results validity (Avellan et al. 2012). As we had to compromise between the availability and accuracy of data, we integrated data from different years and different original resolutions. As the results of our study depend on different variables used as predictors and, in the case of Zabel et al. (2019), to combine with our DFS suitability map, we have to acknowledge that compounding uncertainty from multiple sources is likely to impact our results for example in the case of China. To overcome these uncertainties, we applied strict statistical measures to confirm the robustness of our models and as suggested by other authors, captured levels of uncertainty by applying different thresholds to distinguish suitable from non-suitable areas for DFS rather than a single fixed value (Biber-Freudenberger et al. 2016).

Regardless of these uncertainties we emphasize that our findings are relevant for farmers, investors, land use planners and decision-makers aiming to utilize the potential of DFS for sustainable intensification. Many studies have found that both food production and conservation of biodiversity can be achieved concurrently by utilizing methods like diversification (Kremen et al. 2012; Isbell et al. 2017; Jones et al. 2021; Zhao et al. 2022). With this study we contribute to a better understanding of the conditions defining profitability of DFS and identify areas where diversification might be a viable option to simplified farming systems supporting SI in different ways. These findings are relevant for decision making, especially of farmers, agricultural investors, and land use planners, interested in investing, supporting, or adopting DFS. We conclude that DFS to achieve SI purges the framing of either-or of land sharing and sparing, reframing the narrative of agricultural transformation (Kremen 2015).

5. Evaluating land consolidation decisions in Kenya using Decision Analysis

This chapter has been submitted to *Land Use Policy* and is under review.

5.1 Abstract

In many parts of Sub-Saharan Africa, including Kenya, land fragmentation reduces agricultural productivity and heightens land use pressures. Land consolidation initiatives aim to address fragmentation by targeting smallholder farmers in agriculturally productive areas. However, without experience and data, farmers often lack an overview of uncertainties and risks when deciding whether to consolidate their land. We collaborated with stakeholders and applied Decision Analysis to smallholder farmers' choices regarding voluntary land consolidation in Kenya. We co-developed a decision model with stakeholders to evaluate the financial viability of land consolidation over a 25-year period through a Monte Carlo simulation. Results show a 28% probability of net profit, with maize and lease prices as key determinants. High maize prices favor maintaining current systems, while high lease prices encourage consolidation. Value of Information analysis highlights the need for better data on lease and maize prices to improve decision-making. The approach provides actionable insights for farmers and policymakers regarding land-use strategies under uncertain conditions.

Keywords: Land use; decision analysis; uncertainty; livelihoods; cost-benefit analysis; ex-ante evaluation

5.2 Introduction

Available arable land in Sub-Saharan Africa (SSA) is shrinking (Döös 2002) due to land use change driven by socioeconomic development and population growth (Döös 2002; Olsson et al. 2023). In Kenya, arable land per person has decreased by about 70% from 1962 to 2021 (World Bank 2024b). Rural households in Kenya own between 0.2 and 3 hectares of land (Deininger et al. 2017; Kamau et al. 2018a). With population growth and a lack of government policy on land subdivision, household landholdings are likely to decline due to inheritance customs (GoK 2021; Auya et al. 2022) that promote the subdivision of land among family members. Newly subdivided land often leads to a new type of land use, such as the construction of residential dwellings (Nation Media House 2020; Auya et al. 2022). Fragmentation and land use conversion reduce agricultural land to uneconomical sizes, compelling farmers to practice continuous cultivation for subsistence. Over time, this continuous cultivation often depletes soil nutrients due to crop residue removal, erosion, and leaching. The problem is coupled with farmers' limited access to manure or fertilizers (Tittonell et al. 2005; Wawire et al. 2021), ultimately leading to declining agricultural productivity (Moebius-Clune et al. 2011). The challenges of land subdivision and small farm sizes hinder the transition to modern farming and the use of farm machinery (Kimunge 2021). As subdivision due to inheritance is unlikely to stop in Kenya, there is an urgent need to find solutions to protect agricultural land for food security (Kimunge 2021).

Land consolidation is considered an approach that serves multiple purposes, including agricultural development, landscape restructuring, and rural development (Chen et al. 2018; Del Prete et al. 2019; Bonadonna et al. 2020; Hong et al. 2020). It involves amalgamating individual small and irregular units of land into large, composite parcels of land with regular shapes (Bronstert et al. 1995). In some instances, land consolidation initiatives include the reallocation and rearrangement of fragmented land parcels (Gedefaw et al. 2019), while in others, they aim for unified land use and uniform cultivation of specific crops (MINAGRI 2009). The implementation of land consolidation involves different measures and activities that vary according to location, available resources and characteristics of the implementers. Consolidation activities can range from land amalgamation, leveling, drainage construction, and irrigation setups to infrastructure building, village restructuring, and establishment of social amenities (Guo et al. 2015). Such measures enhance agricultural efficiency (Duan et al. 2021) and promote economies of scale (Zeng et al. 2018). Other impacts associated with land consolidation include effects on soil erosion and runoff. Some researchers found that land consolidation can reduce soil erosion and runoff (Liu et al. 2013b; Zhang et al. 2021; Wu et al. 2023), while others have reported an increase in soil erosion (Evrard et al. 2010; Peter et al. 2014). Additionally, land consolidation is linked to environmental issues, such as reduced biodiversity of soil organisms, pollinator species and crops in the field (Wang et al. 2015; Dudzinska and Prus 2018; Denac and Kmecl 2021; Hirayama and Ushimaru 2022). The loss of biodiversity is often associated with increased use of industrial fertilizers, pesticides and herbicides, which are common in land consolidation projects (Guo et al. 2015; Hu et al. 2021). Nevertheless, successful land consolidation projects have been implemented in European and Asian countries, resolving issues related to subdivision (Crecente et al. 2002; Sikor et al. 2009; Pasakarnis and Maliene 2010; Zhou et al. 2020).

To overcome land subdivision and enhance agricultural productivity in Kenya, the Ministry of Agriculture (GoK 2021) has proposed land consolidation. However, concrete actions remain pending and unclear, as the policy formulation process is slow-paced and frequently disrupted by the need to address more immediate and pressing issues (Mohamed et al. 2018). Consequently, it is currently unclear how land consolidation would be implemented. However, it will affect smallholder farmers, as they often meet the necessary conditions for land consolidation, including the presence of subdivided land, land ownership rights, and farmers’ willingness to participate in land consolidation projects (Abubakari et al. 2016). A partial or complete lack of consideration of these necessary conditions has contributed to the failure of previous land consolidation attempts in some SSA countries (Asiama et al. 2021). Therefore, implementing land consolidation in Kenya must allow farmers to make their own decisions regarding participation in land consolidation programs, as they would bear the consequences of transitioning from the current farming model to one of land consolidation.

Regardless of whether farmers are free to make their own land use decisions, land consolidation can have a range of impacts on them. Uncertain impacts may include loss of autonomy in farm decisions, contentions over benefit sharing due to power imbalance, and the potential for land grabs (Popovici et al. 2018). Conversely, land consolidation can provide benefits to farmers, such as the opportunity for those retiring from farming to pursue alternative income-generating activities and the potential for less strenuous farming activities that can improve their health. However, land consolidation can also have social implications, such as conflicts, emigration (Su and Mai 2020), and rural abandonment (Zhang et al. 2019; Li et al. 2022). Other uncertainties associated with land consolidation, which may yield either benefits or costs to farmers, include changes in local food supplies (Müller et al. 2021) and lifestyles (Lu and Dang 2015; Piras 2020). Environmentally, land consolidation can result in biodiversity loss (Bonfanti et al. 1997; Guvele 2001; Gu et al. 2008; Wang et al. 2015; Dudzinska and Prus 2018; Shi et al. 2021; Denac and Kmecl 2021; Hirayama and Ushimaru 2022), which can adversely affect farmers' well-being. The enforcement of land consolidation measures without farmers' consent can lead to involuntary resettlement (The Economist 2020; Feng 2020), potentially causing conflicts between the people and the government (Hui and Bao 2013).

The impacts of land consolidation on Kenyan farmers, particularly given their challenging colonial history with land consolidation, remain unclear. Uncertainties regarding the impacts of land consolidation can complicate the valuation of its net worth for farmers. Furthermore, differences in socio-economic and ecological contexts make it challenging to apply lessons from other countries that have implemented land consolidation, such as Rwanda, Ethiopia and Ghana. Moreover, there is a paucity of evidence on the evaluation and quantification of benefits, costs and risks for farmers participating in land consolidation programs (FAO 2003). Voluntary land consolidation allows participants to choose whether to join a project rather than coercing them into participation (FAO 2003). The impacts of land consolidation are varied, uncertain, and interrelated, with no clear direction on how these impacts would affect the livelihoods of smallholder farmers, adding complexity to the decision-making.

Valuation is necessary to support decision-making as land consolidation is costly and has varied impacts on farmers. However, most valuation research has been ex-post (Janus and Markuszewska 2017; Muchová et al. 2017), primarily focusing on direct economic outcomes (Hiironen and Riekkinen 2016). Rarely are the indirect impacts of land consolidation captured, either due to a lack of measurement efforts or because of difficulties in selecting appropriate methods. An exclusive focus on either direct or indirect impacts leads to incomplete evaluations that do not adequately represent the consequences of land consolidation for farmers when used for decision-making. Decisions made with incomplete information can lead to a high likelihood of errors (Hubbard 2014). Methodologically, only a few studies have concentrated on ex-ante valuation to support decision-making (e.g., (Zhou et al. 2017; Colombo and Perujo-Villanueva 2019)). These ex-ante studies have focused on the geographic suitability of land consolidation (Zhou et al. 2017; Colombo and Perujo-Villanueva 2019) rather than the overall valuation of the decision to consolidate land from the farmers' perspective. Thus, there is a need for ex-ante valuations that can integrate both direct and indirect impacts of land consolidation, account for uncertainty, and inform decisions.

Decision Analysis is a holistic approach that can evaluate options and support decision-making, even in contexts characterized by complexity and uncertainties. It facilitates decision-making under uncertainty by utilizing existing information (Howard and Abbas 2015) and permits using tools and methods that support inter- and transdisciplinary analyses. This approach involves collaboration with stakeholders to comprehensively assess a land-use decision and forecast its outcomes over time to support the decision-making process (Lanzanova et al. 2019; Rojas et al. 2021). Due to its ability to overcome data challenges through estimates (Hubbard 2014), Decision Analysis has recently found applications in agricultural development contexts. For instance, it aids decision-making when multiple options are available for improved livelihoods or adaptation outcomes, such as energy-efficient cookstoves, poultry farming, beekeeping, and sheep rearing in Ethiopia (Tamba et al. 2021). Decision Analysis has also been used to evaluate different investment options for scaling agro-climate services in Vietnam (Luu et al. 2022), and to support farmers' in deciding whether to protect cherry trees with polythene covers for climate adaptation in Chile (Rojas et al. 2021). Decision Analysis has also been applied to determine the net benefits of investing in beekeeping for biodiversity outcomes in Kenya (Wafula et al. 2018) and to determine overall outcomes for different stakeholders in different water projects, such as a planned irrigation dam in Ethiopia (Yigzaw et al. 2019) or a water abstraction and distribution project in Kenya (Luedeling et al. 2015).

In this study, we apply Decision Analysis to conduct an ex-ante evaluation of the impacts of land consolidation on smallholder farmers. We contribute to the existing literature on land consolidation in two ways: firstly, we demonstrate the use of Decision Analysis based on evidence from local experts, existing literature and other sources in evaluating the impacts of land consolidation on smallholder farmers. Secondly, we present a comprehensive assessment of the anticipated benefits, costs and risks of land consolidation programs, thereby informing decision-making for farmers and policy-makers.

5.3 Methods

Future land consolidation interventions in Kenya will target "high-potential" agriculture regions prone to land fragmentation (GoK 2021; Tyrrell et al. 2022). Factors such as dense population, inheritance customs that encourage land subdivision among children across generations, lack of government policy on land subdivision, and competition for land use contribute to fragmentation in these regions. These regions are also characterized by year-round cultivation by smallholder farmers. At least 20 counties in Kenya fall within western and central Kenya's “high potential” regions. We selected Murang’a County as our case study due to its rural nature, high land use pressure, high population density (419 persons/km^2), low average land size per household (1.4 ha), and a high number of households with land title deeds (about 65%) (GoK 2018). Other counties exhibiting high rates of fragmentation, high population density, and low average household land size include Kisii, Busia, Siaya, Nyamira, Migori, Homa Bay, Kakamega, Vihiga, Nyeri, Meru, and Kirinyaga.

5.3.1 Description of the study area

Murang'a County, located in the central part of Kenya between 0°37' and 1° 7' South and 36° 45' and 37° 27' East (Figure 5.1), is characterized by diverse climatic, topographic, and biophysical conditions. The altitude ranges from 914 to 3,353 m above sea level (GoK 2018). Annual rainfall is bimodal and varies with altitude, ranging from 400 to 1,600 mm. Soils are mostly volcanic in the six agroecological zones found within Murang'a. Agriculture is the primary land use, with the majority of households in Murang’a (73% and 76%) engaged in crop and livestock farming (KNBS 2019), respectively. The main food crops grown in the county include maize, beans, avocados, bananas, sweet potatoes, and assorted vegetables. The main cash crops grown in the highland areas are tea and coffee, while in the lowlands, mangoes, macadamia nuts, avocados, and perishables like tomatoes, kale, spinach, and French beans (GoK 2018; Kamau et al. 2018a; MoALF 2021) are prevalent. Most smallholder farmers combine staple and cash crops to diversify their incomes. Land in Murang’a is highly valued by residents due to its strategic proximity to Nairobi and its high agricultural potential. As a result, land parcels are increasingly subdivided, as even small plots are perceived not only as economically beneficial but also as important symbols of security, wealth, and status. Land is owned mostly by individuals under the freehold tenure system, which grants landowners absolute ownership for life. Leasehold tenure is also common, allowing individuals, organizations, or the government to lease land to or from farmers for an agreed period. In 2013, the majority of the households (65%) had title deeds (GoK 2013), with many others leasing land or farming without secure land tenure. The settlement pattern in the county is predominately linear, with about 80% of households located along the rivers and roads (GoK 2018).

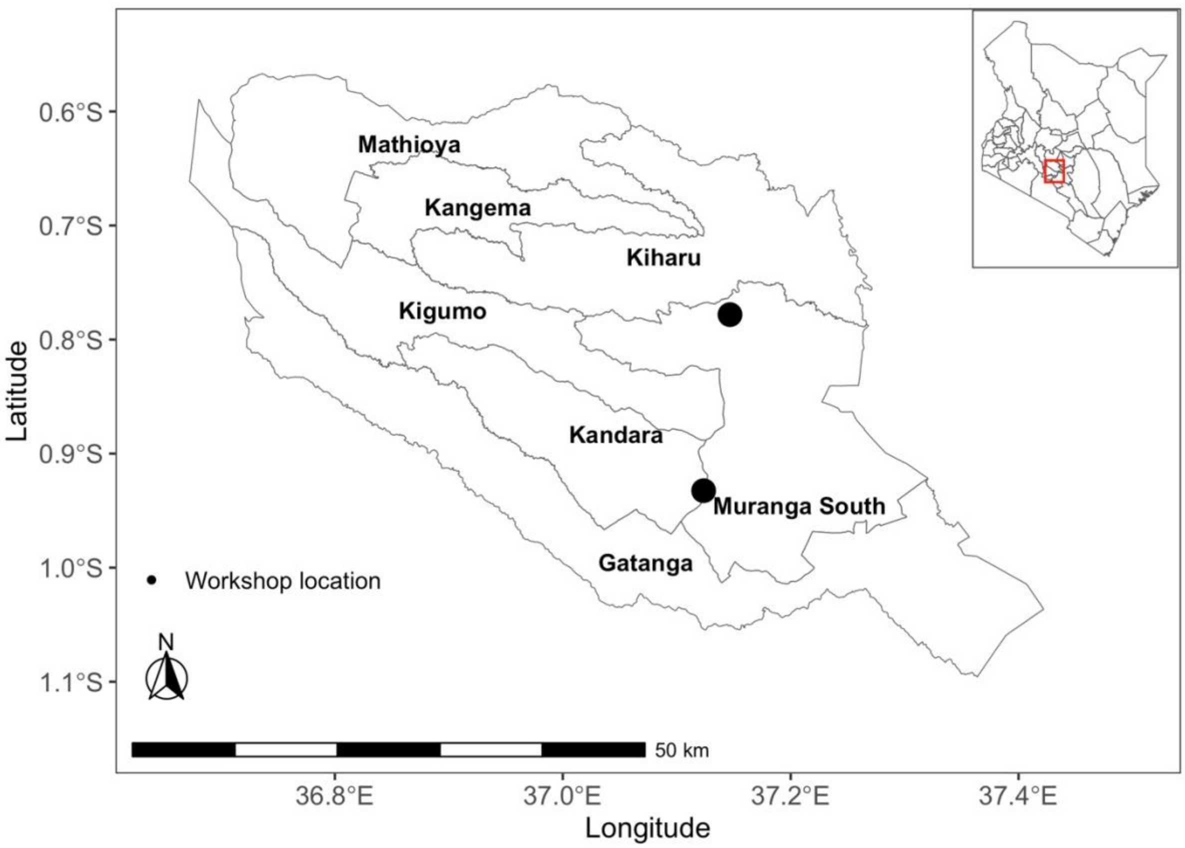

Figure 5.1: Map of Murang'a County showing locations where workshop meetings were held. Murang'a county has seven sub-counties–Mathioya, Kangema, Kiharu, Kigumo, Kandara, Murang'a South, and Gatanga. The inset shows the location of Murang'a within Kenya.

5.3.2 Overview of the Decision Analysis approach

To support evidence-based decision-making, we adopted a Decision Analysis approach (Howard and Abbas 2015). This structured method involves iterative and reflective steps that capture all available forms of knowledge, including scientific literature and expert knowledge, that are representative of the current decision situation (Whitney et al. 2018). By utilizing all forms of available data, this approach can overcome challenges related to data scarcity and facilitate the inclusion of different variables, perspectives, and values in land use decision analysis. We used estimated ranges rather than precise measurements to reflect uncertainty (Luedeling and Whitney 2017; Whitney et al. 2018).

Decision Analysis requires an appropriate framing of the decision problem, which should emulate the way the decision presents itself to the decision-maker. The framing refers to the decision-maker's view of the decision. Views, goals and objectives of a decision can vary among decision-makers; thus, creating an appropriate frame requires refining our understanding of the problem.

The framing process includes defining the goals and objectives of the decision-maker, determining who is involved and their levels of involvement, and identifying the time horizon of the decision with its goals and objectives. Information can come from various sources, including existing literature, primary data, and expert knowledge. Experts are stakeholders who affect and are affected by the decision, hold relevant opinions, or possess specific knowledge on aspects of the decision (Howard and Abbas 2015; Luu et al. 2024). Integrating information from all sources allows obtaining a comprehensive overview of the state of knowledge on model parameters, including relevant uncertainties that affect the decision-outcome relationship. Mirroring this overview back to the stakeholders can prompt them to consider creative decision alternatives with potential for different future outcomes, including the option to take no action. To qualify as a decision-maker, one must evaluate at least two options. These alternatives are shaped by the stakeholder's perspective (the way they view their frame) and the information available to them. Ultimately, each option should undergo a rigorous assessment of its costs and benefits, which enables the selection of the option with the greatest expected net benefits.

A Decision Analysis approach considers stakeholder perspectives and preferences while using logical reasoning throughout the process. Personal biases and emotions often cloud decision-making, which can lead to the use of simple, error-prone heuristics (Tversky and Kahneman 1974; Howard and Abbas 2015). In our approach, we engage stakeholders in a process called calibration. Calibration training aims to raise awareness among stakeholders of their personal biases, convey the impact of these biases on decision-making, and share strategies to overcome them (Hubbard 2014). We adopted the Decision Analysis approach (Figure 5.2) to determine whether the land consolidation decision would enhance farmers' well-being.

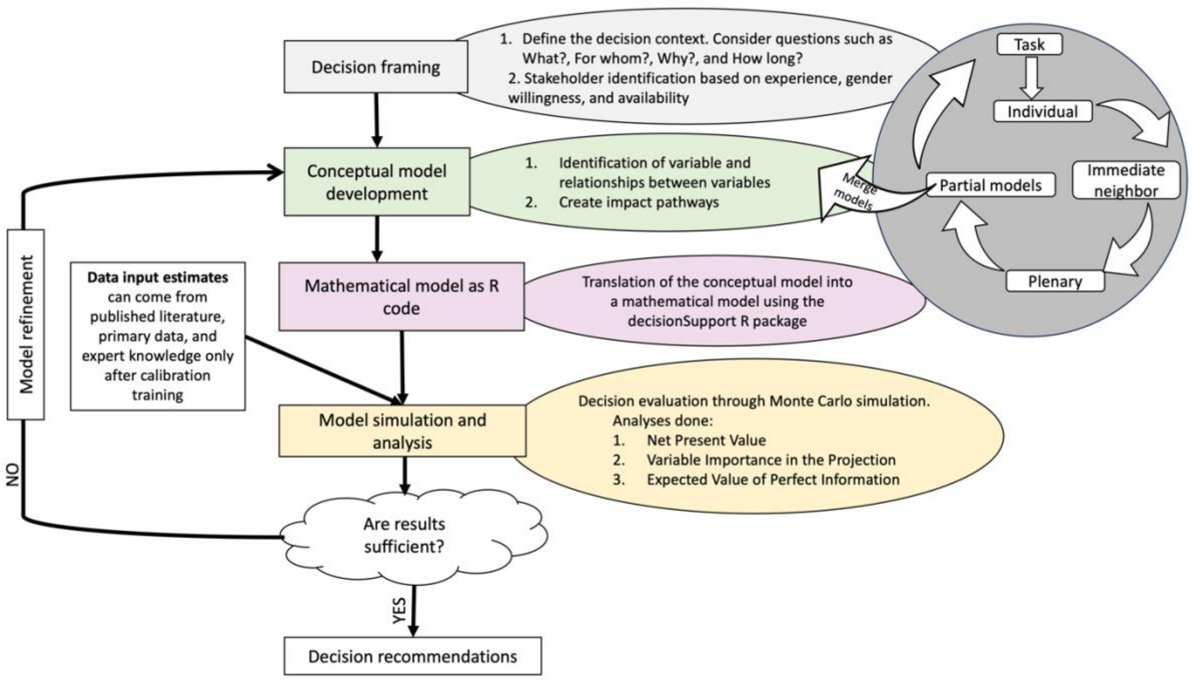

Figure 5.2: Decision Analysis flowchart for the evaluation of the decision to consolidate land by farmers and to support farmers' decision-making. The grey-shaded region shows the application of the World Café method for eliciting and gathering information from stakeholders. The process is both iterative and reflective, encouraging participation from all members. It is useful in different stages including in decision framing, in generating ideas for alternative options, and when developing a conceptual model to capture all factors relevant for the decision-outcome relationship. Adapted from (Luedeling et al. 2015; Whitney et al. 2018).

5.3.3 Model framework for land use decision analysis

5.3.3.1 Decision context and problem framing

As a first step of the Decision Analysis, we framed the decision context to identify the objectives, goals, boundaries, decision-maker, and target group (i.e., those who are supposed to be affected). We relied on the review of policy documents and informal interviews with decision-makers to gather knowledge about land consolidation debates in Kenya and to explore the extent of existing knowledge and documentation on land consolidation processes, guidelines and frameworks relevant to the country.

We reviewed Kenya's official county and national documents and policies to identify Causes and proposed strategies for food security and improving livelihoods. We used county documents (i.e., County Integrated Development Plans) and national-level documents (i.e., agricultural policy documents, strategic plans, and frameworks) to identify reported challenges facing agriculture at the county level, such as land fragmentation into small plots that are no longer economically viable for agricultural purposes. In addition to the policy document review, we conducted a literature review to identify factors that influence decision-making in land consolidation. Here, we searched the Web of Science Core Collection for articles using the search term "*'land consolidation' AND (soil OR machinery OR yield OR migration OR landscape OR 'decision making' OR social)*". The search results are available on SearchRxiv (Kamau 2023). We identified factors that play a role in decision-making regarding land consolidation and used them to set the boundaries of our decision analysis. We complemented the policy and literature reviews by conducting six informal interviews and discussions with different stakeholders, including farmers, government employees, researchers and scientists, at the Africa Climate Week held in Nairobi in September 2023, asking them about prospects of land consolidation in Kenya. In our interviews, we aimed to understand the current level of knowledge among experts about land consolidation impacts and to assess the feasibility of land consolidation for the smallholder farming context in Kenya and its potential benefits, risks, and costs. We also asked the interview respondents to describe how they envisioned implementation of a land consolidation program. The policy and literature review, along with the interviews, helped us refine our decision analysis objectives. We framed the decision around designing a voluntary consolidation program for smallholder farmers. We considered the decision-maker to be a farmer or a household that would be able to join a voluntary land consolidation program. An investor would lease the decision-maker's farmland for a period of 25 years, with lease payment proportional to the land size, and households would not need to relocate. Farmers would retire from farming on their pieces of land, allowing them to pursue other activities, including on-farm activities.

5.3.3.2 Participant identification and engagement

We identified potential participants from the county as groups or individuals interested in land consolidation, those that would be affected, and those that would have an impact on the implementation of such a program. At the county level, we identified the participants with the help of village elders and guidance from the chief. At the national level, we identified participants through informal interviews and discussions during the Africa Climate Week 2023 and through recommendations from the authors' network and partner organization Biovision Africa Trust (BvAT). We selected participants based on their experience, availability and expertise, paying attention to gender balance and age diversity (Luu et al. 2024). We invited 15 participants for the first workshop in Murang'a County, and 12 of them joined us for the entire duration of the workshop. All participants in the first workshop were farmers of varying age, with two-thirds being female. The workshop provided a safe space for them to speak and contribute freely. For the second workshop, held in Nairobi, we invited 15 participants from academia, government ministries, and the private sector. Of the 15 invited, 11 participants joined us for the full duration of the workshop (Figure 5.1). Of the eleven participants, five were female and six were male.

5.3.3.3 Creation and parameterization of the model

We held both workshops to bring different participants, hereafter "stakeholders", to examine diverse perspectives and gather a general understanding of the problem of land fragmentation and its relationship to the proposed solution of land consolidation. We presented the idea of land consolidation to the participants in a plenary session and provided them with information about different forms of land consolidation. We explicitly declared that neither the workshop facilitator nor the researcher was a government representative, which was important to the stakeholders due to the sensitivity of land-related subjects in the Kenyan context. We addressed and clarified questions from the stakeholders. As key questions concerning resettlement emerged, we presented the compact and dense resettlement models commonly utilized in land consolidation and rural planning. Most participants found these resettlement models undesirable, as they had already invested in permanent structures such as stone-built houses. Instead, there was consensus on a land use model compatible with their existing settlement pattern. In this settlement plan, stakeholders expressed interest in land consolidation options that would maintain current household areas and only make arable land available for the consolidation program. Based on the discussions, we also redefined other boundaries, including adjusting the project timeline to 25 years, and established that farmers would receive compensation based on the size of land leased.

5.3.3.4 Development of a conceptual model

As part of our workshop, we asked the stakeholders to consider all the relevant factors that would influence their decision to shift from their current form of farming to consolidating their land. Together, we categorized these factors into four groups: environmental, economic, social, and cross-cutting issues. These categories helped capture and identify all factors and relationships in the decision-making context. Stakeholders independently evaluated the relevance of each factor in each category, then shared with their immediate neighbors for internal peer review, and later with the plenary to reach consensus (Figure 5.2) (Whitney et al. 2018). Next, stakeholders mapped cause-and-effect linkages between the defined factors in the categories. We combined the results from all groups into a common impact pathway model, which provided a graphical representation of the decision-outcome relationship. This impact pathway allowed us to capture the costs, benefits and risks associated with the decision to participate in a land consolidation program.

5.3.3.5 Development of the mathematical model

We translated the impact pathway developed by the stakeholders into mathematical equations. These equations captured the costs, benefits and risks resulting from the decision (Figure 5.2). According to the stakeholders' inputs, we identified all the relevant variables involved and their temporal patterns (one-time or repeated occurrence) during the project timeline. For example, planning costs were treated as a one-off expense at project inception, whereas food costs would accrue throughout the entire project timeline, reflecting the loss of on-farm food production.

Costs and benefits: We consolidated costs into groups such as planning and establishment, loss of goods and services (e.g., food costs not saved, loss of natural assets such as trees), and new costs associated with the new lifestyle. Some costs were one-off, while others recurred. The benefits to farmers from participating in the program included social benefits, revenues from off-farm activities, lease income, production cost savings, a reduction in medical costs incurred due to farm-related diseases, and benefits for their children, who gain time for play or attending school. We coded all the mathematical equations expressing the costs, benefits and risks using functions from the `decisionSupport` package v1.114 (Luedeling et al. 2022a) in the R programming language v4.3.1 (R Core Team 2023).

Risks: We defined risks as either unconditional or conditional. For each risk, we considered the probability of occurrence of the respective event, and the nature of the expected impact. For unconditional risks, we simulated the likelihood of occurrence and the resulting impact on farmers' benefits with and without land consolidation, using the `chance_event` function in the `decisionSupport` R package (Luedeling et al. 2022a). For instance, for natural hazard risks such as floods, we calculated the probability of a flood event in a year and estimated the magnitude of loss that a flood event would cause on benefits derived from crop production. For conditional risks that depend on other uncertain events, we included a conditional probability in our calculations.

We then collected the necessary model input data for all the variables used in the mathematical model in the form of probability distributions rather than single values. These distributions were specified using lower and upper bounds of confidence intervals to capture the range of plausible values of a variable. Such distributions capture a wide scope of data input, thereby mitigating possible errors and accounting for uncertainty, which would not be possible if simulations were based on spuriously precise input data (Luedeling et al. 2015, 2022b). The gathered probability distributions represented the lower and upper bounds of 90% confidence intervals for each variable. We determined these values based on previously published literature and stakeholders' knowledge. In cases where upper and lower bound values are unavailable experts are a useful resource in providing estimates by expressing their state of knowledge. Before obtaining estimates from experts, we first subjected them to calibration training to improve the estimates.

Calibration training: Past research has shown that experts are a reliable resource for estimates, especially in data-scarce situations (Shepherd et al. 2015). However, experts are prone to biases, particularly when asked to provide quantitative estimates (Hubbard 2014). Human heuristics combined with inherent or cognitive biases can sometimes lead to errors (Tversky and Kahneman 1974), resulting in experts who are under- or, more commonly, overconfident (Hubbard 2014). Such biases include anchoring, the availability heuristic, the Dunning-Kruger effect, and the bandwagon effect. To overcome biases and improve estimations, stakeholders underwent calibration training. Such training has been shown to improve stakeholders' ability to estimate their own uncertainty (Hubbard 2014). The calibration training process consisted of a baseline test based on questions on general knowledge and deductive reasoning, where stakeholders were requested to provide answers in the form of lower and upper bounds of their 90% confidence intervals. We then administered a series of tests in sets, introducing different techniques to overcome biases and improve estimation between the test sets. Techniques included the successive narrowing of unreasonably wide ranges to counter anchoring and using an equivalent bet approach that ties stakeholders' estimates to a reward (Hubbard 2014). Additionally, we used Klein's pre-mortem (Klein 2007), and applied Fermi's approach to break down the decision problem into smaller, manageable parts while making reasonable assumptions about each part (von Baeyer, Hans Christian 1988). After calibration, we asked stakeholders to provide estimates of uncertain model inputs.

In cases where data inputs for certain variables were unavailable, we decomposed the variables into variables and indicators for which data inputs were available, as suggested by Hubbard and Millar (2014). For example, social cohesion was identified as a benefit by the stakeholders but initially seemed difficult to quantify. Through group discussion and clarification, we decomposed this variable into the contribution of the feeling of 'community togetherness' made possible because farmers would not be required to work on their farms, allowing them time to meet and socialize outside of farming activities.

5.3.4 Model simulation

We used the mathematical model and the data input collected to run a probabilistic simulation in the R programming environment version 4.3.1 (R Core Team 2023) using the `mcSimulation` function in the `decisionSupport` package v 1.114 (Luedeling et al. 2021). We used Monte Carlo simulation with 10,000 runs. As inputs for the model runs, sets of random values were drawn from the distributions defined by our calibrated estimates. The outcome of each model run was the Net Present Value (NPV) and annual cash flow over 25 years. We then performed summary statistics of the 10,000 outcomes and visualized the summary statistics using `tidyverse` v 2.0.0 (Wickham et al. 2019) and `ggpubr` v 0.6.0 (Kassambara 2023).

To evaluate model sensitivity, we applied Projection to Latent Structures (PLS) regression to determine the strength of relationships between all the input variables and the outcome (Hubbard 2014). Two key output metrics of PLS analysis are the regression coefficient and the Variable Importance in the Projection (VIP). The VIP is the weighted sum of squares of the loading weights, based on the share of response variable variance that each predictor variable can explain. We identified the most influential variables using a cutoff threshold of 1 (Chong and Jun 2005). The PLS regression coefficient indicates the direction (positive or negative) and the magnitude of an input variable's effect.

When Monte Carlo simulation outputs clearly favor one decision option over its alternative, the current and available information is sufficient to support a decision recommendation. However, if no option emerges as clearly favorable, decision uncertainties can be identified. In such cases, critical decision variables can be identified using the Expected Value of Perfect Information (EVPI). The EVPI quantifies the value of eliminating uncertainty for a variable by calculating the difference between the expected value of the optimal decision (the option that a decision-maker would choose with perfect information on a variable), and that under present state of knowledge of the variable. It guides decision-makers in identifying which variables warrant additional data collection to reduce uncertainty or mitigate risks. For example, if the value of lost natural assets is uncertain, targeted interviews can be conducted to determine average tree density per farm, or alternatively, literature review on on-farm tree richness could provide the estimates.

5.3.5 Share results and receive feedback

Finally, we invited the stakeholders mentioned in section 5.3.3.2 to a one-day workshop to share findings and receive feedback. We held two workshops at the same locations as before, Murang’a and Nairobi, inviting all stakeholders who had participated in the earlier workshops. Of the invited, 12 and 6 in respective locations were able to attend, and we received stakeholders' feedback and suggestions.

5.3.6 Model update based on market scenarios

Based on the EVPI, critical uncertainties were associated with market prices, prompting us to create market scenarios using two variables with critical uncertainties: lease prices per acre per season and maize price per kg. For each variable, we established three categories to distinguish between the effects of low, medium, and high prices. For maize prices, the categories were KES 5–86.67, KES 86.68–168.33, and KES 168.34–250. We used data on reported maize prices between 2005 and 2024, which we obtained from the Ministry of Agriculture and Livestock Department (MALD 2024). For lease prices, the categories were KES 10,000–340,000, KES 340,001–670,000, and KES 670,001–1,000,000, based on values provided by the stakeholders and published literature. We created market scenarios for each variable individually and for combinations of both variables. We reran the models as detailed in Section 2.3.3, using the `scenario_mc` function instead of the `mcSimulation` function, as the former allows for multiple specifications of probability distributions of the same input variable, making it suitable for efficiently simulating outcomes for different scenarios.

5.4 Results

5.4.1 Decision framing

Reviewing policy and government documents revealed that nineteen counties reported land fragmentation as a crucial concern and a contributor to low agricultural productivity. The CIDPs indicated that there was a need to mechanize agriculture in the counties, but mechanizing agriculture was hampered by small farm sizes. Smallholder agricultural land areas range from 0.4 to 3 hectares. Policy documents from the Ministry of Agriculture recommended consolidating land. The envisioned spatial plan followed conventional land consolidation models, organizing one or more localities into an administrative unit with household resettlement, and another area designated as agricultural land. The Ministry of Agriculture also recommended that a land consolidation policy be developed. Regrettably, we were informed the policy was incomplete and therefore unavailable for review. We did not find any other plans on land consolidation in the form of a framework, bill, act, or other strategic documentation. Based on the limited information available on consolidation plans, and in agreement with stakeholders, we decided to focus our decision analysis on farmers. A land consolidation program directly affects farmers, and we identified the decision question as follows: “Should the farmer/household voluntarily join a land consolidation program?”. This question formed the basis for the decision model. Since our discussion showed that stakeholders favor a model that allows them to save their homestead areas and consolidate arable farmland, we focused on a leasehold mechanism of implementation. A leasehold mechanism would allow farmers to maintain ownership of land they hold title deeds for as well as their permanent homes, avoiding resettlement. We set the timeline of the lease to 25 years and agreed that the benefit-sharing for the leasehold should be proportional to the size and value of the land. Stakeholders did not prefer the conventional land use planning models based on relocating farmers to centralized community areas (Figure 5.3).

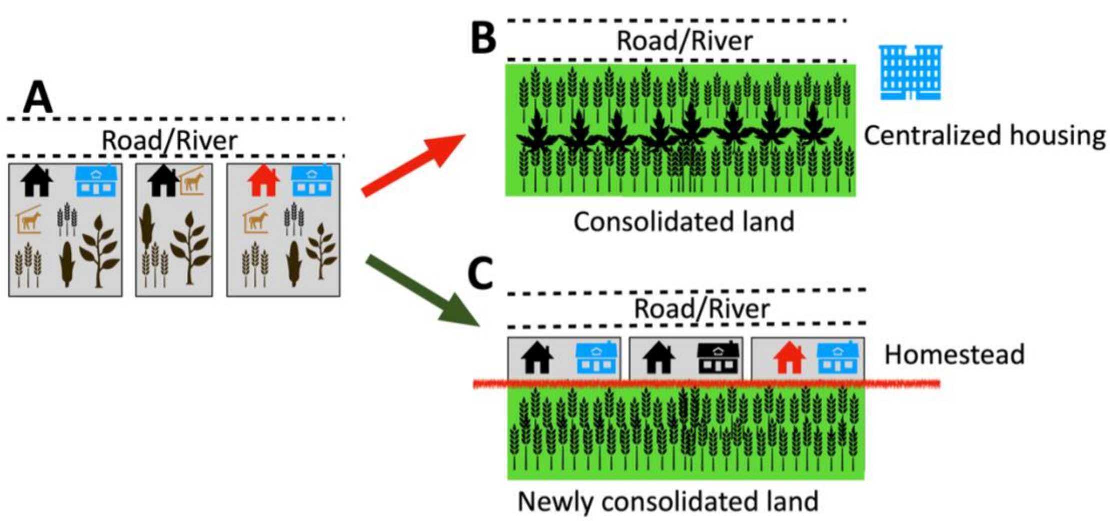

Figure 5.3: Description of the land consolidation model for farmers. A represents the current status, where the households follow a linear settlement pattern along roads or rivers. We presented model B to the stakeholders during the workshop, which involves relocating households to a set location in a centralized community, and consolidating the remaining land for agriculture. Model C is the model stakeholders agreed to. The

thick red line in Model C delineates the homestead area, and only the farm area is consolidated.

5.4.2 Conceptual model

We identified key stakeholders, including technical government officers from different ministries (e.g., Ministry of Land and Urban Planning, Ministry of Agriculture, Ministry of Economic Planning), researchers, and farmers. Researchers' main specializations were in agriculture and farm practices, community engagement, and gender. Based on the consolidated stakeholder inputs, we developed a conceptual decision model with benefits, costs and risks. We identified 38 variables that describe the impact pathway of the overall decision outcome (Figure 5.4). The stakeholders identified benefits, costs and risks in their current system and for a hypothetical scenario where land consolidation was implemented. Stakeholders identified six types of benefits and six types of costs for the "consolidate land" option and three types of costs and three types of benefits for the "maintain farms" option (Figure 5.4).

Stakeholders identified earnings from leaseholds as the major source of income and recognized the potential transformation in their daily activities due to the freeing up of labor for other sectors, such as manufacturing or service. Farmers can seek additional benefits from alternative employment, whether on or off the farm. Health benefits were related to reduced stress-related diseases and accidents due to farm activities and decision-making. Community and social-cohesion benefits were associated with the increasing availability of time for community involvement. Freed family labor from farm activities benefited children as it freed up time for playing and learning.

In the model, we included negative indirect consequences of the proposed land consolidation intervention: Stakeholders identified social costs, including antisocial behavior, drug abuse, and criminal activities. Increased free time without alternative social or economic activities can be detrimental to society and felt at household level, e.g., in the form of domestic violence. In the model, households directly incur the loss of natural capital (e.g., trees on the farm), computed based on the value of perennial crops. Household costs included any damage or destruction of structures beyond the established homestead area, planning costs that included the cost of knowledge acquisition on the land consolidation program and legal fees, the cost of food items no longer obtained directly from the farm, and the cost of sustaining a household before the start of compensation.

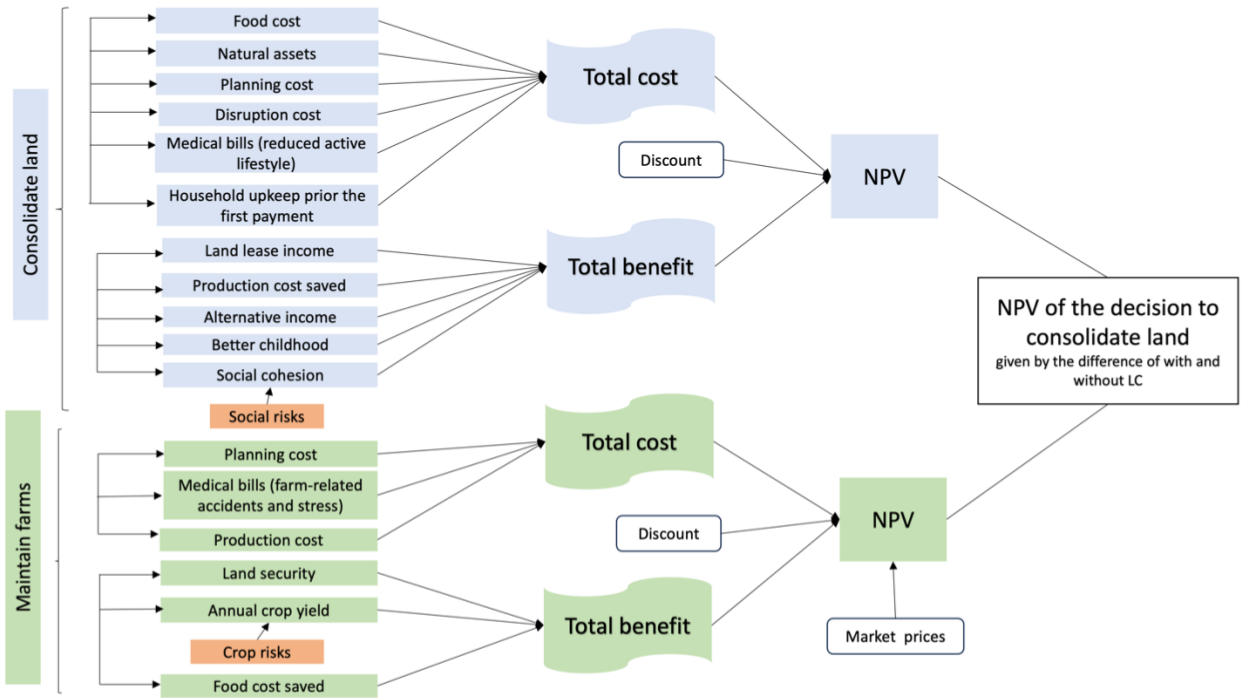

Figure 5.4: Conceptual cost-benefit analysis of the decision to consolidate land among smallholder farmers. The blue color represents the changes with the "consolidate land" option; the green color represents the "maintain farms" option. NPV is net present value.

5.4.3 Projected land consolidation outcomes

5.4.3.1 Net Present Value (NPV)

We identified and used 38 variables in the decision model to comprehensively compute the overall land consolidation costs, benefits, and risks. The results of the 10,000 model runs showed a wide distribution of possible values for the overall outcomes of the two options ("maintain farms" and "consolidate land") (Figure 5.5). For the option of consolidating land, the projected outcomes expressed as NPV per hectare of land were between -28.0 and 15.9 million KES at a 90% confidence interval. The probability of obtaining positive outcomes of the 10,000 model runs for the option of consolidating land was 76.7%. For maintaining current farms, at a 90% confidence interval, the NPV outcomes were between 1.45 and 58.2 million KES with a high probability (98%) that the farmer would have positive outcomes.

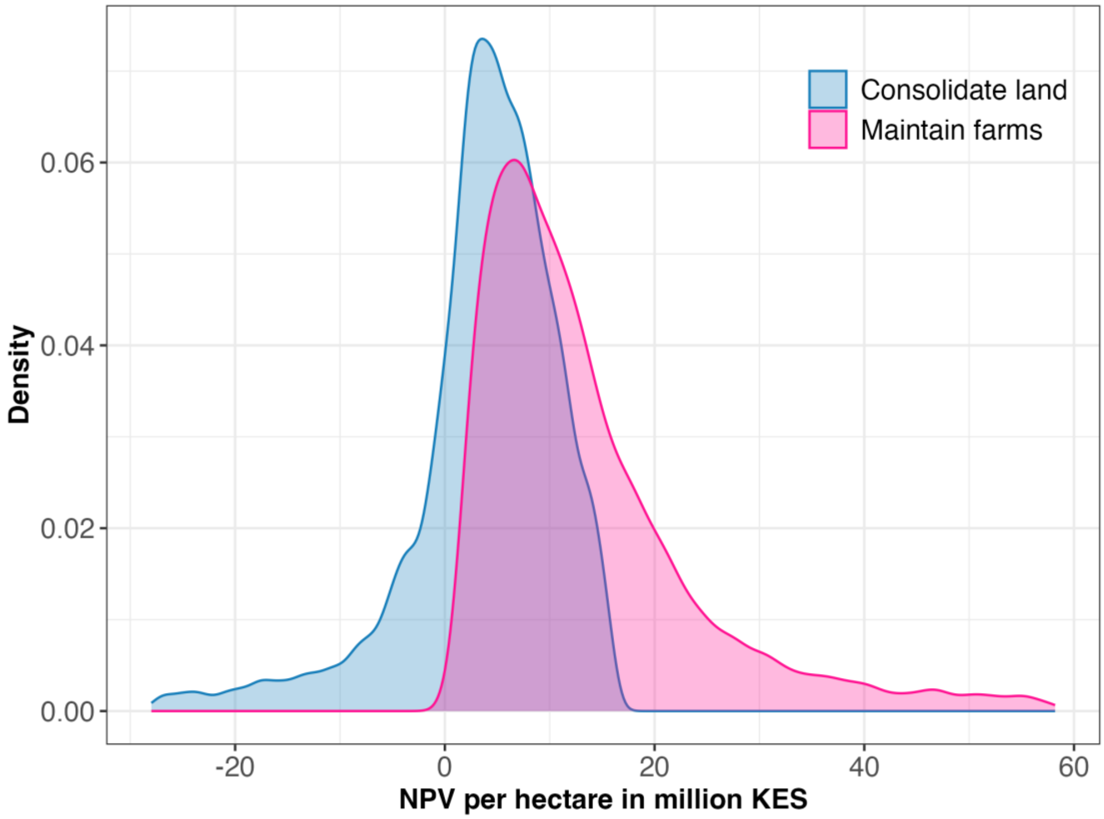

Figure 5.5: Distribution of farmers' projected outcome for two decision options: "maintain farms" and "consolidate land". The density plots are based on a Monte Carlo simulation with 10,000 model runs.

We computed the net benefit of land consolidation as the difference between the two decision options: the NPV per hectare of consolidating land and the NPV per hectare maintaining farms. The results showed that 71% of the NPVs for the decision to consolidate would favor "maintain farms" and only 28% of all NPVs suggest "consolidating land" as the preferable option (Figure 5.6). At a 90% confidence interval, the distribution of the NPV outcomes of the decision to consolidate ranged from -86.4 to 9.6 million KES.

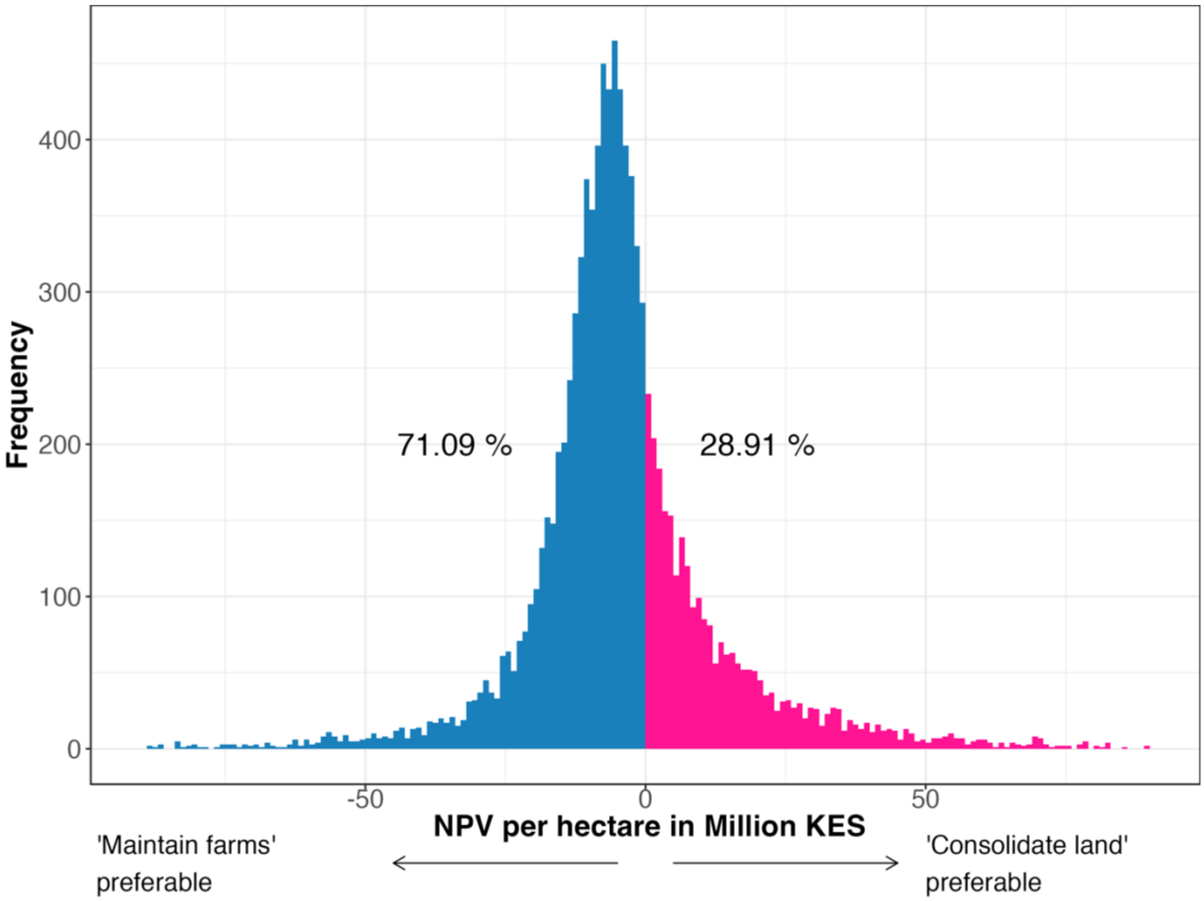

Figure 5.6: Distribution of the NPV of the decision to join the land consolidation program, given by the difference between the NPVs of the "consolidate land" option and the "maintain farms" option. The blue color marks all the negative values which are 71% of the 10,000 scenarios. Conversely, the pink color indicates all the positive values which account for about 29% of the scenarios.

5.4.3.2 Influential variables

Regression analysis results for the 38 variables we used showed that seven variables strongly influenced the project outcome, as indicated by VIP scores >1 (Figure 5.7a). The NPV outcomes were negatively influenced by *maize yield* (VIP = 2.99), *maize price* (VIP = 2.19), and *saved food costs from the farm* (VIP = 1.42). *Lease income* (VIP = 3.12), *household land size* (VIP = 1.73), *saved production costs* (VIP = 1.67), and *alternative business* (VIP = 1.04) positively influenced the NPV outcomes.

5.4.3.3 Expected Value of Perfect Information (EVPI)

The EVPI metric indicates critical uncertainties of the NPV for the decision to consolidate land (Figure 5.7b). *Lease income*, *maize yield,* and *maize price* variables returned high EVPI values (KES 1,409,174, 967,616 and 669,428, respectively), indicating the need for additional data collection.

Loss due to natural hazard event, *proportion of yield lost due to input constraint event*, *household income per year,* and *chance the farmer has inadequate funds for farm inputs* had very small values of KES 43, 31, 10, and 2, respectively.

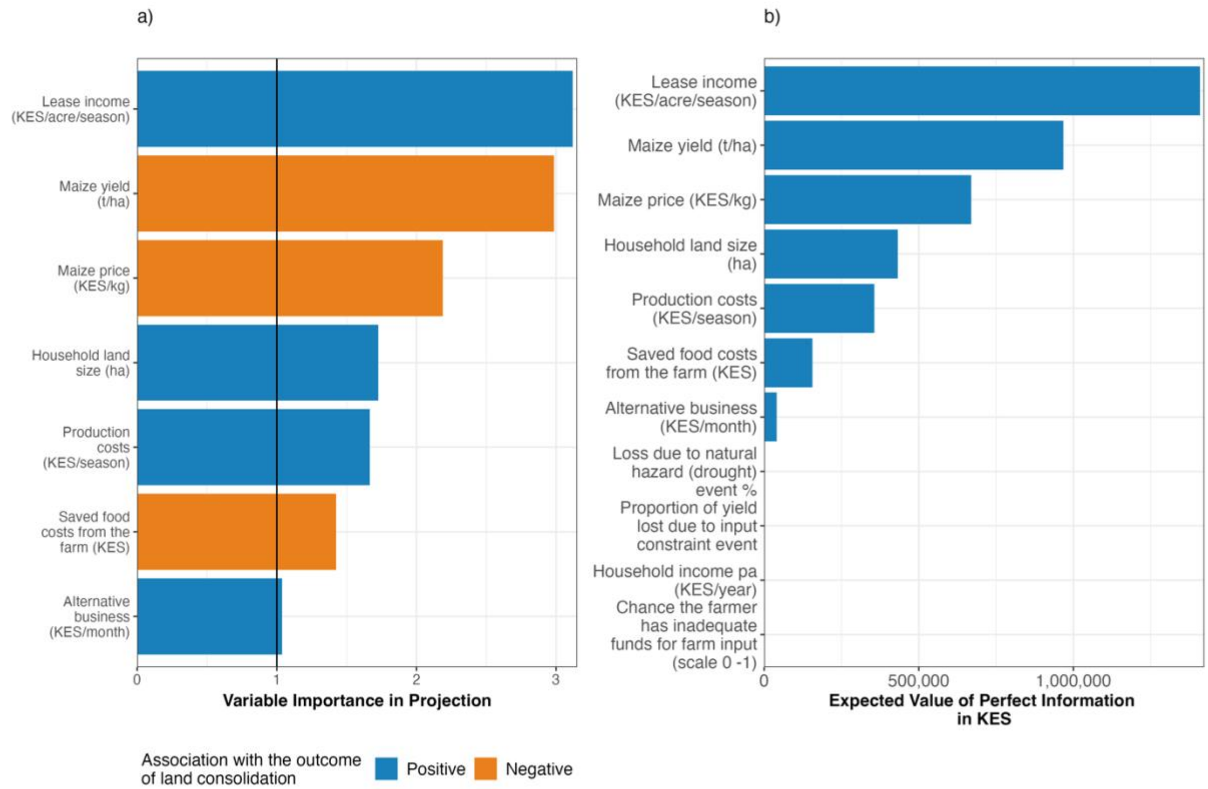

Figure 5.7: Sensitivity analysis (a) and value of information analysis (b) of farmers' land consolidation decision in Kenya. a) The PLS regression analysis identified important variables and expressed them as VIP scores to indicate model sensitivity. The length of the bars represents the magnitude, while the color indicates the direction, such that the variables represented by blue bars have a positive influence on the projected NPVs while the variables represented by orange bars have a negative influence. The blue bars in the left plot (b) represent the results of the Expected Value of Perfect Information (EVPI) analysis of all critical variables with non-zero EVPI values.

5.4.3.4 Impact of the market price scenarios on the NPV of the decision to consolidate land

We compared 15 market price scenarios against the initial model (hereafter referred to as 'baseline') to determine how changes in maize prices and land lease rates affect farmers' net benefits, both individually and in combination. Out of the 15, ten scenarios showed a higher likelihood favoring "consolidate land" as the preferable option over "maintain farms", defined as scenarios in which more than 50% of all the NPVs in a scenario favored 'consolidate (Table 5.1). In contrast, "maintain farms" resulted in favorable NPV outcomes in the majority of scenarios, specifically those involving medium to high maize prices, either alone or in combination with low land lease prices (Figure 5.8).

Table 5.1. Likelihood of decision options being preferable. The likelihood is based on the share of positive NPV outcomes of the decision to join a land consolidation program for farmers for each market price scenario of 10,000 model runs.

Market price scenario	Likelihood of decision options being preferable (%)	
	Maintain farms	Consolidate land
Baseline	71.1	28.9
Low maize prices	47.4	52.6
Medium maize prices	71.6	28.4
High maize prices	83.9	16.1
Low lease prices	65.1	34.9
Medium lease prices	18.5	81.5
High lease prices	10.2	89.8
Low maize prices and lease prices	46.2	53.8
Low maize prices and medium lease prices	14.0	86.0
Low maize prices and high lease prices	9.20	90.8
Medium maize prices and low lease prices	65.4	34.6
Medium maize prices and lease prices	18.1	81.9
Medium maize prices and high lease prices	9.9	90.1
High maize prices and low lease prices	79.0	21.0
High maize prices and medium lease prices	26.6	73.4
High maize prices and lease prices	12.0	88.0

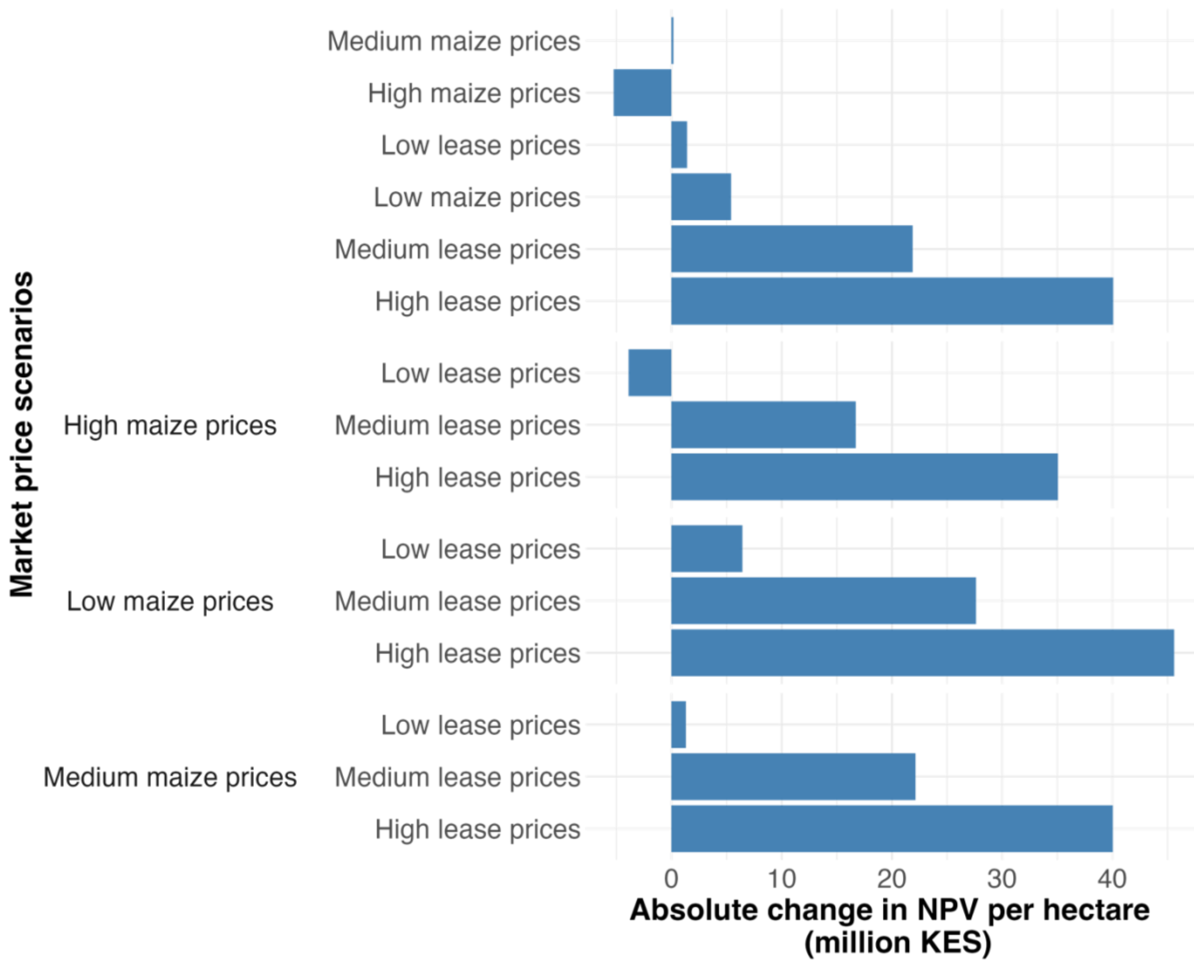

Figure 5.8: Median values of the absolute change of the decision to consolidate land across different market price scenarios. The absolute change was calculated as the difference between each market price scenario and the decision under the "baseline" scenario.

5.5 Discussion

5.5.1 NPV of land consolidation for smallholder farmers

With this study, we aimed to demonstrate the use of Decision Analysis in assessing smallholder farmers' land use decisions of maintaining the farm or consolidating land. Here we assessed the expected impacts of the decision to consolidate land by including benefits and costs with consideration for risks and uncertainties. The overall outcome distributions of benefits for maintaining farms and consolidating land showed a wide range of possible values, necessitating further analyses such as the assessment of information value and variable importance. The NPV of the decision to join a land consolidation program was less favorable compared to not joining the program. We attribute this outcome mainly to changes in disposable income from lease income, saved production costs, and saved costs from medical bills related to farm stress diseases and accidents (Shutske 2018; Daghagh Yazd et al. 2019). Extreme negative outcomes from land consolidation among smallholder farmers may be attributed to compounding effect of multiple adverse factors occurring simultaneously, including high planning costs, low yields, low prices, high discount rates and high inflation rates, each amplifying the overall negative effect. Nevertheless, land consolidation provides benefits such as relief from physically strenuous work, time to engage in social activities, and better childhood experiences. Better childhood benefits are particularly important to children and the society. Many smallholder farming systems in many regions utilize family labor (Boutin 2012; Kamau et al. 2018a) to reduce production costs. However, extensive family labor can be detrimental to the overall well-being of the children. Consolidating land liberates children from the necessity of engaging in farm-related labor, thus allowing them to participate in socialization and educational pursuits. However, quantifying a more nuanced concept of a better childhood presents a challenge, as a multitude of factors shape a positive childhood. These factors include the quality of parental care, the extent of freedom in children's daily lives, the level of appreciation and participation, the degree of satisfaction with institutions, the availability of leisure time, the quality of friendships, and the level of subjective well-being (World Vision Deutschland 2013). Yet, according to stakeholders, this benefit could be assessed by the value of hiring laborers, despite the varied dimensions of quality of life. The high number of positive outcomes for farmers deciding to maintain their farms can be attributed to land security, crop yield, and food cost saved.

Valuing benefits tends to carry greater uncertainty than valuing costs, though the magnitude depends on the context and on which benefits are being valued. For example, valuing of climate services exhibited wider variability for benefits than costs (Perrels 2020), land consolidation followed the same pattern. Under voluntary land consolidation, the financial burden falls on the participating household, and most costs accrue perpetually. For example, in our study, the food expenses and lost benefits from trees contribute significantly to total costs. Yet, these costs can be predicted with a relatively high degree of certainty. In contrast, expected benefits (e.g., lease income or earnings from alternative livelihoods) fluctuate widely. Consequently, most of the variation in projected net outcomes arise from the benefits side rather than from cost estimates.

5.5.2 Important variables and value of information

In our study, *lease income, household land size, saved production cost* and *alternative business* positively influenced the NPV outcome of the decision to consolidate. This is unsurprising, as factors that drive farmers to exit farming include the burden of production costs and attractiveness of off-farm employment (Goetz and Debertin 2001; Peel et al. 2016; Do et al. 2023). Maize yield, price, and saved food costs negatively correlated with the overall benefits of land consolidation. An increase in any of these variables would make it less beneficial for a farmer to consolidate.

Uncertainties of benefits from land consolidation were mostly related to land-related variables such as lease price and land size. This is unsurprising, given that land consolidation is based on land size, number of plots held by a household, and the value attached to land (Kwinta and Gniadek 2017; Gedefaw et al. 2019). While uncertainties in variables such as maize price and yield, production costs per season, food savings, and income from alternative livelihoods can be reduced through additional data collection, uncertainty about lease income per acre per season is challenging. This is largely due to variability in land pricing across both Murang'a county and the country at large. Although targeted studies on farmers' willingness to lease could help reduce some uncertainty, land valuation is inherently subjective. Nonetheless, in decision-making contexts, farmers are typically presented with precise lease value at which point the uncertainty is effectively removed. Another possible approach is to determine lease value based on what households are willing to accept, similar to determined compensation amounts for landowners willing to participate in forest conservation (Adhikari et al. 2022). Alternatively, land valuation can be informed by factors such as infrastructure access (Munshi 2020). In Murang'a, however, such methods may yield volatile results due to the County's proximity to Nairobi, favorable agro-climatic conditions, and the land's competing functions. In cases where lease value is linked to cultivation and sale of high-value crops, prices can reach as high as KES 500,000. Given this wide variability, determining a standard lease is complex. However, since this value would ultimately need to be negotiated between farmers and lessees, a more grounded and realistic approach is to cap the lease price according to the net profitability of high-value agriculture. Based on this rationale, we constrained the plausible lease value to a range between KES 10,000 and 250,000 per acre per season.

Land pricing based on agricultural yields may also be contentious, as smallholder farmers often receive low prices for their produce, whether at the farm gate or in markets, due to resource constraints and inadequate storage capacities that prevent them from timing sales for better prices (Ngeno 2024). To alleviate decision-makers' reluctance regarding this land use decision, we developed scenarios based on key uncertainties of land and maize prices. High maize prices coupled with technical and allocative efficiencies could increase profits for farmers in Kenya (Ngeno 2024). This information is particularly relevant for policymakers, depending on the objective they wish to achieve. For instance, if policymakers are concerned about biodiversity goals, policies that stabilize or improve market conditions and shape market prices for maize could make land consolidation less appealing for farmers, thereby maintaining the present systems of small, diversified plots that support agro-diversity. Such polices could include price support policies (e.g., minimum guaranteed returns above a certain cost of production) to cushion smallholder farmers. Conversely, if the primary objective is rural restructuring and agricultural zoning, land policies that enhance land value could incentive farmers to consolidate land. These may include policies that formalize public-private partnership models specifically tailored to agricultural land consolidation or co-managed commercial farms, and structured subsidy programs that incentivize voluntary consolidation.

5.5.3 Risk preferences of smallholder farmers

Shifting to a system of land consolidation implies a loss of autonomy and decision-making power for farmers. A farmer's decision-making power is influenced by a combination of their social, demographic, and economic factors, along with their goals, motivations, and psychological aspects (Taramuel-Taramuel et al. 2023). Even if the benefits of consolidation outweigh the costs, losing decision-making power can be challenging, as noted by Fan and Zhang (2019) where landowners' socio-demographic characteristics negatively affected the willingness to withdraw from rural homesteads. Socially, a shift towards a system of land consolidation could affect households' power dynamics regarding land and land-related decision-making. Land consolidation could also lead to unintended consequences, such as the problem of landless persons previously on leasehold tenure, further widening the socio-economic disparities within society (Kamau et al. 2022). For example, landless and young people were displaced in China during the implementation of the Link policy that consolidated the land of residents for farmland and resettled the residents to centralized modern communities (Cheng 2022). Rural-to-urban migration of families in search of alternative employment could leave the elderly in the village, a phenomenon observed in China where villages were left vacant either seasonally or permanently, or only the elderly and village elders were left behind (Li et al. 2014). A system of land consolidation could potentially free up labor for other purposes. For instance, freeing up of labor from the agricultural sector due to increase of agricultural productivity and structural transformation in Asian countries such as Japan and China facilitated the emergence and growth of other economies in non-agriculture sectors such as the service and manufacturing sectors (Asian Development Bank 2021; Sawada 2023)

It has been argued that farmers make land-use decisions mainly based on the expected returns and profits (Clough et al. 2016; Michler et al. 2017). Some farmers might want to shift toward land consolidation programs. Smallholder farms often have low productivity due to insufficient input use. By consolidating land under professional management and ensuring adequate input use, productivity is likely to increase. However, such consolidation typically favors a narrow range of priority crops, characteristic of large-scale commercial farming. This shift may come at a cost to local households, particularly in terms of dietary diversity and food security. The connection between land consolidation and food security is complicated as land consolidation may increase available calories while reducing diversity. For example, a focus on crop specialization can lead to the neglect of some food crops that are important for local diets and agro-biodiversity, even though it increases the supply of calorific crops such as maize, rice, and wheat. Consequently, changes in local food security may arise, including changes in food availability, quality, quantity, and diversity (Del Prete et al. 2019).

Two main activities guide land consolidation programs: land reallocation (or readjustment), and agrarian spatial planning. In Kenya, land reallocation is particularly significant due to the prevailing freehold tenure security, which grants farmers absolute rights over their land. This legal framework shapes how consolidation is approached. During stakeholder workshops, stakeholders expressed reluctance toward reallocation and relocation, preferring a model that excludes homestead areas from consolidation. This preference likely reflects concerns about tenure security or fears of power asymmetries, which could be perceived as precursors to land grabbing (Kariuki and Ng'etich 2016).

5.5.4 Methodological considerations

In this study, we developed a conceptual model with stakeholders selected based on their availability, experience, expertise, and gender. However, there is no guarantee that we captured all important variables (Luedeling et al. 2015). The stakeholder group included officials from both state and non-state entities. Such a composition may introduce unfavorable power dynamics and hinder the free exchange of ideas. To mitigate this, we organized two workshops–one exclusively for farmers–to provide a space where farmers could freely express their perspectives. Stakeholder-based modeling can introduce bias, which we minimized through calibration. However, residual bias may still persist, either among stakeholders when estimating inputs or within the researchers at any stage of the Decision Analysis approach.

Validating ex-ante projections is challenging (Luu et al. 2022). Nevertheless, such projections support decision-makers by preparing them for possible outcomes and identifying gaps that require additional information, ultimately aiding in making informed decisions. For example, we identified key uncertain variables related to maize and land prices. Instead of collecting additional information, we developed specific market price scenarios of maize and land prices–both individually and in combination. These scenarios revealed the price ranges under which consolidating land would be preferable for farmers and those in which maintaining farms would. Additionally, policy-makers can leverage the findings of these scenarios to design interventions that either stabilize the markets and support smallholder farmers or increase the attractiveness of land consolidation. For example, policies could include guaranteed minimum returns above farmers' production costs to cushion farmers against price volatility for the larger goal of conserving biodiversity. Additionally, targeted subsidy programs could incentivize voluntary land consolidation, while formalizing public-private partnership models specifically for agricultural land consolidation could help to achieve goals related to rural restructuring and development.

5.6 Conclusion

If policymakers decide to implement voluntary land consolidation programs, smallholder farmers will have to decide whether to or not to join. This decision is constrained by uncertainties surrounding the specific design of that policy and prevailing market dynamics, both of which impede robust decision-making. We used a Decision Analysis approach to evaluate whether the decision to join a land consolidation program is preferable for Kenyan farmers. Our results show that, based on 10,000 model runs, only 28% of the NPVs support the decision to join a land consolidation program as the preferable option, while 71% of the NPVs favor the alternative to “maintain farms”. Analysis of information value revealed that land and maize prices are critical variables, both of which require additional information. Based on these critical variables, we modeled market price scenarios and found that scenarios with high maize prices favored maintaining farms, while medium and high lease prices made consolidating land the more favorable option. Depending on policy priorities, land and maize prices can serve as leverage points for shaping rural land use governance. To date, little research has been done on land consolidation in Kenya, and future studies could consider the impact of cooperation among neighbors (Nyanghura et al. 2024) on land consolidation benefits.

6. Synthesis and policy implications

This thesis examines the need for and feasibility of diversification in agriculture through an integrated analysis of three core domains: science, policy, and practice. Each empirical chapter targets a distinct sub-component of the agricultural system, yet together they contribute to a unified argument that diversification needs to be conceptualized beyond agronomic variation. Commonly understood in terms of crops or farm-level diversity, diversification should also encompass knowledge production and decision-making processes to advance sustainable agricultural transformation. This thesis identifies the need for diversification in empirical studies in the science and policy domains, focusing on knowledge producers and stakeholder groups, respectively. Feasibility of diversification is explored in the practice and policy domains, using socio-economic conditions to predict suitability of financially viable diversified farming systems and by having diverse stakeholders in a transdisciplinary approach to evaluate land use decisions, respectively.

This chapter highlights the synthesis which focuses on key findings from chapters 3 to 5, policy implications, study's limitations, and suggests directions for future research.

6.1 Synthesis

In the science domain, the study presents a baseline assessment of knowledge production related to land science, focusing on the diversity of knowledge producers. A scientometric analysis reveals persistent representation gaps along both gender and ethnic lines across six land-related research areas. Women, particularly those from certain ethnic groups, such as Hispanic and Black communities, remain significantly underrepresented in knowledge production and in terms of authorship and citation impact. These findings reinforce longstanding concerns about structural exclusion in academic knowledge production. Given that women constitute 43% of the agricultural labor force globally (FAO 2011), such underrepresentation has epistemic and practical consequences. This dominance of homogenous authorship networks risks narrowing the scope of scientific inquiry and weakening the contextual relevance of research, particularly in addressing the needs and realities of marginalized populations. By intersecting demographic representation and linking them to authorship position and citation rates, the study reveals how intersectional inequalities shape who produces land-related knowledge. These intersectional inequalities reinforce dominant scientific narratives that often fail to account for marginalized populations, thereby undermining the contextual relevance and objectivity of land-related knowledge production. This analysis substantiates the argument that diversification within epistemic community is not merely normative but central to producing more inclusive and context-sensitive agricultural science.

In the practice domain, the study identifies the socio-economic conditions under which diversified farming systems are financially viable and predicts the global suitability for scaling diversified farming systems. Despite growing interest in diversification as a sustainability strategy, the socio-economic conditions that enable the profitability of diversified farming systems remain poorly understood. By identifying these conditions and adapting ecological niche modeling, a method typically used in species distribution studies (Phillips et al. 2006), the study offers a novel methodological approach for determining the spatial suitability of diversified farming systems. This methodological transfer allows for more precise identification of regions with high potential for profitable diversified farming systems, offering a significant improvement over conventional regression-based model. Results show that profitable diversified farming systems are feasible in areas close to cities in the Global South, where infrastructural access is relatively better. These findings have direct policy implications, particularly for guiding investments in infrastructural development. Moreover, diversified farming systems can act both as a push strategy (stimulating transitions in low-input systems) and a pull strategy (enhancing sustainability in high-input systems). This dual role aligns with the IPCC's (2022) concept of a "window of opportunity" for sustainable intensification, positioning diversification as a viable pathway for climate-resilient agriculture.

In the policy domain, the study evaluates land consolidation decision in a smallholder farming context in Kenya. While land consolidation is promoted in Sub-Saharan Africa as a strategy to address land fragmentation, empirical evaluations of its implications remain limited. Such interventions are often costly, multi-scalar, have unintended consequences, and often lack robust empirical data for evaluation. Stakeholders offer critical insights in such contexts. Employing a transdisciplinary framework based on Decision Analysis, the study incorporates perspectives from diverse stakeholder including heterogenous groups of smallholder farmers, policymakers, civil society actors, and researchers. These stakeholders provided critical insights into the perceived benefits, costs, and risks for smallholder farmers evaluating the decision to or not to consolidate land. Including diverse stakeholders provided experiential knowledge in data-scarce contexts and they challenged the feasibility of existing models of land consolidation for smallholders farming. The result was a co-developed land consolidation model better aligned with smallholder farmers realities. This approach demonstrates the value of stakeholder engagement in co-development processes. However, the study also acknowledges the challenges inherent in transdisciplinary work, including conflict, power asymmetries, and coordination demands. Effective facilitation, adequate time, and resources are essential to realize the full potential of stakeholder-driven evaluations. In the Kenyan context, where land consolidation research is sparse, this case study provides an empirical foundation for further inquiry into its socio-cultural, economic, and ecological dimensions.

Each empirical chapter has areas for further development. In the practice domain, identification of profitable diversified farming systems relied on economic evaluations from existing studies focused primarily on financial returns. Including ecological parameters such as biodiversity would yield a more comprehensive assessment. Nonetheless, financial metrics remain central to farmer decision-making. While this thesis examines diversification as beneficial, it does not sufficiently address its costs or complexities, especially in the science and policy domains. For example, stakeholder workshop costs are not reported, as they fall outside the study's objectives. In the practice domain, complexity is partly captured in yield-based production costs, but not disaggregated enough in the primary articles to isolate the specific cost of diversification. In most primary articles, costs were reported in totality and only in few articles were costs disaggregated into specifics of fixed and variable costs. A further point of reflection is that while the thesis centers on diversification, the policy chapter evaluated land consolidation, a practice that can undermine diversification by promoting monocultures. However, the findings reveal that land consolidation is generally less preferable for smallholder farmers.

The empirical chapters collectively argue that science, policy, and practice in agriculture are deeply interdependent. Due to this interdependence and recursive interactions, the agricultural system evolves. Working in silos or focusing on a single domain impedes systemic transformation. Within this framework, diversification cannot be viewed as a discrete intervention or solely as an agronomic practice, but as a unifying principle across all domains. Diversification has epistemic, institutional, and practical dimensions: in science, it demands rethinking of who produces knowledge that is often legitimized and how inclusive it is; in policy, it requires participatory evaluations that reflect stakeholder heterogeneity; In practice, diversification manifests through cropping systems, market strategies, and livelihood configurations–even if not fully addressed in this thesis.

Diversification functions as a feedback loop: science generates and expands context-sensitive knowledge; policy supports inclusive interventions and participatory evaluations; and farmers adapt based on real-world realities and outcomes. Thus, diversification can serve a prescriptive function, offering a framework to reconfigure agriculture towards sustainability by fostering complexity, adaptability, and inclusivity. However, this also introduces complexity in implementation, management and coordination, which future research especially in science domain could investigate more thoroughly. In policy domain, these costs of complexity may be reflected in planning and coordination and could be reasonably estimated.

In summary, the three empirical studies collectively support the central argument that diversification must be understood as a systemic lever. In science, it involves broadening participation to achieve epistemic justice and research relevance; in practice, it could imply identifying enabling conditions for financially viable conditions for scaling adoption of diversified farming systems; and in policy, it requires inclusive, transdisciplinary evaluation of policy decisions. These findings expand the concept of diversification beyond a technical solution, framing it as a structural and procedural imperative for agricultural sustainability. This thesis challenges simplification models of agricultural transformation and argue instead for inclusive and context-sensitive approaches. Opportunities for diversification exist including technological innovation, social capital, new business models, funding, and credit, and can support this transformation. By integrating insights from scientometrics, spatial modelling, and transdisciplinary evaluation, this thesis demonstrates that diversification, when pursued holistically, offers a promising framework towards sustainability, equity, and resilience.

6.2 Policy implications

In chapter 3, gender and ethnic gaps persist in research areas relevant to land use science. Male researchers publish more than their counterparts and are more likely to occupy first and sole author positions, with their research being cited more frequently. The intersection of gender and ethnicity marginalizes Hispanic and Black women researchers, which has significant policy implications. To address these inequalities, affirmative and supportive actions are needed to empower women and retain them in academia or knowledge production. Tailored actions may include mentorship programs for young female researchers, establishment of women's quotas in senior academic positions, financial and organizational support during parental leave, equal opportunities for grants, the development of stronger institutional capacities for researchers in the Global South, stricter ethical considerations between researchers of Global South and North to curb parachute research, and continued activism against systemic stereotypes affecting Black and Hispanic female researchers. Complementary yet supportive measures for external actors, such as publishing houses, should be strengthened, particularly regarding manuscript acceptance policies, which have been shown to exhibit bias against researchers from lower-income countries (Mammides et al. 2016).

Results of suitability analysis of profitable diversified farming systems in Chapter 4 revealed that key drivers were infrastructure (related to accessibility, electricity coverage, and cell connectivity) and where land allocated to cultivation was between 30% and 60%. This was reflective of many areas in the Global North. However, predicting other suitable areas showed hotspots in the Global South, primarily near cities. Investing in infrastructural developments especially in many countries in the Global South can support scaling up of diversified farming systems.

By involving diverse stakeholders in evaluating land consolidation decision on whether smallholder farmers should or should not join a land consolidation program in Chapter 5, showed that conventional models of land consolidation may not address the needs of smallholder farmers. Stakeholders indicated that farmers would prefer a nuanced land consolidation model that takes into consideration their local realities. Policies should consider different land consolidation implementation models tailored to the needs and contexts of the target communities such as those that would allow smallholder farmers to retain their homestead areas while consolidating arable land only. Simulation results suggested that consolidating land would not be preferable for farmers compared to maintaining the present systems. However, market price scenarios based on critical uncertainties (land and maize prices) indicated that medium to high land prices make land consolidation a more attractive option, while high maize prices favor present system. Policy-makers can take actions that stabilize the markets to support smallholder farmers or increase the attractiveness of land consolidation. For example, policies could include guaranteed minimum returns above farmers' production costs to cushion farmers against price volatility for the larger goal of conserving biodiversity. Alternatively, policy-makers can create targeted subsidy programs that could incentivize voluntary land consolidation, or formalizing public-private partnership models specifically for agricultural land consolidation to help achieve goals related to rural restructuring and development.

6.3 Limitations and future research considerations

The limitations of the studies in Chapters 3 and 4 primarily relate to the datasets used. The analysis of diversity among knowledge producers in land-related research was limited by language and publication format. The study included peer-reviewed journal articles published in English, which likely excluded non-English publications and grey literature, particularly from Global South, where linguistic and publication diversity is greater. Additionally, the tools used for gender and ethnicity assessment may introduce classification bias. Although robustness checks (with error margins between 2% and 5%) confirmed the robustness of the findings, future studies could consider integrating multilingual databases and alternative publication formats to enhance representativeness and inclusivity in scientometric analyses.

The datasets used to model the suitability of profitable diversified farming systems varied in both temporal and spatial resolution, which may affect prediction accuracy. Although we applied rigorous statistical checks and used multiple thresholds to capture uncertainty levels, future research could improve reliability by triangulating niche modeling outputs with other statistical approaches such as generalized linear or additive models. Furthermore, advancing the quality, resolution and temporal consistency of datasets will be essential for improving model robustness.

The stakeholder-driven modeling applied in Chapter 5, while participatory in nature, has inherent limitations. First, it does not guarantee inclusion of all relevant variables, and second, it may reflect subjective biases in stakeholder inputs. We however conducted calibration training to help stakeholders recognize their own biases, and techniques were introduced to help the overcome biases. Validating ex-ante evaluations remains a challenge. Research on land consolidation in Kenya is limited. Thus, future studies could explore the role of cooperation among neighbors in maximizing the benefits of land consolidation. Investigating the perceptions and attitudes of diverse stakeholders such as farmers, input suppliers, and aggregators, can generate valuable insights for shaping land consolidation policy. Additionally, spatial assessments of land suitability for consolidation could help identify priority areas of priority for implementation.

More broadly, across the dimensions of diversification examined in this study, several systemic constraints such as institutional inertia, policy fragmentation, and socio-economic inequality remain understudied. Future research could examine the impacts of specific interventions (e.g., preferential hiring in academia, targeted subsidies for diversified farming systems adoption) on these dimensions and assess their potential to counteract systemic simplification in agricultural systems.

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8. Supplementary information

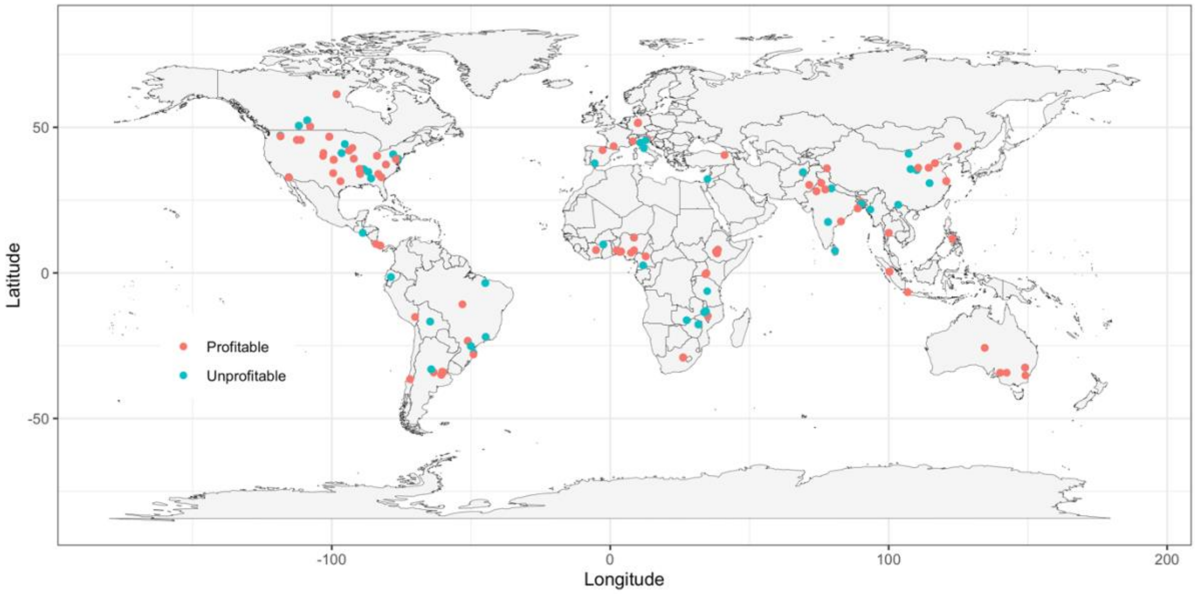
This chapter provides supplementary information for Chapter 4 structured as methods and results.

8.1 Supplementary Note 1: Methods

Meta Analysis

The meta-analysis summarizes data from 119 peer reviewed publications comparing diversified farming systems (intervention) to simplified farming systems (control). Included DFS practices are agroforestry, crop rotation, intercropping, embedded natural habitats and combined practices while simplified farming practices are monocultures, practices when compared with diversified practices have comparatively lower number of varieties or species e.g., a crop rotation with a single crop compared with crop rotation in tandem with intercropping or with multiple crops. Similarly, an agroforestry involving one species compared to a multi-strata agroforestry.

The meta-analysis included studies published between 1968 to 2019 with 62% of the effect sizes focusing on America, 21% on Asia, 13% on Africa, 1% on Oceania and < 1% Europe. Most studies compared crop rotation 42% (Supplementary Table 8.1) to monoculture as a simplified farming practice (85 %). Although diversified practices were studied alongside different crop combinations, cereals and cereal combinations (pulses, vegetables, oil-bearing) had the largest share of 85%. Outcome variables indicating profitability included net income (40%), gross income 17%), gross margin (25%), total cost (15%), and benefit cost ratio (3%). SDM represented 65% of the effect sizes, while log response ratio was 35%. Out of the 3192 effect sizes, 2322 were positive and the remaining 860 were negative (Supplementary Figure 8.1)



Supplementary Figure 8.1: Study locations of profitable (n = 2232, red points) and unprofitable (n = 860, teal points) diversified farming practices based on the dataset provided by Sánchez et al. (2022).

Supplementary Table 8.1: Description of the meta-analytical data obtained from Sánchez et al.

Variable			**%**
Number of effect sizes	3192		
Countries represented	39		
Year of financial assessment	1968	2019	
	NA	2	0.06
	Cereals	1479	46.33
	Vegetables	432	13.53
	Pulses	416	13.03
	Oil bearing	200	6.27
	Cereals, Vegetables	138	4.432
	Fruits	134	4.2
	Cereals, Oil-bearing	109	3.41
	Fibers	73	2.29
	Roots	40	1.25
	Cereals, Oil-bearing, Pulses	36	1.13
	Cereals, Roots	24	0.75
Crops studies according to FAO classification	Stimulants	22	0.69
	Fruits, Spices	18	0.56
	Fodder	16	0.5
	Fruits, Stimulants	12	0.36
	No data	10	0.31
	Cereals, Fodder	10	0.31
	Cereals, Fodder, Stimulants	8	0.25
	Fodder, Pulses	5	0.16
	Tobacco, Vegetables	2	0.06
	Cereals, Roots, Vegetables	2	0.06
	Cereals, Fodder, Sugar	2	0.06
	Sugar	1	0.03
	Cereals, Oil-Bearing, Pulses, Roots, Vegetables	1	0.03
	Monoculture	2727	85.43
	Crop rotation - low diversity	332	10.4
	No cover crops	41	1.28
Simplified farming practices	Agroforestry (simple)	31	0.97
	No hedgerow	30	0.94
	Cover crops - low diversity	23	0.72
	No mixed farming	8	0.25

Diversified farming practices	Crop rotation	1351	42.32
	Intercropping	919	28.79
	Associated plants	547	17.14
	Combined practices	173	5.42
	Agroforestry	121	3.79
	Embedded natural	81	2.54
Financial outcomes	Net income	1265	39.63
	Gross margin	800	25.06
	Gross income	534	16.73
	Total cost	503	15.76
	Benefit cost ratio	90	2.82

Predictor Variables

We included environmental, social, economic, and governance variables to wholesomely describe factors that shape conditions for profitable agriculture (Supplementary Table 8.2). Inclusion of these variables was informed by varied published literature on drivers of profitability in the context of agriculture.

Environmental variables related to cropland extent and soil organic carbon, we obtained from Potapov et al.(2022). Different indicators like soil organic matter, soil organic carbon, water retention capacity, and hydraulic capacity, major soil elements (e.g., nitrogen, potassium, sodium, and phosphorus) represented gridded soil organic carbon data up to a depth of 2m (Batjes 2016). Literature on farm size and diversification is conflicting. For example, Derso et al. (2022) in Ethiopia found that farmers with small land parcels are likely to diversify crops while an increase of farm size by unit hectare negatively affects probability of diversification by over 25 percent. On the other hand, Makate et al. (2016) found farmers with larger farm sizes were more likely to diversify and over 15 percent probability increase in adoption of diversification with an increase in a unit acre of farm size in Zimbabwe. Regardless of the lack of consensus on farm size, the proportion of land under cropland remains relevant in assessing profitability of the diversified farming systems. Furthermore, such information is useful to farmers as either small- or largescale farmers can shift from their current farming systems to DFS. Conversely, other land related factors like tenure could play a bigger role in aiding or hindering adoption of DFS especially long term practices like agroforestry, crop rotation, and organic certified farming (Sain et al. 2017; Kamau et al. 2018b) but are not considered in this study.

We use population size and density as indicators for the presence of labor and consumers of agricultural products. Studies show correlation between high education levels and increased application and consumption of sustainable farming practices like diversified farming systems, organic farming, agroecology among others and their products (Kurgat et al. 2018). To reflect the rationality of decision making and the impact of education on application and adoption of diversified farming practices on land, we used the composite Human Development Index (HDI). In addition, this index provides information on the living standards which is likely to correlate with the purchasing power of the people. We also used the Gross Domestic Product per capita (purchasing power parity) (GDP per capita) as an indicator of economic growth to show the income levels of the nation. While previous studies have found correlation between HDI and GDP per capita (Elistia and Syahzuni 2018), we included both variables as the former is a measure of human development and one of the indicators of economic growth and GDP per capita. Gridded data on GDP per capita and HDI were obtained from (Kummu et al. 2018).

Economic development is shown in this study by infrastructural dynamics. For example, we relate accessibility and proximity to goods and services to time taken to travel to the nearest cities or urban centers. Transport costs contribute to variable costs. Less time spent on the road to reach markets provides numerous benefits through reduction of physical and market risks (Bowman and Zilberman 2013; Bendinelli et al. 2020). Furthermore, access to and development of transport infrastructure positively correlates with increased efficiencies in terms of delivery, access to resources, market information labor, and establishment of new businesses (Warr 2010; Amador-Jimenez and Willis 2012). Increased delivery efficiencies reduce costs by shortening time taken to transport produce while preserving their freshness consequently reducing the need for on-farm storage, and speeding up trade. To show travel time, we used a gridded accessibility global raster map that reflects time required to get to the nearest urban center (continuous area with 1500 inhabitants or more per square kilometer or with a population of 50,000 inhabitants) (Weiss et al. 2018).

Nighttime lights represented electricity coverage. Nighttime lights have been used as indicators of the intensity of socio-economic activities like urbanization and electricity consumption across scales (Li et al. 2020). Electricity coverage has previously been linked to reduction of post-production risks of food wastage from lack of preservation or value addition (Bendinelli et al. 2020), which cushions the farmers from market risks. In Brazil for instance, an increase in rural electrification as part of universal access to electricity for poverty alleviation resulted in an increased conservation by reducing firewood use from 25% to 12% before and after electrification and an increased agricultural production through irrigation using water pumps (da Silveira Bezerra et al. 2017). For Uganda, Elias and Bower (2015) estimated a 50% income change from business as usual (rainfed) to irrigated agriculture enabled through the provisioning of electricity among coffee, beans, and maize farmers. We obtained nighttime data from the NASA SEDAC website (Small et al. 2018).

ICT is important for information sharing and acquiring for farming technologies and marketing. In Kenya for example, Irungu et al. (2015) found that the youth leveraged ICT to enhance agriculture through formation of programs where they can gain information and knowledge on practices and eventually gain niche markets for their produce. In Malawi, Jolex and Tufa (2022) found that profitability of the 'agriprenuers' increased with the number of ICT tools, for instance, over 4 ICT tools translated to an odds ratio of 130 points. Obtaining data on mobile coverage as a measure of ICT coverage was challenging because of proprietary issues.

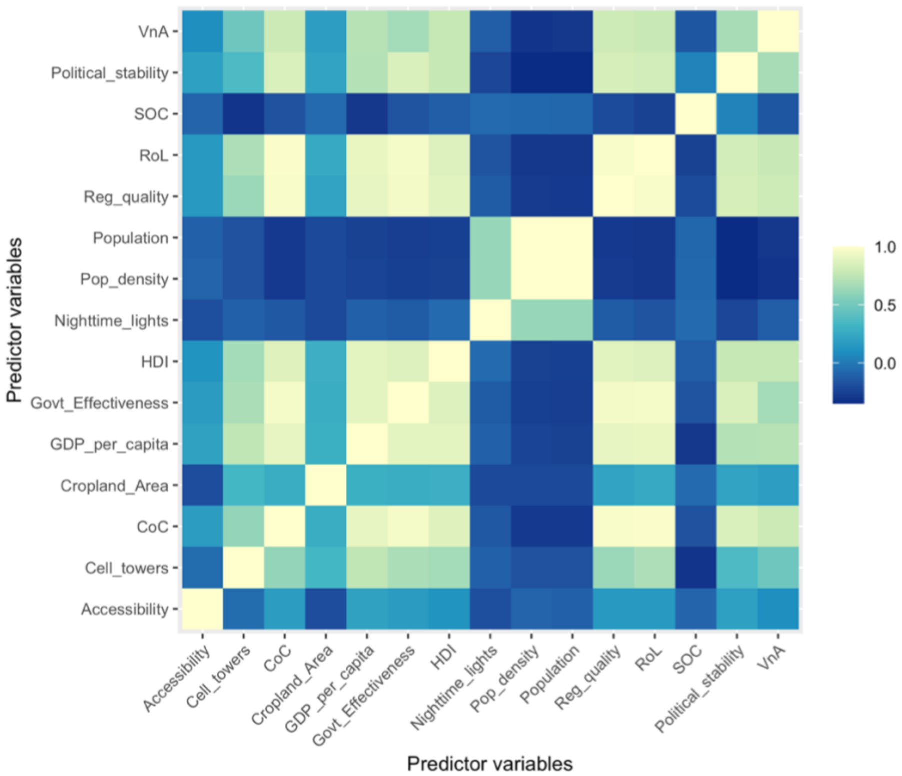
Instead, we used national level data on the number of cell towers obtained from the Homeland Infrastructure Foundation–Level Data (HIFLD).

Policies and governance shape market prices and conditions. In this study we used governance variables from the Worldwide Governance Indicators (WGI) comprised of six indices that capture government processes from its formulation to operation, the government's ability to make and implement policies and to respect those policies regarding citizens and its institutions (Kaufmann et al. 2010). These indicators are voice and accountability, political stability and no violence, governance effectiveness, regulatory quality, rule of law, and control of corruption. Each indicator estimates governance by an estimate that ranges from 2.5 (strong) to -2.5 (weak). Governance and its regulations affect market and economic efficiencies, labor markets and profits (Yung and Root 2019; Al-Thaqeb and Algharabali 2019), hence supporting the inclusion of these variables.

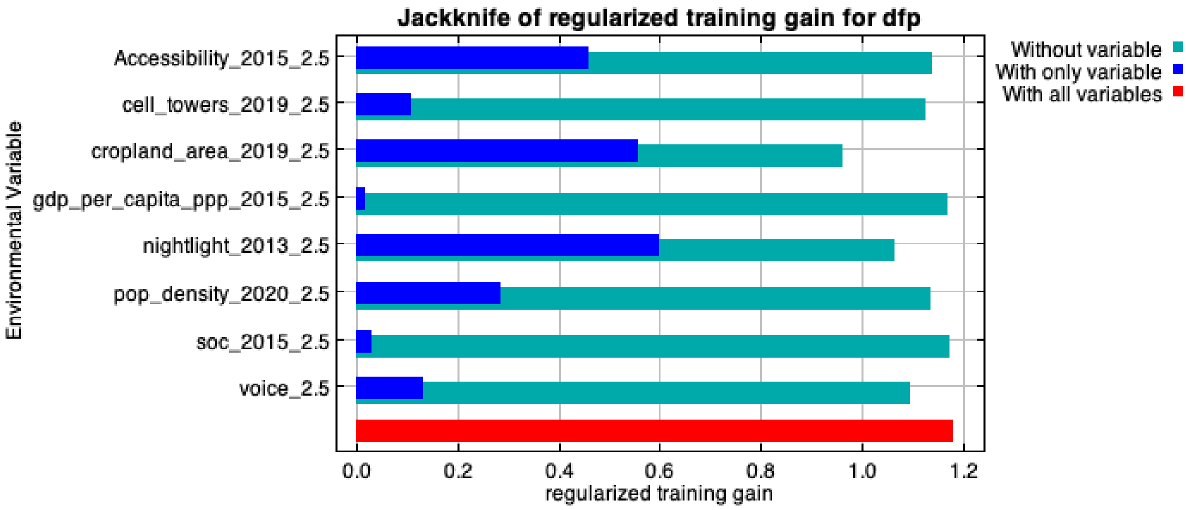
Prior to modelling, we conducted a correlation test and excluded highly correlated variables (Pearson correlation coefficient > 0.8) as recommended Feng et al. (2019) (Supplementary Table 8.3, Supplementary Figure 8.2).

Modeling

Model creation and evaluation was based on the MaxEnt approach and executed on R (R Core Team 2022) using `kuenm` package (Cobos et al. 2019). The first model run was done using 8 predictor variables while the second model was based on the jackknife results of the first model (Supplementary Figure 8.3)



Supplementary Figure 8.2: Heatmap of Pearson correlation coefficients between predictor variables. Note: Full names of variables as they occur: - Market accessibility, Number of cell towers, Control of Corruption, Cropland area, GDP per capita (PPP), Government effectiveness, Human development Index, Nighttime light, Population density, Population count, Regulatory quality, Rule of Law, Soil Organic Carbon, Political stability and no violence and Voice and Accountability.



Supplementary Figure 8.3: Jackknife results indicating variable importance of the selected model. While the dark blue bars indicate the regularized training gain if only that one variable was used to create a model, the length of the teal bar indicates the gain if this respective variable was excluded.

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Supplementary Table 8.2: Summary of the original formats, sources, units and temporal as well as spatial extent of the predictor variables

Category	Predictor variable	Source	Units	Temporal Extent	Spatial Extent	Original format
Environmental	Cropland area	Potapov et al. 2021	% of croplands/pixel	2019	1.5 arc min	Geo Tiff
	Soil organic carbon	Batjes 2016	MgC/ha	1950-2015	0.5 arc min	Geo Tiff
Social	Population density		persons/Km^2		2.5 arc min	ESRI ascii
	Population count		persons		2.5 arc min	ESRI ascii
Economic	Gross Domestic product per capita (PPP)	Kummu et al. 2018	USD	1990-2015	0.5 arc min	netCDF
	Human Development Index	Kummu et al. 2018		1990-2015	0.5 arc min	netCDF
	Nighttime light coverage	Small et al. 2018		1992, 2002, 2013	0.25 arc min	Geo Tiff
	Accessibility	Weiss et al. 2018	minutes	2015	0.5 arc min	Geo Tiff
	ICT coverage[1]	HIFLD		2019	National	Xlsx
Governance	Voice and accountability	Kaufmann et al. 2010		1996 - 2020	National	Xlsx
	Political stability and no violence	Kaufmann et al. 2010		1996 - 2020	National	Xlsx
	Governance effectiveness	Kaufmann et al. 2010		1996 - 2020	National	Xlsx
	Regulatory quality	Kaufmann et al. 2010		1996 - 2020	National	Xlsx
	Rule of law	Kaufmann et al. 2010		1996 - 2020	National	Xlsx
	Control of Corruption	Kaufmann et al. 2010		1996 - 2020	National	Xlsx

[1] (https://hifld-geoplatform.opendata.arcgis.com)

Supplementary Table 8.3: Pearson correlation matrix of predictor variables with levels of significance

Variables	Accessibility	Cell towers	Control of Corruption	Cropland Area	GDP per capita	Government Effectiveness	HDI	Nighttime lights	Population density	Population count	Regulatory quality	Rule of Law	Soil Organic Carbon	Political stability	Voice and Accountability
Accessibility	**1**	-0.06	0.17	-0.2*	0.2*	0.16	0.12	-0.19*	-0.1	-0.11	0.15	0.15	-0.1	0.19*	0.09
Cell towers		1	0.61****	0.33***	0.75****	0.68****	0.66****	-0.11	-0.18	-0.18	0.63****	0.69****	-0.31***	0.36***	0.48****
Control of Corruption			1	0.27**	0.9****	0.96****	0.87****	-0.15	-0.29**	-0.29**	0.97****	0.98****	-0.18*	0.85****	0.79****
Cropland Area				1	0.29**	0.27**	0.28**	-0.22*	-0.22*	-0.22*	0.21*	0.25**	-0.07	0.21*	0.18
GDP per capita					1	0.89****	0.89****	-0.11	-0.24**	-0.25**	0.9****	0.91****	-0.3**	0.71****	0.72****
Government Effectiveness						1	0.86****	-0.14	-0.26**	-0.27**	0.95****	0.96****	-0.17	0.85****	0.66****
HDI							1	-0.07	-0.25**	-0.26**	0.88****	0.86****	-0.13	0.77****	0.77****
Nighttime lights								1	0.62****	0.62****	-0.14	-0.17	-0.07	-0.23*	-0.13
Population density									1	1****	-0.28**	-0.3**	-0.08	-0.35***	-0.31***
Population count										1	-0.29**	-0.3**	-0.09	-0.35***	-0.3**

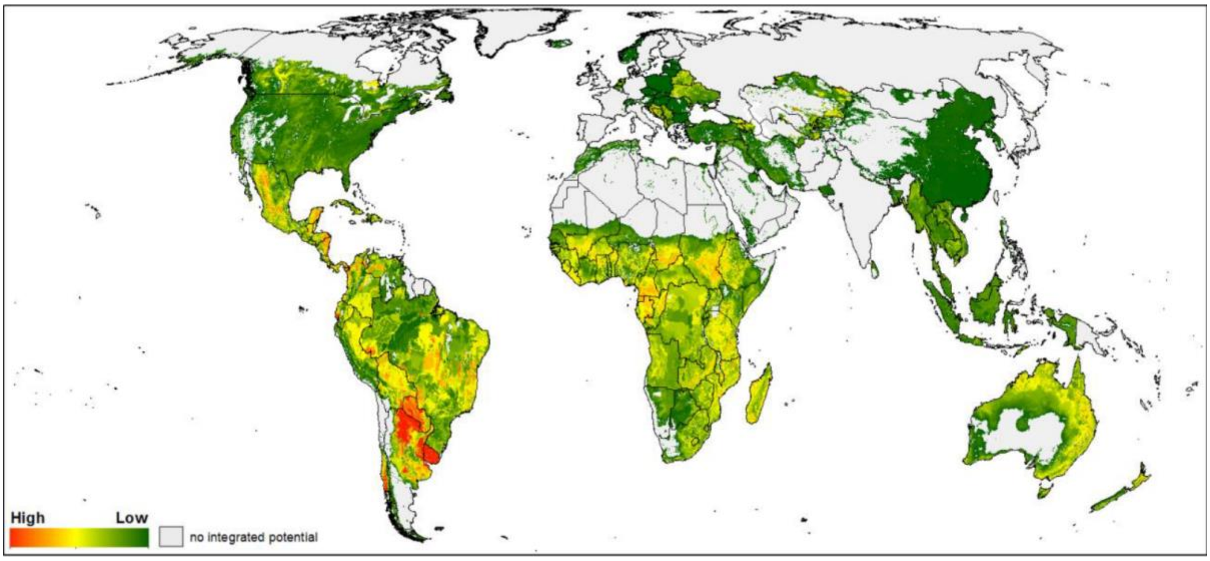
Regulatory quality	1	0.97****	-0.21*	0.83****	0.8****
Rule of Law		1	-0.25**	0.82****	0.78****
Soil Organic Carbon			1	0.04	-0.16
Political stability				1	0.67****
Voice and Accountability					1

a) *Note: Significance levels: p ≤ 0.0001 ****, p≤ 0.001 ***, p ≤0.01 **, p≤ 0.05 **

Boxes in red were considered perfectly correlated (Pearson correlation coefficient > 0.8)

Integrated potential for crop expansion

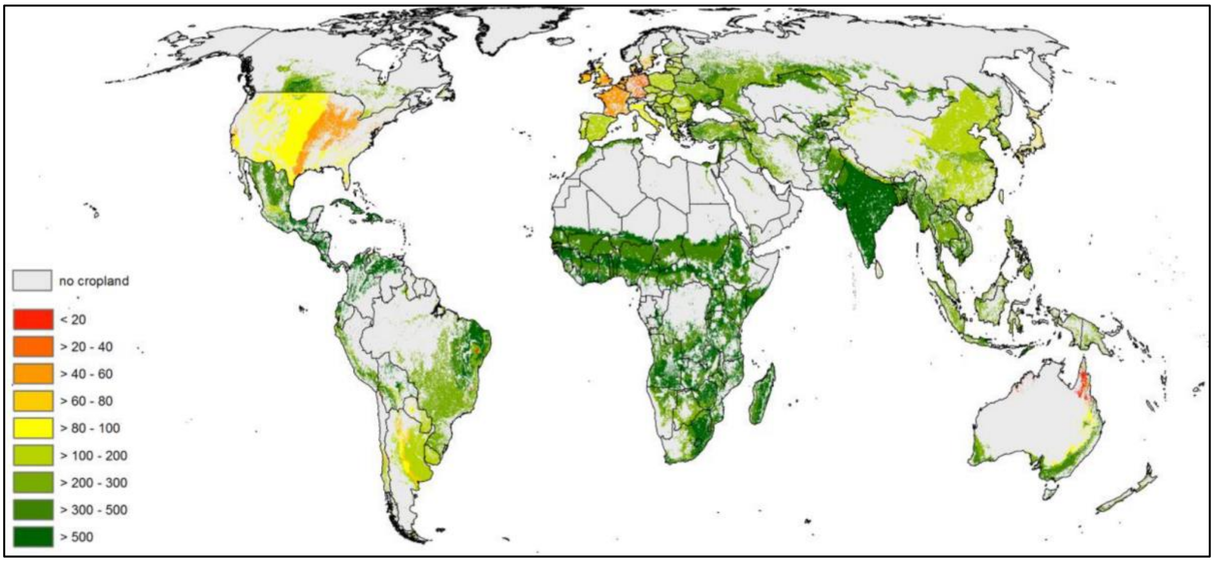
Supplementary Figure 8.4 shows the integrated potential for cropland expansion by 2030, which is as a result of the combination of biophysical constraints of agriculture and socio-economic conditions. First the biophysical expansion potential was determined through combination of 17 crops suitability with available land for expansion. Available land for expansion was defined as all suitable land except that that is already under cultivation or has been urbanized. Available land was based on land use/cover classification of ESA-CCI (Ramankutty et al. 2018). The end map was obtained through weighting the biophysical expansion potential with the socio-economic expansion forecast by 2030 by FAO (Alexandratos and Bruinsma 2012). Areas marked with red color indicate high suitability for biophysical potential and socio-economic expansion rate, while green color indicate less potential for either biophysical or expansion rates. In areas where expected potential for cropland was expected to decrease, it was set at zero.



Supplementary Figure 8.4: Integrated potential map for cropland expansion. This map is sourced from Zabel et al. (2019). Bright red color indicates high suitability for both biophysical potential and socio-economic expansion by 2030. The green color shows less potential for either biophysical or socio-economic expansion while grey areas show unsuitability.

Integrated potential for intensification

Supplementary Figure 8.5 represents the integrated potential for intensification, which was derived by firstly, simulating the biophysical potential of yields of the 17 crops under ideal management. The ideal conditions assumed in the simulation included; presence of adequate nutrient, absence of pests and diseases, timely and optimal sowing dates, cropping density (number of harvests per year), and crop adaptation to climate conditions of 2011-2040. Simulated yields of 17 crops were aggregated across different regions and models validated at field scale. The simulated yield was compared against the statistical yield at country level to yield a ratio, biophysical intensification potential. The biophysical intensification potential ratio was then combined with the marginal profitability of crops through the general equilibrium model Dynamic Applied Regional Trade (DART/DART-BIO) to allocate crops by maximizing profits. To achieve a stable allocation of the model, modeling is done iteratively. During the iterations, the model allows for changes in dynamics over time like changing agricultural productivities, technological advancements, shifts in consumption patterns, farmers' changing decisions on cropping, or climate change, which reallocates the marginal profitability until a stable allocation is reached. In simpler terms, supplementary figure 5 reflects the potential yield achievable on presently cultivated cropland areas if optimal crop management were implemented under market-oriented conditions.



Supplementary Figure 8.5: Shows integrated potential for intensification given in percent of the potential yield increase in comparison to statistical yields. Sourced from Zabel et al. (2019). Red color indicates less low intensification potential while green indicates where intensification is high.

8.2 Supplementary Note 2: Results

Model parameters and evaluation

Supplementary Table 8.4: Characteristics of models that met the selection criteria of being statistically significant (partial ROC), having omission rates ≤ 5% and lowest (≤ 2) delta AICc. FC is feature classes and RM is regularization multiplier of the selected mode

Model number	FC	RM	Mean AUC	Mean AUC ratio	Partial ROC	Omission rate 5%	AICc	Delta AICc	Weight AICc	Number of Parameters
Initial model	lq	1	0.878	1.51	**0**	0.056	3307.49	**0**	1	13
Subsequent model	lq pt	3	0.896	1.53	**0**	0	3307.06	**0**	0.64	13

Maxent Suitability thresholds

Different thresholds imply different results in suitability distribution. However, in our modeling when different thresholds were applied (Supplementary Table 8.4), the distribution of suitable habitats was high in the Global North and around cities and coast lines in the Global South (Supplementary Figure 8.3).

Supplementary Table 8.5: Threshold values of different threshold types applied to predict distribution of suitable areas for profitable diversified farming practice.

Threshold type	Initial	subsequent
Balanced training omission, predicted area and threshold value	0.0672	0.0755
Maximum training sensitivity plus specificity	0.2685	0.2978
Equal training sensitivity and specificity	0.2608	0.3185
10 Percentile training presence	0.157	0.1995

Area of the suitable habitats

Based on binary maps of suitable and unsuitable maps in Supplementary Figure 8.6, we calculated the size of suitable land for profitable diversified farming systems.

Supplementary Table 8.6: Area in km^2 of the suitable land for profitable diversified farming systems when different thresholds were applied

Threshold type	Threshold	Global suitable area in km^2	% of total land
Balanced training omission, predicted area and threshold value	0.0755	93,221,627	62.59
Maximum training sensitivity plus specificity	0.2978	31,451,649	21.12
Equal training sensitivity and specificity	0.3185	29,130,185	19.56
10 Percentile training presence	0.1995	45,979,800	30.87

Based on Figure 4.1 in chapter 4, which combines different models with different thresholds to distinguish low and high suitability areas, we calculated the area of the categorized suitability (Supplementary Table 8.7)

Supplementary Table 8.7: Area in Km^2 of suitable land when 4 models are combined as in Figure 4.1

Suitability level	Global suitable area in km2	% of total land
Highly suitable (4)	29,130,185	19.56
Moderately suitable (3)	2,321,464	1.56
Suitable (2)	14,528,151	9.75
Least suitable (1)	47,241,827	31.72
Unsuitable (0)	79,050,165	53.08

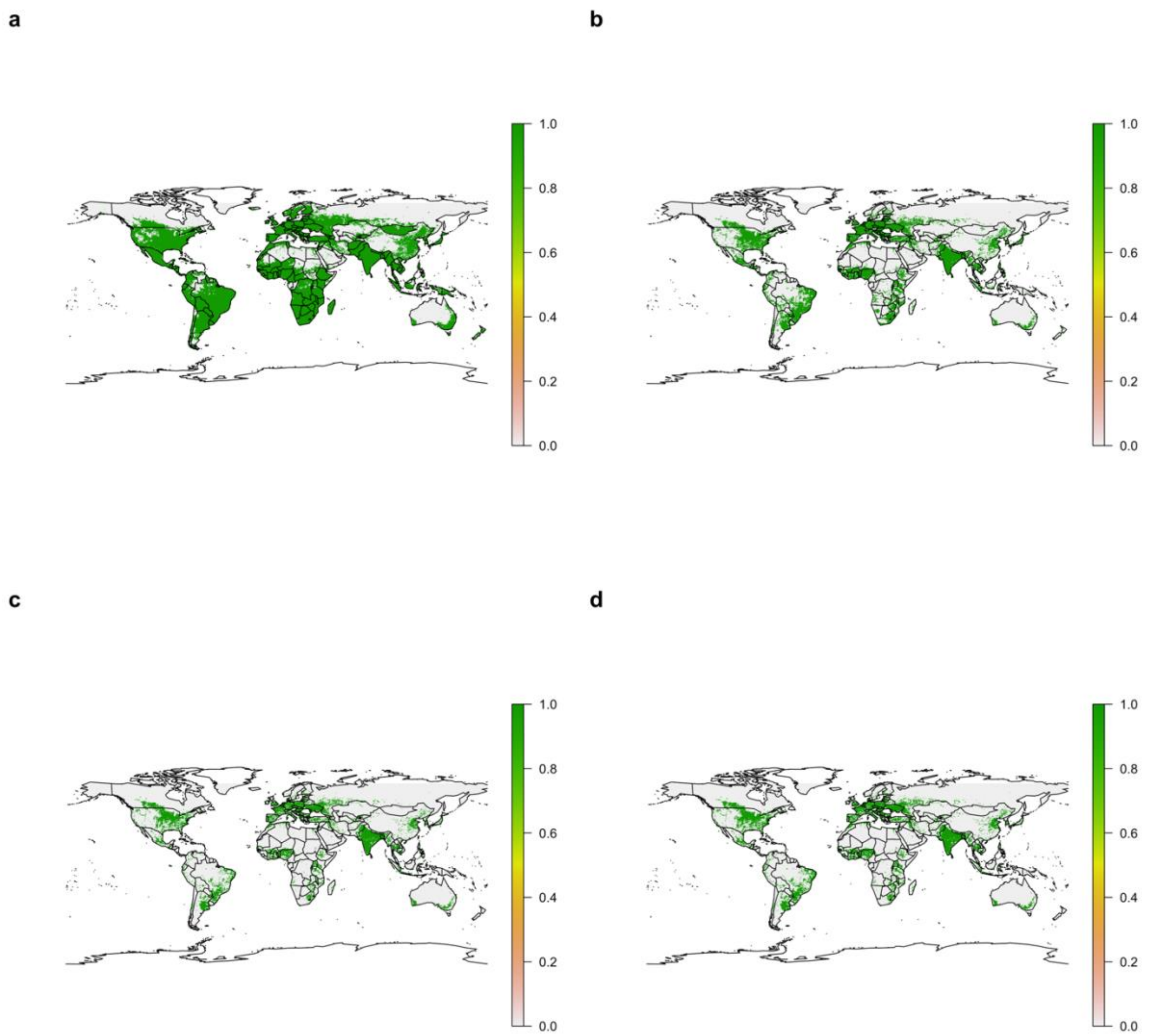
Socio-economic variable importance and their impact

Supplementary Table 8.8: Percent contributed by variables to the models with relative estimate of permutation importance.

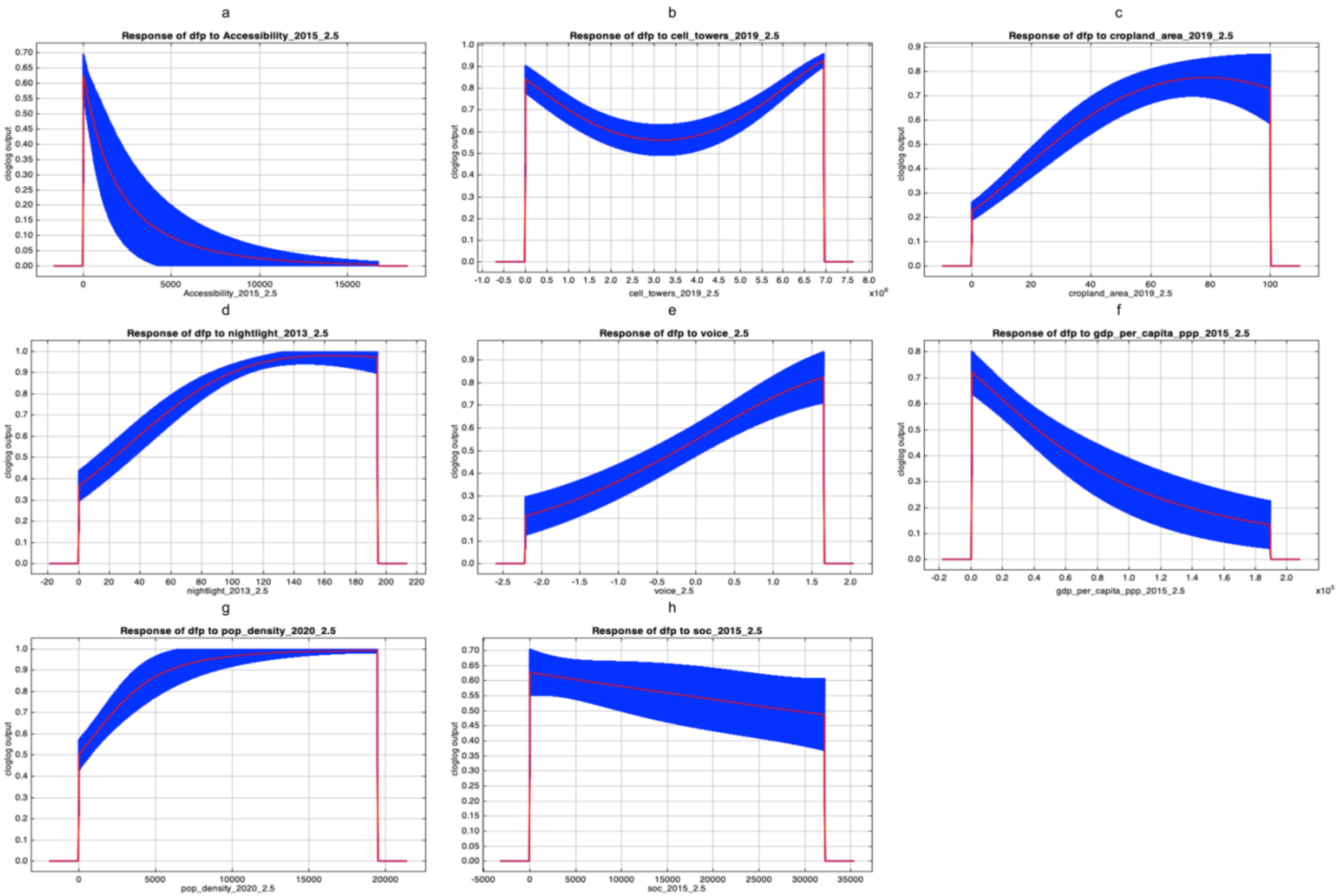
Variable	Permutation Importance	
Accessibility	35.6	32.3
Cropland area	26.5	21.5
Voice and accountability	16.1	15.6
Electricity coverage	10.5	21.1
GDP per capita ppp	4.8	9.5
Cell towers	3.5	
Population density	2.3	
Soil organic carbon	0.7	

Response curves

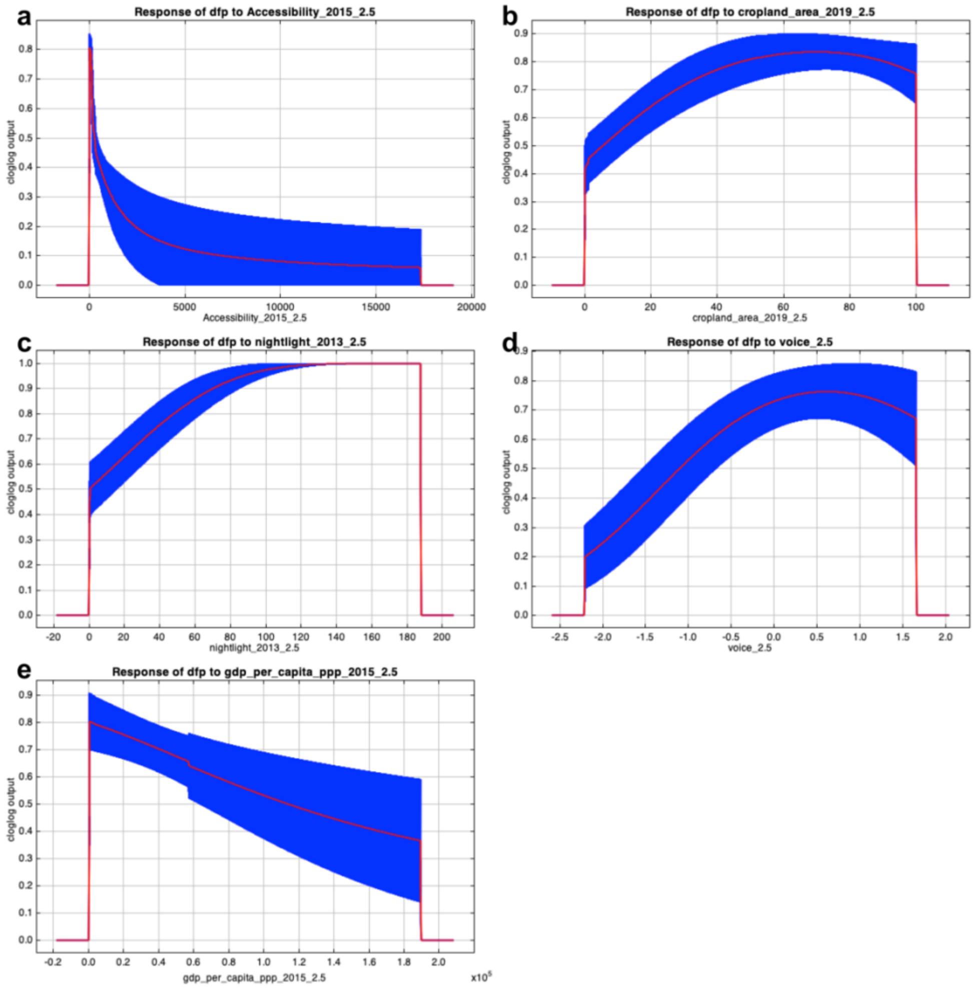
Supplementary Figure 8.7 and Supplementary Figure 8.8. Maxent generates the response curves of each of the predictor showing the probability of presence when the variable is varied. The Figures represent response curves when we used 8 and 5 predictor variables in our initial and subsequent model runs.



Supplementary Figure 8.6: Current potential distribution of profitable diversified farming practices under different thresholds. **a** represents balanced training, predicted areas threshold value (0.0755), **b** is maximum training sensitivity plus specificity (0.2978), **c** is equal training sensitivity and specificity (0.3185), and **d** represents 10 percentile training presence (0.1995) all in cloglog threshold.



Supplementary Figure 8.7: Marginal response curves of the maxent model showing corresponding variation of probability of presence of profitable diversified farming practices when predictor variables are varied. **a** is accessibility, **b** is cell towers, **c** is cropland area, **d** is electricity coverage, **e** is voice and accountability, **f** is GDP per capita, **g** is population density, and **h** is soil organic carbon.



Supplementary Figure 8.8: Marginal response curves that show the probability of presence (profitable diversified farming systems) in clog-log output when five predictor variables were varied. **a** represents variable accessibility in time, **b** is variable cropland area in %, **c** is the value of electricity coverage given in nighttime light, **d** is governance variable–voice and accountability–and **e** represents GDP per capita in dollars.

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