Sustainable agricultural adaptation under climate change: Insights from Northeast India and the Brazilian Amazon

Dissertation

zur Erlangung des Doktorgrades
an der Fakultät für Mathematik, Informatik und Naturwissenschaften
Fachbereich Erdsystemwissenschaften
der Universität Hamburg

vorgelegt von
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Hamburg, 2024

Fachbereich Erdsystemwissenschaften

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Abstract

Climate change, increasing global pressure on land resources, and society's ambition to reduce environmental impacts demand a sustainable adaptation of the agricultural sector. This includes the adoption of agricultural practices that efficiently manage natural resources, conserve soils and carbon stocks, and avoid expansion into tropical forest areas while providing sufficient food for a growing world population. This thesis analyzes sustainable agricultural adaptation for two case study regions in tropical forest-agriculture frontiers, where interactions between agricultural production and environmental impacts are evident and severe. The first case study region is Nagaland State in Northeast India, where upland smallholder production by tribal communities dominates the agricultural landscape. The second case study region is Novo Progresso in the Brazilian Amazon, a region dominated by extensive cattle ranching, which has become a hotspot of agricultural expansion and forest loss as a result of increasing integration into global agricultural commodity markets. By focusing on sustainable adaptation at the farm level, this thesis is concerned with two strategies: the adoption of soil and water conservation practices (SWCP) and land intensification (LI). Based on an interdisciplinary study approach, this thesis aims to identify factors that motivate and constrain the adoption of SWCP and LI and to analyze the specific effect of climate change on these adaptation strategies. From a methodological perspective, this thesis aims to identify gaps in model-based land use assessments and potentials for improving agricultural land use projections. Considering agriculture as a complex socio-ecological system, I combine different methods from the social and natural sciences, namely qualitative and quantitative surveys, behavioral theories, biophysical modeling, and statistics.

Key results of this thesis provide empirical evidence that agricultural adaptation in both contexts is often motivated by economic incentives, justifying, at least in part, utility and profit maximization-based land use modeling approaches. However, results also reveal various context-independent and context-specific constraints of adaptation. On the producer level, limited knowledge and poor access to financial resources, labor force, and markets were found to slow down adaptation in both study regions, while context-specific factors are mostly related to farmers’ attitudes. In the Brazilian Amazon, risk-averse attitudes largely restrict pasture-to-cropland conversions, while in Northeast India, social and ecological attitudes shape adaptation preferences. Likewise, climate change effects on adaptation are context-dependent, with perceived climatic changes promoting the adoption of SWCP in Northeast India while being largely ignored in the Brazilian Amazon. This thesis also highlights a trade-off between climate change adaptation and land intensification in Northeast India, as simulation results indicate soil erosion increases from both rising precipitation and cropping intensities. While underlining the role of actor and landscape constraints in agricultural adaptation, results show that these were considered only to a limited extent in existing land use models. In particular, risk aversion and infrastructure variables remain underrepresented in most modeling approaches. Results emphasize a lack of empirical data as a main limitation in land use modeling and the importance of model integration for improving the plausibility of agricultural land use projections.

This thesis advances research on the agriculture - climate change - adaptation interface in a two-fold way. On the one hand, by identifying relevant factors of farm-level adaptation and comparing these to agricultural land use models, this work improves the empirical knowledge about adaptation processes and reveals gaps in model-based land use assessments. On the other hand, this work strengthens the connection between different disciplines for a study context that can only be comprehensively understood through interdisciplinary research. In doing so, this thesis can contribute to improving policies on and projections of sustainable agricultural development.

Zusammenfassung

Der Klimawandel, der steigende globale Flächendruck, und die zunehmend an Bedeutung gewinnende gesellschaftliche Forderung, Umweltauswirkungen landwirtschaftlicher Produktion zu reduzieren, erfordern eine nachhaltige Anpassung des Agrarsektors. Dies beinhaltet die Verbreitung landwirtschaftlicher Anbauformen, die eine effiziente Ressourcennutzung sowie den Schutz von Böden und Kohlenstoffspeichern sicherstellen und eine weitere Ausdehnung der Landwirtschaft in tropische Waldbestände verhindern, gleichzeitig aber eine ausreichende Nahrungsmittelproduktion für eine wachsende Weltbevölkerung gewährleisten. Diese Doktorarbeit beschäftigt sich mit einer nachhaltigen Anpassung der Landwirtschaft in zwei tropischen Agrar-Frontier Gebieten, wo die Beziehungen zwischen landwirtschaftlicher Produktion und Umweltauswirkungen offensichtlich und gravierend in Erscheinung treten. Die Forschungsregionen dieser Arbeit umfassen den nordostindischen Bundesstaat Nagaland, in dessen Hochgebirge ein Großteil der Landwirtschaft durch kleinbäuerliche Produktion indigener Stammesgemeinschaften geprägt ist, sowie die Gemeinde Novo Progresso im brasilianischen Amazonasgebiet, dessen Landwirtschaft sich hauptsächlich durch eine extensive Rinderweidewirtschaft auszeichnet und die in Folge einer zunehmenden Integration in globale Agrarrohstoffmärkte zu einem Hotspot landwirtschaftlicher Expansion und damit in Verbindung stehenden Waldverlust geworden ist. Diese Doktorarbeit konzentriert sich auf die nachhaltige landwirtschaftliche Anpassung auf Betriebsebene und untersucht zwei konkrete Anpassungsstrategien: zum einen die Anwendung von bodenschonenden und wassersparenden Managementmethoden (SWCP) und zum anderen verschiedene Formen der Landintensivierung (LI). Auf der Grundlage eines interdisziplinären Forschungsansatzes zielt diese Arbeit darauf ab, Faktoren zu identifizieren, die eine LI sowie die Anwendung von SWCP begünstigen oder erschweren, wobei der Einfluss des Klimawandels im Spezifischen analysiert wird. Aus methodischer Sicht beabsichtigt diese Arbeit zudem die Identifizierung von Defiziten in modellbasierten Landnutzungsanalysen sowie Potenzialen zur Verbesserung von Landnutzungsprojektionen für den ländlichen Raum. Landwirtschaft wird hierbei als komplexes sozial-ökologisches System verstanden und verschiedene Methoden aus den Sozial- und Naturwissenschaften kombiniert, insbesondere qualitative und quantitative Befragungen, Verhaltenstheorien, biophysikalische Modellierung und statistische Methoden.

Die zentralen Ergebnisse dieser Arbeit zeigen, dass landwirtschaftliche Anpassung in beiden Kontexten überwiegend ökonomisch motiviert ist, was, zumindest teilweise, nutzen- und gewinnmaximierende Modellansätze empirisch legitimiert. Die Ergebnisse zeigen jedoch auch verschiedene kontextübergreifende und -spezifische Faktoren auf, die eine Anpassung der landwirtschaftlichen Produktion trotz möglicher wirtschaftlicher Anreize begrenzen. Auf Erzeugerebene sind hierbei begrenztes Wissen und schlechter Zugang zu finanziellen Ressourcen, Arbeitskräften und Märkten als hemmende Faktoren in beiden Kontexten zu nennen, während kontextspezifische Faktoren hauptsächlich mit den Einstellungen der Landwirte verbunden sind. Im brasilianischen Amazonasgebiet begrenzen risikoaverse Einstellungen besonders die Umwandlung von Weide- in Ackerland, während im Nordosten Indiens soziale und ökologische Haltungen die Anpassungspräferenzen beeinflussen. Insbesondere hat sich auch der Einfluss des Klimawandels auf Anpassungsentscheidungen als kontextabhängig herausgestellt. Während die Verbreitung von SWCP in Nordostindien signifikant von wahrgenommenen Klimaveränderungen beeinflusst wird, bleiben klimatische Veränderungen in der brasilianischen Forschungsregion weitgehend unberücksichtigt. Die Ergebnisse dieser Arbeit deuten zudem auf einen Trade-off zwischen Klimawandelanpassung und Landintensivierung in Nordostindien hin, wo die Simulationsergebnisse eine Zunahme der Bodenerosion durch sowohl steigende Niederschlags- als auch Anbauintensitäten nahelegen. Diese Arbeit unterstreicht die Bedeutung von Anpassungsrestriktionen auf der Akteurs- und Landschaftsebene und zeigt zudem, dass diese in bestehenden Landnutzungsmodellen nur

begrenzt Berücksichtigung finden. Der Mangel an empirischen Daten wird als eine wesentliche Einschränkung in der Landnutzungsmodellierung herausgestellt und die Bedeutung der Integration verschiedener Modelltypen zur Verbesserung der Plausibilität von Landnutzungsprojektionen unterstrichen.

Diese Arbeit trägt in zweifacher Hinsicht zu der Weiterentwicklung des Forschungsfeldes Landwirtschaft – Klimawandel – Anpassung bei: Einerseits werden durch die Identifizierung relevanter Faktoren in betrieblichen Anpassungsentscheidungen und deren Vergleich mit Landnutzungsmodellen die empirischen Kenntnisse über ländliche Anpassungsprozesse verbessert und Lücken in modellbasierten Landnutzungsanalysen aufgezeigt. Andererseits fördert diese Arbeit die Verbindung zwischen sozial- und naturwissenschaftlichen Disziplinen für einen Kontext, der nur durch interdisziplinäre Forschung umfassend verstanden werden kann. Diese Arbeit kann somit einen Beitrag dazu leisten, politische Maßnahmen zur Erreichung einer nachhaltigen landwirtschaftlichen Entwicklung zu optimieren und interdisziplinäre Forschungsansätze auf diesem Gebiet zu stärken.

Publications related to this dissertation

1. Schröder, L. S., Rasche, L., Jantke, K., Mishra, G., Lange, S., Eschenbach, A., Schneider, U. A. (2023), *Combined effects of climate change and agricultural intensification on soil erosion in uphill shifting cultivation in Northeast India*, published in *Land Degradation & Development*, 1–17.

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3. Schröder, L. S., Tello, C., Mitter, H., Jantke, K., Scheffran, J., Schneider, U. A. (ready for submission to a scientific journal), *Producers' perspectives on agricultural intensification in the Brazilian Amazon: Bridging behavioral theory, empirical evidence, and land use models.*

Declaration of author’s and co-authors’ contributions

Article 1

Schröder, L. S., Rasche, L., Jantke, K., Mishra, G., Lange, S., Eschenbach, A., Schneider, U. A. (2023), *Combined effects of climate change and agricultural intensification on soil erosion in uphill shifting cultivation in Northeast India*, published in *Land Degradation & Development*, 1–17.

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Manuscript: Lea S. Schröder (completely)

Review: Livia Rasche, Kerstin Jantke, Annette Eschenbach, Uwe A. Schneider

Article 2

Schröder, L. S., Bhalerao, A. K., Kabir, K. H., Scheffran, J., Schneider, U. A. (2024), *Managing uphill cultivation under climate change – An assessment of adaptation decisions among tribal farmers in Nagaland state of India*, published in *Journal of Environmental Management*, 349 (119473), 1–14.

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Visualization: Lea S. Schröder (completely)

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Article 3

Schröder, L. S., Tello, C., Mitter, H., Jantke, K., Scheffran, J., Schneider, U. A. (ready for submission to a scientific journal), *Producers' perspectives on agricultural intensification in the Brazilian Amazon: Bridging behavioral theory, empirical evidence, and land use models.*

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Methodology and analysis: Lea S. Schröder (mainly), Carlos Tello

Visualization: Lea S. Schröder, Uwe A. Schneider (equal share)

Manuscript: Lea S. Schröder (completely)

Review: Hermine Mitter, Kerstin Jantke, Jürgen Scheffran, Uwe A. Schneider

Danksagung

Diese Doktorarbeit wäre nicht ohne die Unterstützung anderer Menschen ausgekommen, denen ich an dieser Stelle danken möchte.

Mein erster Dank geht an meine beiden Betreuer Uwe Schneider und Jürgen Scheffran. Danke, dass ihr mir mit dem Stellenangebot in CLICCS-C2 diese Doktorarbeit ermöglicht und mich bis zum Schluss bei ihrer Fertigstellung unterstützt habt. Danke für unzählige Meetings, eure Ideen und euer Feedback, das ich nicht selten sehr kurzfristig in Anspruch genommen habe. Insbesondere möchte ich euch dafür danken, dass ihr mich bei den vielen Pandemie-bedingten Themenanpassungen beraten und unterstützt habt. Danke Uwe, dass du dir so viel Zeit dafür genommen hast, mich bei Datenauswertungen und dem Aufsetzen der EPIC Simulationen zu unterstützen. Danke Jürgen, für deine Einblicke in die agenten-basierte Modellierung.

Neben meinen Betreuern möchte ich auch meinem Panel Chair, Christian Beer, für seine Unterstützung danken. Dein Engagement und deine kritischen Rückfragen in sieben intensiven Panel Meetings haben meine Promotion in strukturierte Bahnen gelenkt und sicherlich beschleunigt.

Ein weiterer großer Dank geht an Kerstin Jantke, die mit unglaublichem Einsatz das C2-Projekt zusammenhält und dabei immer ein offenes Ohr für uns Doktorand*innen hat. Danke Kerstin, dass ich meine Fragen und Sorgen und manchmal auch meinen Frust mit dir teilen konnte, dass du dir immer Zeit für ein Gespräch genommen - mir Mut gemacht hast, dass ich so viel von dir lernen durfte. Und danke für dein Engagement als Co-Autorin, vom dem ich und auch zwei meiner Manuskripte definitiv profitiert haben!

Ich möchte an dieser Stelle auch meinen anderen Co-Autor*innen danken, ohne die diese Arbeit so nicht möglich gewesen wäre. Danke Hermine, für deinen Input zu qualitativer Forschung und Verhaltenstheorien. Danke Livia, für deine hilfreichen Ratschläge zu allen EPIC Fragen und Problemen. Danke Khondokar, für deine Hilfe bei der Vor- und Nachbereitung des Surveys und der Veröffentlichung der Studie. Danke Annette, dass du mein erstes Manuskript mit deiner bodenkundlichen Expertise bereichert hast.

Diese Doktorarbeit wäre ohne Datenerhebungen nicht denkbar gewesen. Dabei haben mich ein paar Personen besonders unterstützt: Danke Amol, für deinen unermüdlichen Einsatz bei der Datenerhebung in Indien zu Hochzeiten der Pandemie, als mir die Einreise verwehrt war; und dafür, dass du mir ein Jahr später die Möglichkeit gegeben hast, die Forschungsregion und ihre Menschen kennenzulernen. Danke Ben, dass du mich auf dieser Indienreise begleitet hast und mir auch in vielen anderen wissenschaftlichen Fragen beratend zur Seite standst. Danke Carlos, dass du mich zu dem Abenteuer Brasilien eingeladen und es drei Wochen mit mir ausgehalten hast.

Mein Dank geht auch an die SICSS Graduiertenschule. Danke Berit, dass du Kurse, Retreats, Sommer- und Weihnachtsfeiern für uns Promovierende möglich machst und dass du uns in allen Belangen beratend zur Seite stehst. Ohne dich und die SICSS wäre diese Promotion deutlich einsamer gewesen. Danke an meine Mitstreiter*innen Liz, Lutz, Jihye, Nicole, Claire, Alexandre, Alex, Clara und viele weitere, die ich in der SICSS oder im Büro kennenlernen durfte und gute Freundinnen und Freunde geworden sind.

Zuletzt möchte ich meinen lieben (anderen) Freund*innen, meinem Partner und meiner Familie danken. Ich bin unglaublich froh, so viele tolle Menschen an meiner Seite zu haben. Danke an Anne, für deinen mentalen Support, und vielen weiteren wunderbaren Freundinnen und Freunden aus Hamburg und anderen Ecken. Danke Jan, für deinen Zuspruch und deine aufopferungsvolle Unterstützung auf den letzten Metern. Danke Mama, Papa und Helge, dass ihr mich nicht nur auf diesem Weg begleitet und unterstützt habt. Danke, dass ihr immer für mich da seid!

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Acronyms

General

CC	cover crops
FF	far future
GHG	greenhouse gas
IC	intercropping
LAI	leaf area index
LI	land intensification
MA	manure
MU	mulching
NF	near future
PHU	potential heat units
REF	reference study
RWH	rainwater harvesting
SAA	sustainable agricultural adaptation
SAD	sustainable agricultural development
SOC	soil organic carbon
SWC	soil and water conservation
SWCP	soil and water conservation practices
TOL	tolerance
VIF	variance inflation factor

Regions, organizations, names

BA	Brazilian Amazon
CMIP	Coupled Model Intercomparison Project
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
KVK	Krishi Vigyan Kendras (Indian agricultural extension center)
NEI	Northeast India
NP	Novo Progresso
RCP	Representative Concentration Pathways
SDGs	Sustainable Development Goals
SSP	Shared Socioeconomic Pathways
UN	United Nations

Theories and models

ABM	agent-based model
ASM	agricultural sector models
BLM	binary logit model
CGE	computable general equilibrium (model)
EPIC	Environmental Policy Integrated Climate (model)
GLOBIOM	Global Biosphere Management Model
IAM	integrated assessment model
MP-MAS	Mathematical Programming-based Multi-Agent Systems
MPPACC	Model of Private Proactive Adaptation to Climate Change
PMT	Protection Motivation Theory
PT	Prospect Theory
RUSLE	Revised Universal Soil Loss Equation
TERM	The Enormous Regional Model
TPB	Theory of Planned Behavior
VIABLE	Values and Investments for Agent-based interaction and Learning in Environmental systems
VBN	Values Beliefs Norms Theory

I Unifying Essay

1 Introduction

1.1 Background: Global challenges for the agricultural sector

More than any other sector, agriculture is at the epicenter of global change. Increasing demands from population and economic growth, climate change, and environmental impacts from production pose massive challenges for agricultural development. At the same time, the relevance of agricultural development is undisputed: Through providing food and energy supplies, agriculture is the cornerstone for the survival of modern societies.

With population growth reaching 10.4 billion people in the 2080s, as recently projected by the United Nations (United Nations, 2022), food demand continues to rise. In addition, even more importantly, food demand increases will be driven by per capita income growth associated with a shift in dietary patterns toward increasing demand for animal-based food in low- and middle-income countries (Fukase and Martin, 2020; Tian et al., 2021). Despite inherent uncertainties related to demographic and economic trends, this may lead to crop demand increases by approximately 60 to 100% until 2050 compared to 2005 (Fukase and Martin, 2020; Tilman et al., 2011; Valin et al., 2014), not accounting for potential increases in demands for biofuels which may disrupt global crop demand projections (Ausubel et al., 2013; Nonhebel and Kastner, 2011).

The growing global crop demand necessitates an increase in production. Since the 1960s, a substantial increase in global production of 250% was achieved, mainly through an increase in productivity per unit of land, while only 11% of production increases were associated with cropland expansion (Blomqvist et al., 2020). Most productivity increases resulted from pure yield increases; additional contributions came from increasing cropping intensities and a shift towards higher-yielding crops (Blomqvist et al., 2020). However, the current annual yield growth rates of maize (1.6%), rice (1%), wheat (0.9%), and soybean (1.3%), the four crops contributing two-thirds to the global human calorie intake, will not suffice to meet the rising demand until 2050 (Ray et al., 2013). In addition, future improvements in pure yields were projected to slow down due to the reaching of biophysical yield potentials of cultivated varieties in America and Europe and a combination of geographical and socio-economic limitations in Asia and Africa (Tian et al., 2021).

While yield projections generally underly uncertainties, e.g., due to hard-to-predict technological developments, additional uncertainties arise due to climate change. Previous studies have revealed an essential connection between yield variability and variations in climate (Ray et al., 2015) and showed that, based on statistical models for a period between 1980–2008, climate change resulted in a net loss in global maize and wheat production of 3.8 – 5.5% (Lobell et al., 2011). Future adverse effects of climate change on crop yields were projected particularly in tropical regions and in the second half of the century, with impacts becoming more severe as the magnitude of climate change increases (Challinor et al., 2014; Wheeler and von Braun, 2013). Yield declines were estimated at between 3.1 and 7.4% for wheat, rice, maize, and soybeans with each degree Celsius of global warming; however, projections did not account for adaptation and technological improvement (Zhao et al., 2017). Particularly droughts and heat stress were estimated to adversely affect future crop production (Deryng et al., 2014; Feng et al., 2021; Leng and Hall, 2019) while quantifying the effects of changing precipitation patterns remains complex (Agnolucci et al., 2020). In general, regions and crops will be affected differently (Agnolucci et al., 2020; Waldhoff et al., 2020), but adverse impacts will be particularly severe for smallholder production systems where productivity declines directly affect livelihoods (IPCC, 2019).

Projected decreases in yield improvements, even if not accounting for technological change, raise concerns about future agricultural production and its impacts, particularly when reductions in yield improvements are compensated by agricultural expansion. Until the end of the last century, the conversion of 70% of grasslands, 50% of savannas, 51% of the tropical, and 47% of the temperate deciduous forest area to pasture or cropland resulted in severe losses of habitats, biodiversity, and carbon storage (Foley et al., 2011; Ramankutty et al., 2008). In addition, land clearings account for almost half of the agricultural sector's total contribution to global greenhouse gas (GHG) emissions, which amount to about 22% (IPCC, 2022a; Ramankutty et al., 2018). As carbon losses from land conversions in the tropics are nearly double those from conversions in temperate regions, while crop yields are only about half, the recent shift of harvested area from high-yielding to low-yielding countries suggests a future increase in the environmental impact of agriculture (Blomqvist et al., 2020; West et al., 2010).

However, the environmental impact of agriculture is not limited to land conversion. More than half of the agricultural GHG emissions are attributable to methane emissions from livestock and rice paddies and nitrous oxide emissions from fertilizer and manure application (Ramankutty et al., 2018). In addition, intensified agricultural management has contributed to soil degradation, disrupted hydrological and nutrient cycles, and increased energy demand and environmental pollution (Foley et al., 2011; Ramankutty et al., 2018). If current dietary trends continue, the environmental burden of agriculture may further increase (Davis et al., 2016).

Increasing pressure from demand- and supply-side factors, including population and economic growth, decline in yield improvements, climate change, and societal expectations to reduce environmental impacts, pose major challenges for agricultural development.

1.2 Sustainable agricultural adaptation

Balancing future agricultural demand and supply under changing socio-economic and climatic conditions while reducing adverse environmental impacts will require adaptation of agricultural production systems.

Agricultural adaptation is here defined as the process of changing agricultural production in response to social, institutional, political, and/or environmental changes. While agricultural adaptation can take place at many scales (Wall and Smit, 2005), I focus on adaptation at the farmer’s field scale while recognizing that field-scale adaptation can be driven by larger-scale processes, such as market dynamics and environmental politics. Agricultural adaptation ranges from changes in specific management practices to the conversion of entire production systems, while the latter may also involve changes in land cover, e.g., as a consequence of agricultural expansion. Given the diverse challenges for the agricultural sector (see section 1.1) and the fact that these have different regional effects, agricultural adaptation can take many forms, making it practically impossible to draw up a comprehensive list of agricultural adaptation measures.

Adapting agricultural systems in a way that meets societal and ecological needs has been addressed with the concept of sustainable agricultural development (SAD). SAD draws on sustainable development, defined as “…development that meets the needs of the present without compromising the ability of future generations to meet their own needs…” (WCED, 1987), which has been taken up as a new paradigm for development since the publication of the Bruntland Report, “Our Common Future”, in 1987 (Ruggerio, 2021; Wall and Smit, 2005). Accordingly, SAD comprises management systems that safeguard long-term productivity and social-ecological resilience while preserving environmental health and ecosystem services (Rockström et al., 2017; Wall and Smit, 2005). This implies the use of agricultural practices that avoid the degradation of soil and water resources, which would ultimately prevent future generations from meeting their needs (FAO, 2014).

Sustainable agricultural adaptation is key in meeting several UN Sustainable Development Goals (SDGs), particularly SDG 2, “Zero Hunger”, SDG 12, “Responsible Consumption and Production”, SDG 13, “Climate Action”, and SDG 15, “Life on Land” (Kanter et al., 2018; United Nations, 2015; Rockström et al., 2017). Specifically, SDG 2.4 calls for the implementation of “agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change […] and that progressively improve land and soil quality” (United Nations, 2015). Thereby, natural resources are to be used and managed efficiently (SDG 12.2), and the degradation of natural habitats and related loss of biodiversity reduced (SDG 15.5). However, previous research has revealed trade-offs in meeting different SDGs, making sustainable adaptation a complex endeavor (Hinz et al., 2020). Concepts such as climate-smart agriculture (Lipper et al., 2014), sustainable intensification (Pretty, 1997), and conservation agriculture (Kassam et al., 2015) may help to navigate sustainable agricultural development under these trade-offs, suggesting a variety of adaptation strategies.

This thesis analyzes two adaptation strategies: soil and water conservation (SWC) and land intensification (LI). SWC relates to the concept of conservation agriculture and englobes diverse management practices that aim to sustain water resources and soil fertility (Kassam et al., 2014). Soil and water conservation practices (SWCP) were shown to reduce soil erosion while increasing nutrient and water availability and soil organic carbon (SOC) (Adimassu et al., 2017; Anantha et al., 2021; Kassie et al., 2013; Kaye and Quemada, 2017), thus contributing to the long-term stability of yields. In this thesis, I focus on the application of five specific SWCP in NEI, namely cover crops, mulching, intercropping with legumes, manure application, and rainwater harvesting (RWH).

LI, on the other hand, refers to increasing the production per unit of land. With a production growth potential of 44% (Ray and Foley, 2013), LI has been recognized as a promising option to meet rising future crop demand while avoiding the loss of natural habitats (Waha et al., 2020; Wu et al., 2018). However, LI cannot be considered sustainable per se, as it can imply adverse environmental impacts when associated with excessive use of fertilizers and pesticides (Arancibia et al., 2020; Burney et al., 2010; Mugizi and Matsumoto, 2020; Squire et al., 2015) or when higher income from intensification in the absence of environmental regulations incentivizes agricultural expansion (García et al., 2020; Müller-Hansen et al., 2019). Therefore, the concept of sustainable intensification was introduced that, albeit lacking a common definition, employs (agro)ecological principles to minimize environmental impacts from intensification while preserving (agro)biodiversity, carbon sinks, and ecosystem services (Petersen and Snapp, 2015; Rockström et al., 2017; Wezel et al., 2015). In this thesis, LI strategies are analyzed for NEI and the BA. For NEI, I assess the effects of increasing cropping intensities. For the BA, I analyze influencing factors of pasture-to-cropland conversion and the integration of different production systems.

Previous studies revealed synergies of SWCP and LI with climate change adaptation (Kuyah et al., 2021; Lin et al., 2008; Naazie et al., 2023). Soil conservation practices, including the cultivation of cover crops and mulch application, were shown to enhance long-term yields by restoring physical and chemical soil properties while minimizing erosion increases from rising precipitation intensities under climate change (Naazie et al., 2023). Likewise, integrated coffee-banana cultivation was shown to improve farm productivity while providing shade for heat-sensitive Arabica coffee plants under rising global temperatures (Campbell et al., 2014; van Asten et al., 2011). It follows that using SWC and LI practices can potentially promote sustainable agricultural development by simultaneously increasing production, reducing environmental costs, and contributing to climate change adaptation (Campbell et al., 2014).

However, agricultural adaptation is not a straight-forward process. Instead, diverse technical, social, economic, and institutional constraints were shown to slow down adaptation.

These may include, beyond farm-level factors such as limited farming experience, small farm size, and restricted financial resources (Abid et al., 2015; Ahmed et al., 2021; Hamazakaza et al., 2022), dysfunctional land institutions (Cohn et al., 2016; Kassie et al., 2015), as well as lacking access to transportation infrastructure, commodity markets, credits, and extension services (Adeagbo et al., 2021; Ayantunde et al., 2020; Bryan et al., 2009; VanWey et al., 2013).

It follows that sustainable agricultural adaptation may potentially contribute to solving global challenges arising from social and environmental change and to overcoming trade-offs from partly conflicting development goals while at the same time being impeded by diverse implementation barriers. Additional research is needed to identify and quantify barriers and trade-offs in agricultural adaptation processes.

Through analyzing factors and trade-offs in sustainable agricultural adaptation, this thesis is situated at the interface of global change and individual decision-making. Thereby, economic, social, and environmental forces transforming agricultural landscapes are exemplarily depicted for two different geographical contexts.

2 Outline of thesis

2.1 Research gap

Sustainable agricultural adaptation has been assessed for diverse contexts and within various disciplines. Thereby, adaptation is typically analyzed at a national, subnational/regional, or local level, the latter looking at individual villages or farms. Many studies focus on African countries, followed by studies from Europe and Asia. Less scientific attention has been paid to American countries, in spite of America’s importance as a global food producer and the strong rurality of many Latin American countries, particularly Brazil (Taboada et al., 2021). Several studies looked at smallholder adaptation, mainly in Africa, but only very few focused on tribal farming communities, which are particularly vulnerable due to their socio-political marginalization, as reported for India (Mishra et al., 2023). In terms of disciplines, a systematic search query for “sustainable agricultural adaptation” in abstracts from the Web of Science database (conducted on 01/15/2024) showed that most research studies are associated with the natural science disciplines, particularly environmental sciences, including ecology and geosciences. Social science studies are fewer in number and mainly from economics and development studies. Methodologies applied include household/farmer/stakeholder surveys, interviews, workshops or focus group discussions, field experiments, economic models, crop or hydrological models, statistical models, and spatial analyses.

One research focus of sustainable agricultural adaptation is on the assessment of factors that favor or impede the adoption of sustainable management practices and often overlap with climate change adaptation. These factors are typically analyzed using quantitative surveys (Bryan et al., 2009; Deressa et al., 2009; Eshetu et al., 2021; Khanal et al., 2018; Kolapo and Kolapo, 2023), qualitative interviews (Biggs et al., 2013; Chenani et al., 2021; Lawson et al., 2020; Manalo et al., 2022; Mitter et al., 2019), or a combination of quantitative and qualitative approaches (Assan et al., 2020; Gebru et al., 2020; Kabir et al., 2021). Likewise, albeit to a lesser extent, previous research assessed constraints of sustainable intensification, mostly from stakeholder surveys (Ayantunde et al., 2020; Cohn et al., 2016; Hamazakaza et al., 2022; Mutyasira, 2020).

Besides influencing factors on adaptation, the impacts of farm management practices on crop yields and the environment have been analyzed. For example, the effect of conventional and conservation agricultural practices on crop yields and natural resources has been assessed using crop and hydrological models (Bijay and Craswell, 2021; Hengsdijk et al., 2005) and field experiments (Adil et al., 2023; Geiger et al., 2010; Nandan et al., 2019; Schmitz et al., 2014b; Wang et al., 2018). Also, several studies analyzed sustainability effects of intensification, often focusing on the interactions between intensification and agricultural expansion, using empirical data and econometric techniques (García et al., 2020; Maertens et al., 2006; Willy et al., 2019).

While these studies provide valuable insights into the constraints and impacts of different adaptation strategies, they were mostly conducted within disciplinary boundaries, analyzing agricultural adaptation either from a social, economic, or biophysical point of view. Based on my own systematic research of the Web of Science database (conducted on 01/16/2024), I found that only very few studies remain when the search term “sustainable agricultural adaptation” is combined with at least two of the above methodologies from the social and natural sciences (e.g., “interviews” AND “crop model”). While a combination of stakeholder surveys with statistical models is relatively common (Alauddin and Sarker, 2014; Below et al., 2012; Molla et al., 2023), studies connecting social and natural science disciplines are rare. Exceptions include studies combining crop with economic modeling to assess climate change impacts on farms (Habib-ur-Rahman et al., 2022) and stakeholder workshops with crop modeling to identify sustainable intensification measures (Palosuo et al., 2021).

These rare examples show that previous research has taken insufficient account of the fact that agricultural systems are complex systems governed by diverse interlinked human-environment interactions (Haro et al., 2021; Soriano et al., 2023). While these systems, also called socio-ecological systems, are primarily shaped by humans, they also inherently depend on biophysical processes between biotic and abiotic elements of the ecosystem (Haro et al., 2021). Therefore, analyzing agricultural adaptation with a socio-ecological study approach, overcoming disciplinary boundaries, has been suggested (Lereboullet et al., 2013; Martínez-Fernández et al., 2023).

One approach to connecting social and natural dynamics in agricultural research involves model-based assessments. Land use models are applied to predict agricultural development based on scenarios for different spatial scales (Heistermann et al., 2006). While linking social, economic, and natural factors to varying degrees, they often depend on various assumptions about farmers’ decision-making, lacking empirical evidence. In particular, many models presume profit maximization as the rationale for adaptation (Heistermann et al., 2006; Meiyappan et al., 2014; Schreinemachers and Berger, 2011), neglecting the complexity of human behavior as proposed in established behavioral theories (Schlüter et al., 2017). Therefore, land use models have been criticized for over-simplification, and the integration of social, political, and cultural factors, as well as human decision-making processes in models has been demanded (Dalla-Nora et al., 2014; Lambin et al., 2000; Le et al., 2012; Schmitz et al., 2014a). A thorough understanding of agricultural land use decisions based on empirical findings is required to account for this claim.

While previous studies have contributed to empirical knowledge on agricultural adaptation already (Abid et al., 2015; Dang et al., 2019; Deressa et al., 2009; Gil et al., 2016), most studies were aligned to specific contexts, and the generalizability of findings remains questionable. Also, only parts of the elements involved in adaptation behavior have been assessed, including socio-economic variables, institutional factors, and resource constraints (Dang et al., 2019), while culturally-influenced goals and values behind farmers’ decisions remain understudied. A holistic empirical analysis including farmers’ goals and values, beyond a single geographical context and based on behavioral theory, is required to obtain a comprehensive understanding of factors involved in agricultural adaptation processes. Connecting empirical factors involved in agricultural adaptation to a behavioral theoretical framework allows to situate findings within the complexity of human decision-making, compare findings from different contexts, and derive conclusions for future modeling approaches.

This thesis builds on the following identified research gaps:

1.) **Lack of empirical evidence on motives and barriers in adaptation**: Empirically-based knowledge of decision-making in agricultural adaptation is only fragmentarily available for specific contexts, often without consideration of an overarching theoretical framework. Previous case studies have rarely analyzed adaptation in upland tribal farming systems.
2.) **Insufficient assessment of gaps in land use models**: Model-based land use assessments have been criticized for insufficiently representing factors involved in agricultural adaptation processes, but actual comparisons between land use models and empirical findings on factors influencing farmers' adaptation decisions are lacking.
3.) **Lack of interdisciplinarity**: Agricultural adaptation has mostly been assessed within disciplinary boundaries, while the socio-ecological character of agricultural systems calls for an interdisciplinary study approach that connects natural and social sciences.

2.2 Aim of thesis

This thesis aims to improve empirical knowledge of agricultural adaptation processes using an interdisciplinary study approach that bridges methods from natural and social sciences. Thereby, motivating and constraining factors of and trade-offs in adaptation, as well as current gaps in agricultural land use models are to be identified.

Against the background of a widening gap between increasing demand and decreasing production growth and the call for reducing the environmental impact of the agricultural sector, this thesis focuses on sustainable agricultural adaptation (SAA). SAA processes will be analyzed in the context of climate change, given the increasing pressure of climate change on local food production. Thereby, potential trade-offs between climate change and agricultural adaptation, particularly land intensification, will be identified.

This thesis analyzes SAA on a regional scale. As agricultural adaptation is often context-dependent, considering local boundary conditions is essential for understanding adaptation decisions. In particular, the role of climate change in agricultural adaptation must be analyzed context-specifically since effects and perceptions of climate change vary among places. Aiming for the analysis of SAA beyond a single context while being limited by the time and resources constraints of this doctoral project, this thesis analyzes SAA for two case study regions with very different boundary conditions and agricultural systems. These include Nagaland State in Northeast India and the municipality of Novo Progresso in the Brazilian Amazon. In Northeast India, I analyze a traditional smallholder subsistence farming system of indigenous tribal communities, which will be increasingly affected by climate change due to changing monsoon precipitation and an erosion-prone agricultural landscape while being highly understudied at the same time. In the Brazilian Amazon, I analyze the transition from cattle ranching to large-scale industrial, crop-based production systems. Becoming increasingly integrated into the global agricultural commodities market, this region, perhaps more than any other, stands for the global expansion of agriculture into natural habitats. The two case study regions will be presented in detail in section 2.3.

By analyzing SAA for two different case study regions, I aim to answer the following research questions:

1. Which factors influence and constrain SAA?
2. How does climate change affect SAA?
3. Which gaps limit the plausibility of model-based land use assessments?

By empirically identifying key parameters in SAA processes, this thesis improves the scientific understanding of farmers' adaptation decisions with relevant implications for agricultural policies. Further, by identifying gaps in agricultural land use models, this research creates the basis for increasing the plausibility of future land use projections. Lastly, this thesis aims to reveal potential links between social and natural science methods that may help to address agricultural adaptation with a socio-ecological system approach.

2.3 Case study regions

I assess SAA for two case study regions: Nagaland State in Northeast India (NEI) and Novo Progresso in the Brazilian Amazon (BA) (Figure I.1). While these regions are very different with regard to climatic, terrain, and agricultural characteristics, they have in common that they are situated at or close to tropical forest-agriculture frontiers. Forest-agriculture frontiers herein refer to remote areas with extensive forest stands subject to human destruction through agricultural activities (Gardner et al., 2014). These agricultural activities can vary from industrial cropland expansion to smallholder cultivation practices but are typically linked to deforestation processes at varying spatial and temporal scales (Eigenbrod et al., 2020). As both frontier regions intersect with important habitats for biodiversity, such as the Key Biodiversity Areas (BirdLife International, 2023) and the Global 200 Ecoregions (Olson and Dinerstein, 2002), sustainable agricultural adaptation processes in these regions directly affect the preservation of species and ecosystems. Both study regions thus represent critical locations where inherent trade-offs between UN SDGs are constantly being reconciled. Below, the two case study regions and their main agricultural production systems are introduced.

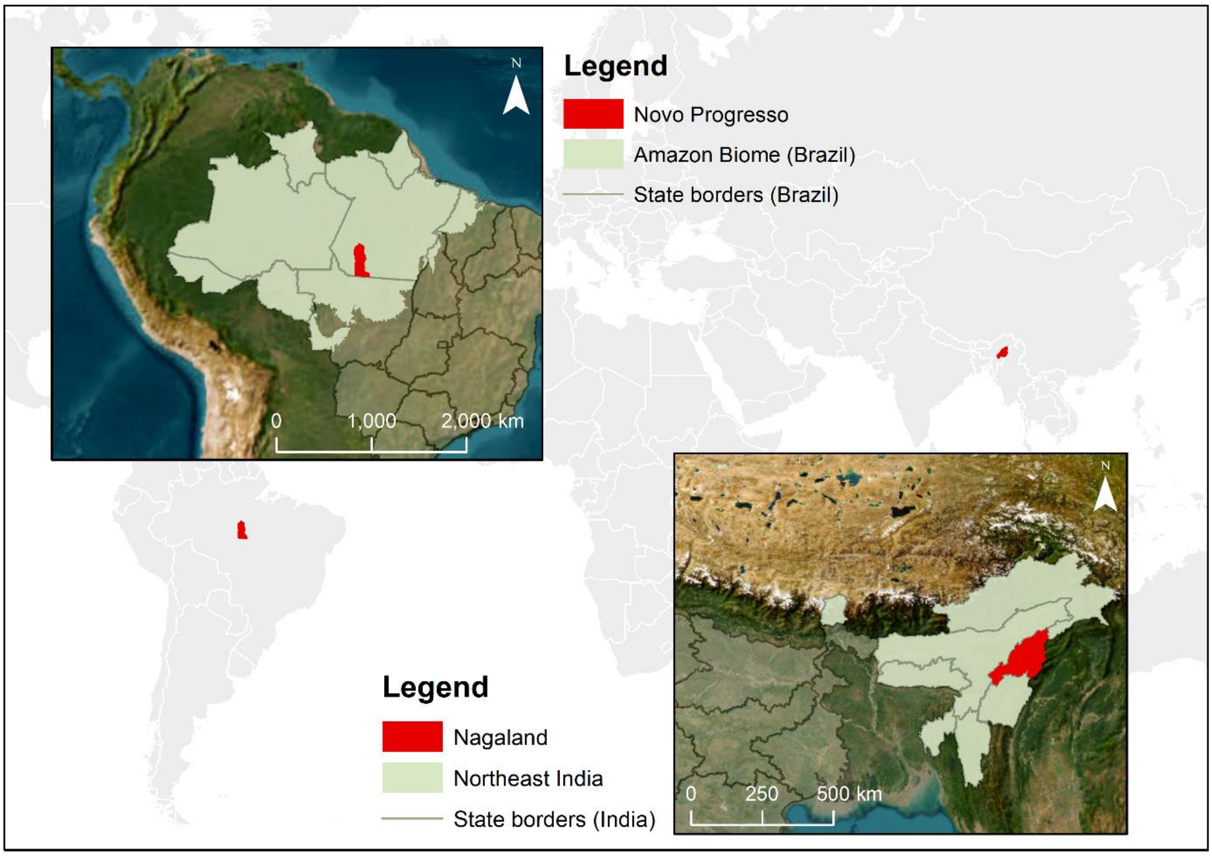

Figure I.1: Case study regions.

The Brazilian Amazon is shown on the left, Northeast India on the right.
Source of background imagery: Esri, Maxar, Earthstar Geographics, and the GIS User Community.

2.3.1 Northeast India

NEI is located at the foothills of the Eastern Himalaya Mountains, connecting India with Southeast Asia. The remote, sparsely populated region is characterized by steep hills, poor infrastructure development, and large forest areas (60%) which belong to the Himalayan and Indo-Burma biodiversity hotspots (Mittermeier et al., 2004; Ravindranath et al., 2011). Due to the complex topography, the climate is governed by different regimes, dominated by the Indian Summer Monsoon, making up more than 90% of the total annual precipitation (Dikshit and Dikshit, 2014).

The large rural population of NEI (82%) consists of diverse indigenous tribal communities, widely depending on agriculture and associated activities (Ravindranath et al., 2011). Agriculture is dominated by smallholder subsistence production, typically under organic management, with rice being the most important crop in the region (Das et al., 2017). As much of the agricultural production takes place along the mountain slopes under rainfed conditions, productivity is highly sensitive to climate variability and erosion-caused soil degradation (Ravindranath et al., 2011).

On the steeper mountain slopes of NEI, the agricultural landscape is dominated by shifting cultivation (Figure I.2). Shifting cultivation, locally called *jhum*, is a traditional smallholder rotation farming system in which short periods of crop cultivation alternate with typically longer fallow periods. Rice is the most important crop in the system and is typically grown along with other cereals, vegetables, and root crops under rainfed, low-input conditions. The cultivation period is preceded by the slashing and burning of selected plots of land. After a maximum of two years of cultivation, the field is abandoned, and secondary vegetation starts to grow until the cycle recommences.

While the distribution of shifting cultivation in many tropical regions has decreased over the last decades because of political and economic pressures (Rasul and Thapa, 2003; van Vliet et al., 2012), in NEI, the practice is still widely distributed. Although practiced in all eight states of NEI, shifting cultivation is most prevalent in Nagaland state, where about 116,000 families depend on it (Government of India, 2015). Nagaland State has therefore been selected as one focus region of this thesis.

Nagaland, the state with one of the largest tribal populations (87%) (Government of India, 2015), covers 16,579 km² and is inhabited by approximately 2 million people, almost three-quarters of them living in villages (71%) (Government of India, 2011). It is traversed by mountain ranges, with more than 60% of the area having slopes steeper than 30% and altitudes ranging from 194 to 3840 meters above sea level (Government of Nagaland, 2019; NASA SRTM, 2013). The climate is sub-tropical to sub-montane temperate and characterized by high rainfall intensities, with an average annual precipitation of 1200 to 2500 mm (Jayahari and Sen, 2015).

Nagaland Sate provides an interesting context for studying agricultural adaptation under climate change. The purely organic, extensive farming system, traditionally characterized by low cultivation intensities, has, in some areas, recently been experiencing rising pressures on land resources. Combined effects from population growth and the propagation of settled agriculture have increased land competition and, hence, in some areas, resulted in a reduction of shifting cultivation cycles from around 40 to now 5-10 years (Choudhury and Sundriyal, 2003; Jayahari and Sen, 2015; Lestrelin et al., 2012). Rising precipitation intensities under climate change can be suspected to further increase land pressure through higher soil erosion. It has been suggested that the resulting land scarcity may not only lead to rising soil degradation from intensified cultivation cycles but also to an expansion of cultivation in previously unused lands (Jayahari and Sen, 2015; van Vliet et al., 2012; Ziegler et al., 2009).

Figure I.2: Shifting cultivation in Nagaland, Northeast India.

Field after clearing (top) and field preparation (bottom) in March 2023.

To avoid future soil degradation and biodiversity loss in uphill agroecosystems, understanding the interactions between climate change and sustainable adaptation is crucial. The shifting cultivation system of Nagaland has been selected as a case study for this thesis to assess the dynamics between climate change, land intensification, and sustainable management in uphill smallholder production.

2.3.2 Brazilian Amazon

The Amazon biome accounts for 40% of the world's remaining tropical forest stand, with an aboveground living biomass of 93 ± 23 Pg of carbon (Laurance et al., 2001; Malhi et al., 2006). With an area of 8.4 million km², it stretches across nine countries, with the largest area being located in Brazil, covering about 60% of the biome (MapBiomas, 2023).

More than any other part of the Amazon region, the BA and its deforestation dynamics have become the focus of global attention. In particular, with the opening up of infrastructural development and the massive expansion of cattle production since the 1970s, followed by the soybean boom in the early 2000s, scientific and public concern was raised about the advancement of the forest-agriculture frontier and associated increases in forest loss (Coy et al., 2016).

Figure I.3: Cattle and crop production in Novo Progresso, Brazil.

Ranch with grazing cattle (top) and field with soybean-maize rotation (bottom) in April, 2022.

The highest forest loss has been observed in Pará (INPE, 2023). The northern and second-largest state of Brazil, characterized by a tropical monsoon climate with an average annual precipitation of approximately 2300 mm in Itaituba (Secretaria de Meio Ambiente e Sustentabilidade, 2023), has evolved as the largest cattle producer in Brazil, with pastures making up about 75% of the cleared areas (Coy and Klingler, 2011). While extensive cattle ranching, often characterized by low production intensities of below one head per hectare, still dominates the agricultural landscape of Pará (Hampf et al., 2020; Olimpio et al., 2022), expansion of mechanized crop production, particularly of soybeans is on the rise. Since 2000, the cropland area in Pará has increased by more than 800%, with pasture conversion being the primary source of cropland (Zalles et al., 2019).

In the peripheral south-west of Pará, agricultural expansion concentrates on the margins of the federal road BR-163, an export corridor traversing Novo Progresso (NP), the municipality with one of the highest deforestation rates in the entire BA (INPE, 2023), which has been selected as the second case study of this thesis. NP covers about 38,162 km² and contains more than 33,500 inhabitants (IBGE, 2023). Most inhabitants originate from southern states of Brazil and were attracted by new economic opportunities due to the opening up of the region since the 1980s (Coy et al., 2016). Today, 18% of the working population of NP is involved in agriculture (IBGE, 2022, 2023a). The majority of agricultural land is dedicated to cattle production (Figure I.3), but crop cultivation is on the rise, with soybeans making up 73% of the total cultivated area (IBGE, 2023b).

The highly dynamic agricultural landscape involving land use conversions and the expansion of mechanized agriculture as a result of the integration into global commodities markets make NP a suitable study region for this thesis. In contrast to Northeast India, where agricultural processes at the forest frontier are dominated by traditional farming practices of indigenous smallholder communities, Novo Progresso in Brazil provides an example of large-scale land intensification processes mainly driven by global market dynamics. These contrasting agricultural environments allow SAA processes to be examined from completely different angles.

2.4 Methodology - Bridging natural and social sciences

Understanding agriculture as a socio-ecological system shaped by the interlinkage of physical and social processes requires a holistic assessment of this system from an interdisciplinary perspective. Particularly, the connection of natural and social science methods is demanded. This research aims to contribute to the integration of natural and social sciences in agricultural research by combining different methodologies from both fields. In particular, this research uses biophysical modeling combined with mixed methods from the social sciences, including standardized and semi-structured interviews, behavioral theory, and statistical approaches.

Figure I.4 illustrates the different methods used for each study. As shown, the collection of empirical stakeholder information provides the foundation of this research. Since agricultural adaptation processes largely depend on the management decisions of people, particularly producers, understanding the driving factors in such management decisions from the stakeholders' perspective forms the basis of this thesis.

I collected stakeholder data in both case study regions through (on-site) surveys. In both regions, agricultural producers were interviewed in the local language (translation in NEI through local extension workers) about their farming practices and perceived challenges and adaptation options, including perceptions about climate change. While both surveys aimed at the identification of factors influencing adaptation, different survey types were applied. In NEI, a quantitative survey was conducted with 372 tribal farmers, using a fully structured questionnaire based on single- and multiple-choice questions (study 2). The collected information was complemented by findings from (unpublished) semi-structured follow-up interviews. In the BA, 25 semi-structured, in-depth interviews were carried out with producers involved either in cattle ranching, soybean-maize double cropping, or both (study 3). Questions were mainly open-ended to encourage the interviewees to elaborate on their experiences, perspectives, and opinions. While these different survey designs were partly due to travel restrictions during the COVID-19 pandemic, their combined use in this thesis provides a more comprehensive insight than would be gained by a single approach, although this complicates the comparison of the two study contexts.

Although different in type, both surveys were built and interpreted based on behavioral theories. Behavioral theory stems from psychology and behavioral economics and describes how individuals take behavioral decisions depending on their contexts, using a variety of formal models (Schlüter et al., 2017). Having entered the field of natural resource management, behavioral theories have been applied to analyze adaptation behavior in the context of climate change and environmental risks. Examples include the Theory of Planned Behavior (TPB) (Ajzen, 1985), the Protection Motivation Theory (PMT) (Rogers et al., 1983), the Model of Private Proactive Adaptation to Climate Change (MPPACC) (Grothmann and Patt, 2005), and the Values Beliefs Norms Theory (VBN) (Stern, 2000), all applied to study farmer adaptation to rising climatic risks (TPB: Arunrat et al. (2017); Zhang et al. (2020), PMT: Dang et al. (2014); Delfiyan et al. (2021), MPPACC: Mitter et al. (2019); Zobeidi et al. (2022a), VBN: Sargani et al. (2023); Zhang et al. (2020)). In this thesis, key components from established behavioral theories have been used to prepare the collection of stakeholder data and to analyze adaptation decisions. By using concepts from behavioral theory for the empirical assessment of farm adaptation, findings from different cultural and environmental contexts can be compared and evaluated from a conceptual view point.

Due to the differences in the collection procedure, producer surveys were analyzed using multiple methods. Quantitative survey data from Northeast India were analyzed by descriptive statistics and a binary logit model (BLM) (study 2). BLMs describe the binary decision of farmers on whether to adopt a particular adaptation strategy based on various factors, which can include both categorical and continuous variables. BLMs allow to assess different adaptation strategies independently while not being restricted by assumptions of linear regressions (e.g., normality) (Abid et al., 2015; Ali and Rose, 2021) and have therefore been applied in diverse previous studies to assess farmers' adaptation behavior (Ahmed et al., 2021; Jin et al., 2016; Khan et al., 2020; Sertse et al., 2021; Thoai et al., 2018). By utilizing a widely recognized and established statistical model, I build upon existing research and facilitate comparisons with prior findings.

Qualitative interviews from Brazil, by contrast, were analyzed using a qualitative content analysis (study 3). Therefore, word-by-word transcripts of the recorded interviews were analyzed following the content-structuring approach (Mayring, 2010; Schreier, 2014). I combined deductive and inductive coding to allow analytical flexibility as widely recommended (Gläser and Laudel, 2013; Kuckartz, 2018; Schreier, 2014). Accordingly, the entire interview material was coded in a multi-step process, in which codes were first derived from the interview guide, research questions, and theoretical framework and then iteratively added, modified, and reorganized based on the interview transcripts. This approach allowed the identification of diverse perspectives and factors shaping producers' land use decisions beyond those aspects presumed from previous work and theory.

Apart from producers, I also surveyed scientists engaged in land use modeling (study 3). This survey with land use modeling experts allowed to compare empirical evidence about driving and constraining forces in land use decision-making with different types of land use models. An online survey combining single- and multiple-choice with open-ended questions was distributed among land use modeling experts from different modeling communities. The survey aimed to systematically uncover how relevant factors identified from semi-structured producer interviews were represented in different land use models and how their representation could be theoretically improved. Results from the survey were analyzed using descriptive statistics.

To allow a comprehensive picture of climate change impacts on shifting cultivation, perceptions identified from interviews in NEI were complemented by soil erosion simulations using a biophysical crop model. Due to the steep topography, it can be assumed that the sustainability of shifting cultivation will largely depend on future soil erosion; however, erosion effects typically manifest only gradually and are, therefore, more difficult to detect from interviews. By integrating different physically based processes, crop models depict interactions between climate, land management, and landscape characteristics and thus allow to identify climate change impacts that could hardly be determined from observations. I used the process-based Environmental Policy Integrated Climate (EPIC) model, which has been applied in numerous previous studies on soil erosion (Carr et al., 2021; Izaurralde et al., 1997; Lee et al., 1999; van Zelm et al., 2018) to assess interactions between climate change and cropping intensities (study 1). By analyzing soil erosion impacts from different climate change scenarios, cultivation intensities, and slope ranges, I assess the possibility space of future upland shifting cultivation and quantify trade-offs between land intensification and climate change adaptation.

Lastly, this thesis employs data from other studies. These include soil data from a pedological survey carried out by a co-author (unpublished) and used as crop model input in study 1, as well as statistically downscaled and bias-corrected climate model data from phase

3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) (Lange, 2019a; Lange and Büchner, 2021). ISIMIP3b climate data were used as crop model input in study 1 and to identify climatic trends in study 2.

By combining various natural and social science methods, this thesis attempts to advance interdisciplinary research in agricultural land use science. Admittedly, full integration of the different methods through multidirectional feedback loops, in which the individual assessments influence and inform each other, was not possible here. This was due to COVID-19-related restrictions during the data collection phase, resulting in different study setups in the two study regions and data gaps from limited field research (see section 3.2). However, this thesis provides case examples of how different disciplinary approaches may stimulate each other to enrich assessments of socio-ecological systems, of which agriculture is a textbook example. Thus, this work contributes to bridging different disciplines in climate impact and adaptation research.

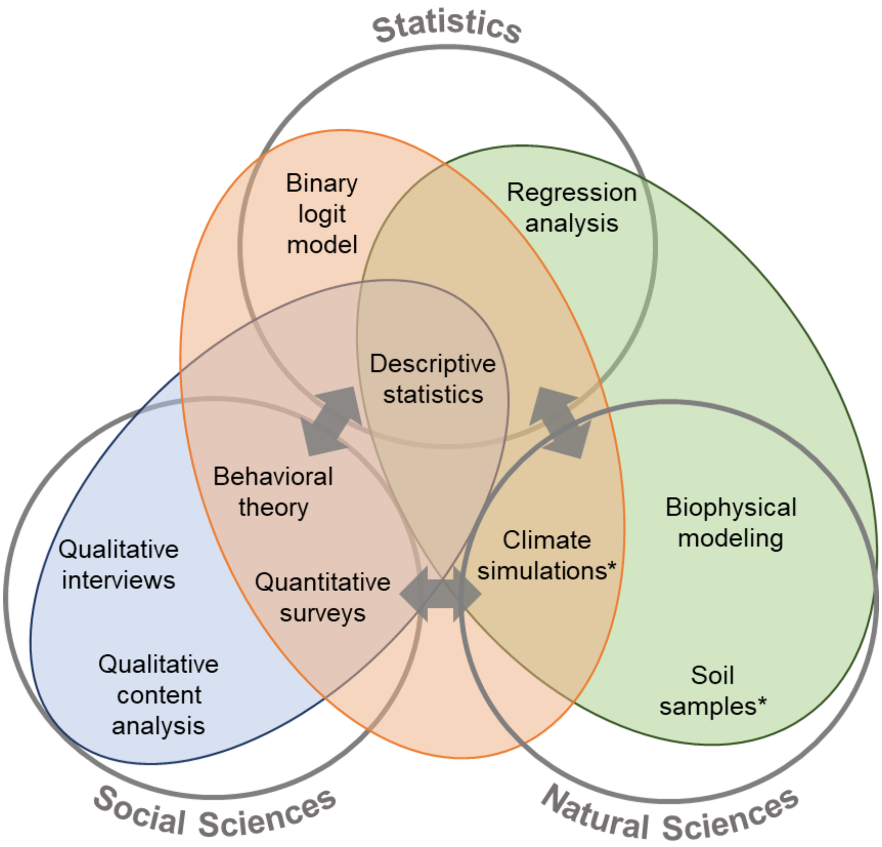

Figure I.4: Methods from different disciplines applied in studies.

Colors indicate different studies (green: study 1; orange: study 2; blue: study 3).
** Method conducted and provided by co-author.*

2.5 Overview of studies

The findings of this thesis are based on three research articles. Articles I and II were published in international peer-reviewed journals, and some of their findings were presented at international conferences.

I. Schröder, L. S., Rasche, L., Jantke, K., Mishra, G., Lange, S., Eschenbach, A., Schneider, U. A. (2023), *Combined effects of climate change and agricultural intensification on soil erosion in uphill shifting cultivation in Northeast India*, published in *Land Degradation & Development*, 1–17.

This study analyzes interactions between different cropping intensities, slope inclinations, and climate change scenarios with respect to soil erosion for uphill shifting cultivation systems of NEI. Specifically, it applies a biophysical crop model to quantify the relationship between fallow periods and soil erosion, as well as global warming and soil erosion and also looks at combined effects. Thereby, trade-offs between climate change adaptation and the intensification of shifting cultivation cycles are revealed.

Some of the results were presented at the EGU General Assembly 2023 in Vienna (Austria), the Tropentag 2023 in Berlin (Germany), and the WCRP Open Science Conference 2023 in Kigali (Rwanda).

II. Schröder, L. S., Bhalerao, A. K., Kabir, K. H., Scheffran, J., Schneider, U. A. (2024), *Managing uphill cultivation under climate change – An assessment of adaptation decisions among tribal farmers in Nagaland state of India*, published in *Journal of Environmental Management*, 349 (119473), 1–14.

This study analyzes climate change perceptions and adaptation decisions of tribal farming communities in NEI, focusing on SWCP. Using a standardized survey and a binary logit model, this study identifies significant factors influencing the adoption of SWCP and quantifies adaptation potentials under perfect conditions in terms of knowledge dissemination and socio-economic factors. The study also depicts farmers' goals and values regarding cultivation and adaptation, thus increasing the understanding of adaptation decisions of subsistence farmers in remote, mountainous regions.

Some of the results were presented at the Tropentag 2023 in Berlin (Germany) and the WCRP Open Science Conference 2023 in Kigali (Rwanda).

III. Schröder, L. S., Tello, C., Mitter, H., Jantke, K., Scheffran, J., Schneider, U. A. (ready for submission to a scientific journal), *Producers' perspectives on agricultural intensification in the Brazilian Amazon: Bridging behavioral theory, empirical evidence, and land use models*.

This study analyzes producers' perspectives on agricultural intensification in the BA and links them to behavioral theory and land use simulation models. Motivations, influencing factors, and constraints of pasture-to-cropland conversion, crop-livestock integration, and other intensification strategies are identified from semi-structured interviews and compared to findings from a standardized survey conducted with scientists from land use modeling. Thereby, an outlook on plausible agricultural futures in the BA is provided based on producers' opinions, and strengths and shortcomings of current land use models are revealed.

3 Results and outlook

3.1 Summary and discussion of results

3.1.1 Influencing factors of sustainable agricultural adaptation

Results from 2 and 3 illustrate which internal and external factors motivate and restrict farmers' adaptation decisions. Building on established behavioral theories (Michie et al., 2011; Schlüter et al., 2017), specific motivations and attitudes influencing adaptation intentions were identified, and the effect of different factors on the individual's capabilities and opportunities in agricultural adaptation was assessed, considering the environmental, economic, infrastructural, and socio-political-institutional context. Below, the most important findings are summarized.

For the internal factors, findings from both case study regions reveal increasing income and production as the most important motivations for adaptation. Diversification of livelihoods, as a potential strategy for risk reduction, was likewise mentioned as motivation in both contexts but found less important. In NEI, sustaining natural resources was additionally identified as a goal of agricultural adaptation, which could not be observed in the BA. This difference in motivation could be culturally and historically justified, as tribal farmers in NEI have lived and cultivated in the same environment for centuries and depend on intact soils and forests for their livelihoods. Producers interviewed in the BA, by contrast, were comparatively new to the region and saw the expansion of agricultural production in the Amazon as valorization of previously unused land.

Attitudes and capabilities restrict adaptation decisions. Among the attitudes, preferences for practices with reduced workload were observed in both contexts. In the BA, I found risk aversion to be a key limitation of adaptation, while in NEI, preferences for traditional farming practices that support social coherence and conserve natural resources influence management decisions. It can be derived that values such as cultural identity, social conformity, and nature conservation are more relevant in the adaptation of traditional smallholder production systems, while land intensification in large-scale production systems with high upfront investments is mainly restricted by risk attitudes. Thereby, unregulated land tenure enhances risk aversion. Among the capabilities, I identified experimental knowledge as a key constraint for adaptation. In the BA, previous experience in crop cultivation positively influenced pasture-to-cropland conversions, while in NEI, participation in a training on agricultural practices was found to be the most important factor for the adoption of SWCP.

Also, diverse internal and external factors limiting the individual's opportunities were found critical in adaptation. These include limited access to financial assets, markets, labor force in both contexts, land resources, machinery, road and processing infrastructure in the BA, and livestock and extension services in NEI. In NEI, in addition, participation in a civil society organization significantly increased the likelihood of adaptation, while interviews in the BA did not show any indication of the influence of social networks on adaptation. Likewise, environmental factors, particularly terrain constraints, limit adaptation. Climate change plays an ambivalent role, which is outlined in section 3.1.2.

Embedded in a behavioral theoretical framework, these findings suggest that farming preferences, risk aversion, availability of experimental knowledge, and access to diverse resources influence the individual's perceived self-efficacy and the perception and evaluation of behavioral options, resulting in varying adaptation intentions. Perceived self-efficacy is thereby understood as the degree to which individuals feel capable of performing a particular adaptation strategy. Studies 2 and 3 further indicate that perceptions, capabilities, and attitudes may be influenced by socio-demographic factors, particularly the producer's age, and that perceptions were affected by cognitive biases. The latter, however, could not be proven by this thesis.

It can be concluded that empirical evidence provided in this thesis justifies the use of economic principles in land use assessments; however, these principles do not fully explain adaptation behavior. In addition to utility maximization, adaptation behavior is shaped by various, sometimes context-dependent, factors at the actor and landscape level.

3.1.2 Role of climate change

The results of this thesis revealed different climate change impacts on SAA, depending on the regional context and adaptation strategy.

In Northeast India, I identified a trade-off between climate change impacts and land intensification. Results of study 1 show that both climate change and an increase in cropping intensities will lead to a rise in erosion rates, thus putting the sustainability of future shifting cultivation at risk. Specifically, I found a positive, non-linear relationship between global warming and erosion rates, indicating an erosion increase by more than 60% when global warming levels increase from 1.5 to 3.0 °C. At the same time, study results reveal a negative relationship between fallow period length and soil erosion, indicating an increase of soil erosion by more than 120% when fallow periods were decreased from 10 years to 1 year. Although impacts on agricultural productivity were not analyzed here, previous research suggests a similarly negative effect due to decreases in yields from cumulative soil losses and nutrient depletion under short fallow cycles (Gafur et al., 2003; Lestrelin et al., 2012; Zhang et al., 2021). Increasing erosion rates and decreasing yields under rising rainfall intensities and intensified cropping cycles indicate a trade-off between climate change adaptation and land intensification.

While (at least theoretically) discouraging land intensification, climate change seems to incentivize the adoption of SWCP. Survey results from study 2 indicate that perceived climatic changes, specifically increased drought frequencies, rainfall and soil erosion intensities, and a decrease in rainfall quantity, increase the adoption rates of SWCP. However, results from this study also show that perceived climatic changes are not necessarily coherent with those indicated by climate models. While climate models predict an increase in precipitation, farmer adaptation currently tends to be geared towards drier conditions. While I did not determine to what extent this contrast is related to short-term climate variability or cognitive biases (Dhakal et al., 2020; Hasan and Kumar, 2020a), the results raise concerns about the effectiveness of agricultural adaptation in NEI.

In Brazil, I didn't find any influence of climate change on recent land use decisions of producers. Even though producers named rainfalls during the harvest season of soybeans as one of the main perceived production risks impeding pasture-to-cropland conversion and, thus, land intensification, they rarely reported any changes in rainfalls or other climate variables over time (study 3). This reveals a surprising contrast between the perception of weather-related risks and the simultaneous ignorance of potential climatic changes in production decisions. It remains to be assessed whether the locally perceived absence of climatic changes can be confirmed by climate data or is more likely the result of cognitive biases, e.g., due to motivated reasoning (Kunda, 1990), a psychological phenomenon in which individuals tend to seek and accept exclusively evidence that confirms their existing views. Based on this phenomenon, previous research suggests that climate change skepticism may justify producers' behavior (e.g., with regard to deforestation) and is more common among people with right-of-center political opinions (Whitmarsh, 2011), which applied to a majority of interviewed producers in the BA. In the future, a potential reduction in rainfalls (Marengo et al., 2018) might accelerate pasture-to-cropland conversions due to reduced risks of soybean losses but, at the same time, restrict the profitability of double-cropping due to a shortened rainy season (Carauta et al., 2021a), revealing a potentially ambivalent effect of climate change on land intensification in the BA context in the future.

It can be concluded that climate change positively affects the adoption of SWCP in NEI, while the effect on land intensification is more complex, revealing a trade-off in NEI and a potentially ambivalent effect in the BA. Also, climate change perceptions strongly vary between contexts and are most likely influenced by cognitive biases, with climate change being largely neglected in the BA context while widely reported and influential for adaptation in NEI.

3.1.3 Methodological implications for the assessment of agricultural systems

Results of study 3 show that although land use models operate at different spatial scales, a majority is driven by economic surplus or profit maximization. Based on empirical findings of studies 2 and 3 (see section 3.1.1), this can be empirically justified, as economic considerations were found crucial in producers' land use decisions.

Focusing on computable general equilibrium (CGE) models, agricultural sector models (ASM), and agent-based models (ABM), I analyzed the representation of commodity markets, actor characteristics, risk aversion, resource access, and local landscapes, including environmental and infrastructural features, in land use models. Thereby, I asked not only for the quality of representation of these factors in different model types but also whether they were considered endogenously or exogenously and explicitly or implicitly.

Expert survey results revealed that economic incentives and disincentives are considered to be accurately represented in CGE models and ASMs, with commodity and resource use prices being mostly endogenously and explicitly implemented. Market representation in ABMs, by contrast, was found to be poor and mostly implemented exogenously and implicitly. Besides profits, however, studies 2 and 3 underlined the importance of adequately representing adaptation barriers at the decision-maker, typically the farmer, and landscape level in agricultural land use assessments. Decision-makers and characteristics influencing their self-efficacy are fairly accurately, endogenously, and explicitly represented in ABMs but not in CGE models and ASMs. Risk aversion, essentially limiting land intensification in the BA, is barely represented in land use models. The representation of access to resources such as labor and financial assets ranged from poor to fairly accurate in ASMs and ABMs, respectively. Zooming to the landscape level, environmental factors, such as soil, terrain, and climate, are better represented than infrastructure variables, such as roads and processing facilities. While the natural environment is fairly accurately and explicitly depicted in ABMs and ASMs, infrastructure remains underrepresented in most models.

In general, the unavailability of data was found to be a more significant model limitation than computing capacity and impeded particularly the representation of actor characteristics and risk attitudes. To increase the plausibility of future land use projections, findings underlined the need to integrate different modeling approaches, as CGE models and ASMs more adequately represent economic drivers of agricultural development, which are global by nature but also effective at the local level, while constraints of adaptation, specifically those at the stakeholder level, are more accurately depicted in ABMs. Further, improving the empirical database to appropriately represent stakeholder characteristics in models and reduce existing knowledge gaps in decision-making processes has the potential to improve projections on agricultural development.

Studies 2 and 3 contribute to enhancing the empirical knowledge on drivers and constraints of agricultural adaptation from a stakeholder's perspective for two different contexts. Thereby, findings indicate that combining quantitative and qualitative surveys has the potential to provide more comprehensive information than a single method. The standardized survey in NEI was proven suitable to quantify the significance of different factors in adaptation for a representative group of farmers, demonstrating the outstanding importance of agricultural training for adopting SWCP. On the other hand, qualitative interviews from the BA revealed unexpected linkages, such as the role of rainfall intensities during the soybean harvest season for pasture-to-cropland conversions, which neither a quantitative survey nor a biophysical simulation would have shown without prior stakeholder consultation. The potential of a “mixed-methods approach” in understanding behavior was also recognized and applied by previous studies on agricultural adaptation (Quandt et al., 2017; Roesch-McNally et al., 2018; Starr, 2014). In addition, this thesis has shown that linking surveys on adaptation decisions with behavioral theory is suitable for enabling the comparability of results from different survey types and study contexts. Likewise, complementing empirical surveys with biophysical model simulations proved helpful in uncovering potential trade-offs in adaptation processes that could not be identified from stakeholder observations only.

Lastly, some factors in agricultural adaptation were found to be context-dependent. This includes, e.g., the role of climate change in adaptation decisions, attitudes towards risks and nature conservation, and the importance of civil society organizations. It follows that the extrapolation of agricultural dynamics determined for one context to another context requires careful consideration. Therefore, this thesis confirms the suitability and necessity of regional case studies to understand agricultural adaptation processes and ultimately increase the plausibility of land use projections. Specifically, this thesis recommends future research on agricultural adaptation to focus on the differences between general and context-dependent drivers in adaptation decisions.

3.2 Limitations

While this thesis offers valuable insights into agricultural adaptation in two study contexts, it also has limitations that should be noted. Empirical findings about farmers’ perceptions and adaptation decisions were based on surveys conducted within a limited time frame and at a specific point in time and may therefore only reflect part of the factors involved in adaptation. Longer observation periods at different points in time would be required in order to obtain a larger picture.

Also, generalization of the findings based on two study regions is difficult. Although very different agricultural contexts were chosen here, a scientifically sound abstraction of findings would require a larger sample of study regions.

Lastly, the fieldwork of this thesis was severely impacted by the COVID-19 pandemic, leading to various limitations of the study setup. Initially, qualitative and quantitative surveys in both study regions were planned to complement each other and link stakeholder information with biophysical simulations. However, travel restrictions during the first two years of this research led to considerable delays in the collection of stakeholder data and the remote execution of the field survey in NEI. Consequently, stakeholder data from the BA lacks a quantitative assessment to evaluate the importance of different factors in land use decisions. On the other hand, the quantitative survey in NEI could not be preceded by a qualitative exploration of local farming dynamics, potentially missing out on other relevant factors in management decisions that were not included in the standardized survey setup. The standardized survey in NEI had to be executed by external, local staff, and coordination and supervision of the collection procedure were only possible to a limited extent. Therefore, quality shortcomings in the data collection led to the exclusion of more than 50% of participants and a few key questions, such as those on adaptation constraints, from the analysis. Lastly, the biophysical simulation study, originally intended to be fed with management data from qualitative interviews and to provide information for the quantitative survey, had to be carried out at the beginning of this research, thus restricting possibilities to connect the different methods. In summary, gaps in the methods used and the data collected, as well as the suboptimal order in the execution of the studies, restricted the possibilities of linking natural with social science methods through multidirectional feedback loops. For future research, careful consideration of an adequate sequence of performing different research methods and early identification of interfaces between social and natural science methods is recommended.

3.3 Conclusion and outlook

Against the background of declining yield improvements, rising societal expectations to reduce environmental impacts, and increasing demand for agricultural products from population and economic growth, this thesis analyzes sustainable agricultural adaptation for two case study regions. The adoption of sustainable agricultural practices that conserve carbon stocks and natural resources while providing sufficient production for current and future generations is becoming increasingly important in the face of climate change, which affects food production but is at the same time driven by GHG emissions from the agricultural sector.

While agricultural adaptation, herein understood as farm-level response to changing conditions, can take diverse forms, this thesis focuses on two adaptation strategies: the application of soil and water conservation practices (SWCP) and land intensification (LI). Specifically, this thesis assesses how diverse factors determine farmers' adoption of both strategies. The role of climate change effects on adaptation is analyzed in particular. Also, the representation of these factors in land use models is assessed to identify methodological gaps in agricultural land use projections.

I analyzed agricultural adaptation for two different contexts located in tropical forest-agriculture frontiers and important biodiversity habitats. Besides the Brazilian Amazon (BA), where the expansion of industrial crop cultivation and, thus, land intensification is gaining ground, agricultural adaptation was assessed for Northeast India (NEI), where upland shifting cultivation dominates the agricultural landscape. As the influence of climate change on and adaptation in upland tribal farming systems remains largely understudied, by focusing on tribal Himalayan farming communities, this thesis makes a first step to understanding adaptation behavior in this remote and highly vulnerable farming context, thus closing an important research gap.

Acknowledging agriculture as a complex socio-ecological system, I combined different natural and social science methods in this thesis. In NEI, a standardized survey with tribal farmers was combined with biophysical process modeling of soil erosion. In the BA, semi-structured interviews with cattle and crop producers were combined with a standardized survey with land use modelers. All stakeholder surveys were based on a theoretical framework of adaptation behavior to allow comparability of findings across different contexts. The combination of two study contexts in one theoretical framework using different methods from the natural and social sciences advances interdisciplinary research on agricultural adaptation, as previous research was mostly conducted within disciplinary boundaries and limited to one study context without significant attempts to synthesize findings across contexts.

From this interdisciplinary research, the following novel key findings can be drawn:

1. Agricultural adaptation is motivated by an increase in production and income. This applies equally to commercial farming systems in the BA and tribal smallholder production in NEI, and empirically justifies land use modeling approaches based on profit or utility maximization.
2. While some constraints in adaptation were found to be context-specific, limited experimental knowledge and poor access to financial assets, labor force, and markets were found to be relevant constraints in both study contexts. However, as illustrated by the example of NEI, adoption probabilities can be significantly increased under improved conditions, particularly when agricultural training is provided.
3. Attitudes towards agricultural practices are relevant for adaptation but vary between contexts. While risk aversion was found to be a key limitation of adaptation in the BA, in NEI, social and ecological attitudes were found to be important, which could hardly be

observed in the BA context. It follows that production decisions in different contexts are guided by different value systems, underlining the need to tailor agricultural policies to the specific context. This finding is novel, as goals and values in farmers' adaptation decisions have rarely been empirically assessed.

4. The influence of climate change on agricultural adaptation is context-dependent. While farmers in NEI observed various climatic changes, which positively influenced the adoption of SWCP, climatic changes in the BA were largely neglected. Concerning land intensification, a trade-off between increased cropping intensities and climate change adaptation was revealed for NEI, as both increasing precipitation intensities from climate change and a reduction in fallow cycles enhance erosion-caused soil degradation. This critical trade-off in the adaptation of vulnerable upland smallholder farming has not been analyzed by previous studies.
5. Market incentives and environmental factors are fairly accurately depicted in more than one model type; characteristics and resource access of producers were mainly considered in agent-based models, while risk aversion and infrastructure variables remain underrepresented in a majority of models. To improve the plausibility of agricultural land use projections, this thesis underlines the importance of integrating different modeling approaches and the need to improve the empirical database of agricultural adaptation decisions.

While analyzing agricultural adaptation processes, this research allows insight into future agricultural developments in the two case study regions. In NEI, rising precipitation intensities and competition with other land uses will increase the pressure on cropping intensities of shifting cultivation. To what extent this will lead to landscape degradation will rely on demographic trends, the political protection of tribal farming systems, and the spread of SWCP supported by extension services and agricultural training. In the BA, plausible further land intensification through large-scale pasture-to-cropland conversions will likely increase land prices and landholding sizes with uncertain effects for agricultural expansion, which will largely be determined by future land tenure regulations, environmental enforcement, and political developments.

By analyzing agricultural adaptation for two different contexts, this thesis improves the empirical knowledge of farm-level adaptation processes. Findings from the presented studies can help to tailor agricultural policies to farmers' needs, thus promoting future adaptation and sustainability of the agricultural sector. In addition, identified strengths and gaps in agricultural models lay the groundwork for improving future land use projections through steering further model development.

It remains to be noted that the category of sustainability can encompass many different criteria. Depending on which criteria are applied, the sustainability of land intensification may be critically debated. In this thesis, land intensification is considered more sustainable than extensive cattle ranching as it can potentially reduce further agricultural encroachment into natural habitats while increasing food supply. Also, the analyzed land intensification strategies of pasture-to-cropland conversion and integration of production systems were found to potentially reduce net GHG emissions and nutrient runoff while restoring soil fertility (Cohn et al., 2016; Gil et al., 2016; Gil et al., 2018), thus contributing to climate change mitigation, efficient resource use, and improvement of soil quality. Nevertheless, all adaptation practices, in particular those related to land intensification, may also involve ecological and social drawbacks, which must be taken into account when designing agricultural policies. To allow a sustainable agricultural development in the future, appropriate adaptation measures aligned to the specific environmental, social, and cultural context must be carefully considered. While this thesis contributes to understanding and projecting the distribution of these measures, further research will be needed to reduce adverse effects from agricultural practices and, thus, trade-offs in sustainable development.

Article 1

II Combined effects of climate change and agricultural intensification on soil erosion in uphill shifting cultivation in Northeast India

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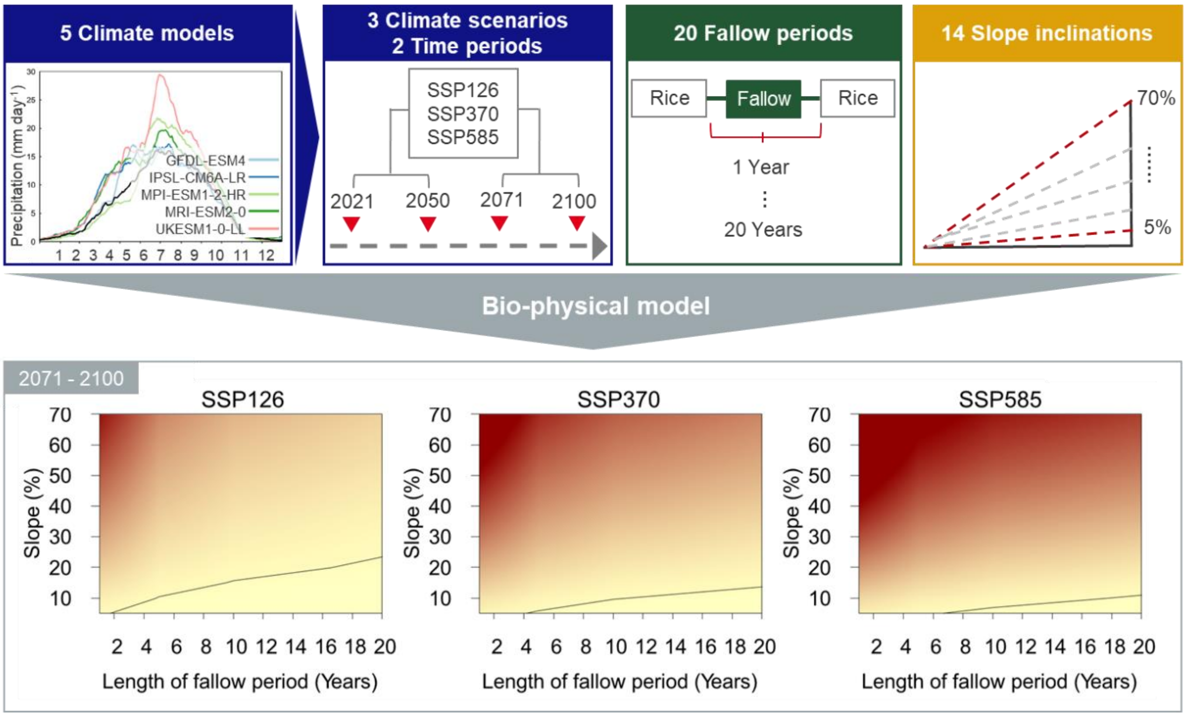
This chapter is published in *Land Degradation & Development* under the DOI:
https://doi.org/10.1002/ldr.4944



Graphical abstract 1

Abstract

Shifting cultivation will face increasing pressure from erosion-related land degradation caused by rising cultivation intensities and climate change. However, empirical knowledge about future trends of soil erosion and thus land degradation in shifting cultivation systems is limited. We use the Environmental Policy Integrated Climate (EPIC) model to first explore the combined effects of climate change and agricultural intensification on soil erosion of uphill shifting cultivation systems, using six surveyed soil profiles. We assess interactions between climate change, the length of the fallow period, and slope inclinations for a near (2021-2050) and far (2071-2100) future period, considering three climate scenarios, five climate models, fallow periods between one and 20 years, and slopes between five and 70% steepness. Our results show a significant nonlinear relationship between global warming and erosion. Until the end of the century, erosion is estimated to increase by a factor of 1.2, 2.2, and 3.1 under the SSP126, SSP370, and SSP585 scenarios, respectively, compared with the historical baseline (1985-2014). Combined effects from climate change, fallow length, and slope inclination indicate that steep slopes require longer fallow periods, with an increase of slope from 5% to 10% multiplying the required fallow length by a mean factor of 2.5, and that fallow periods will need to be extended under higher global warming if erosion rates are to remain at current levels. These findings are novel as they link climate change effects on shifting cultivation systems to different slopes and fallow regimes, making an important contribution to understanding future erosion dynamics of traditional smallholder production systems in mountainous terrain, with relevant implications for policies on agricultural intensification.

Keywords

agricultural intensification, climate change, Northeast India, shifting cultivation, soil erosion modeling, South Asia

1 Introduction

Population growth and political agendas on agricultural development have led to an intensification of shifting cultivation and, thus, rising land degradation due to soil erosion in uphill regions of South and Southeast Asia. In addition, future increases in precipitation intensities due to climate change can be expected to accelerate soil erosion, thus putting additional pressure on uphill shifting cultivation systems. In this study, we seek to address the interplay between climate change and the intensification of shifting cultivation cycles on future soil erosion.

Shifting cultivation is a smallholder rotation farming system where short periods of crop cultivation alternate with typically longer fallow periods. The system is highly vulnerable to climate change because it depends on the natural regeneration of soil fertility during the fallow period. Increasing erosion rates under climate change have the potential to undermine soil recovery of shifting cultivation systems because they result in losses of the organic-carbon-rich top soil, thus reducing soil stability and productivity.

Besides climate change, reductions in the length of fallow periods are increasingly challenging soil productivity. Population growth and political agendas aiming for agricultural intensification through the propagation of settled agriculture have recently increased the pressure on productive land in South and Southeast Asia (Rasul and Thapa, 2003; Ziegler et al., 2012; Castella et al., 2013; Fox et al., 2014; Bruun et al., 2017; Bose, 2019). As a consequence of increasing land competition, shifting cultivation has migrated toward higher altitudes (Nongkynrih et al., 2018; Adhikary et al., 2019; Feng et al., 2021) and fallow cycles have been reduced (Choudhury and Sundriyal, 2003; Lestrelin et al., 2012; Prokop and Poreba, 2012; van Vliet et al., 2012), thus increasing the risk for soil erosion and challenging the sustainability of shifting cultivation systems.

Previous studies from South and Southeast Asia already observed serious increases in soil erosion and linked these to a reduction in fallow periods (Ziegler et al., 2009; Grogan et al., 2012; Jayahari and Sen, 2015). Mishra and Ramakrishnan (1983) measured sediment loss to be higher under a 5-year compared with a 10-year shifting cultivation cycle. However, the exact relationship between the length of the fallow period and soil erosion remains unclear.

Previous studies have also shown that increases in erosion, in particular, take place on the cultivated steeper slopes (Gafur et al., 2003; Sati, 2020). The significant effect of slope steepness on soil erosion has been widely proven (El Kateb et al., 2013; Shen et al., 2019). However, research on the combined impact of slope steepness and cultivation intensity is scarce. While both variables tend to increase soil erosion, their combined effects on erosion have not yet been studied. Filling this research gap is important because increasing demand for agricultural production has led to a simultaneous shortening of fallow periods and the cultivation of steeper slopes.

Several studies have pointed to an increasing risk of soil erosion under climate change in the Himalayas, mainly northern India, where erosion was estimated to increase by 15% - 235% until the end of the century, compared with the late 20th and early 21st century (Gupta and Kumar, 2017; Khare et al., 2017; Kumar et al. 2022; Choudhury et al., 2022; Sooryamol et al., 2022). However, most of these studies exclusively consider the effect of changing precipitation patterns on the rainfall-runoff erosivity factor, hence missing other climate-related effects on soil erosion, such as indirect effects from temperature, precipitation, and rising CO_2 concentrations on biomass growth and soil moisture (Li and Fang, 2016). Likewise, previous studies do not focus specifically on shifting cultivation systems. Choudhury et al. (2022) analyzed erosion for integrated farming systems, including abandoned shifting cultivation fields, but did not consider areas under active shifting cultivation. Closing this research gap is urgently required since shifting cultivation plays an essential role in securing food supply for the tribal population of uphill regions (Pandey et al., 2020).

We address existing research gaps by analyzing the combined effects of climate change, fallow period length, and slope inclination on future soil erosion of shifting cultivation systems. In particular, we ask: (1) How will climate change affect future soil erosion in shifting cultivation, and what is the relationship between erosion and global warming? (2) How will the seasonal distribution and daily intensity of erosion change? (3) How do fallow periods and slope inclinations influence soil erosion under shifting cultivation? (4) How do combined effects from climate change scenarios and fallow period lengths affect soil erosion on different slopes?

We selected Nagaland state of Northeast India as a study region where shifting cultivation is still widely practiced (Government of Nagaland, 2012). Due to the steep topography and recent reductions in fallow periods, the region has become a potential hotspot for soil erosion and degradation (Sharda et al., 2010; Krug et al., 2013).

We assess interactions of climate change, fallow periods, and slope inclination using a modeling approach based on six surveyed soil profiles from Nagaland. Therefore, we analyze soil erosion rates for the near (2021-2050) and far (2071-2100) future under three climate scenarios, link erosion to global warming levels, and assess changes in the seasonal distribution and daily intensity of erosion. Further, we examine the individual and combined effects of fallow period length and average field slope on future erosion and relate our results to a soil loss tolerance. Finally, we discuss implications for soil degradation and place our findings in the context of increasing agricultural intensification. Our results improve the understanding of future erosion dynamics of uphill shifting cultivation systems and provide recommendations for decision-makers on the field and policy level.

2 Materials and methods

2.1 Study area

For this research, we selected Mokokchung district of Nagaland state as a study area. Though shifting cultivation, locally called *jhum*, is practiced in all states of Northeast India, the practice is most dominant in Nagaland state (Jayahari and Sen, 2015). Rice is the most important crop in the system, although, in many places, rice is grown along with other cereals, vegetables, fruits, and root crops (Choudhury and Sundriyal, 2003; Chatterjee et al., 2021). The *jhum* cycle typically consists of a 2-year cropping phase following slashing and burning (Figure II.1) and a fallow period after cultivation with an average length of currently 8 years (Government of India, 2015).

Nagaland is traversed by mountain ranges, with approx. 98% of the state being mountainous (Jayahari and Sen, 2015). Altitudes range from 194 to 3840 m above sea level (Government of Nagaland, 2019). Accordingly, steep slopes dominate the region, with 63% of the area having slopes steeper than 30% and even 26% steeper than 50% (NASA SRTM, 2013).

Figure II.1: Shifting cultivation landscape.

Photos were taken during the burning operation (left, © Lea S. Schröder), field preparation (center, © Amol Bhalerao), and cultivation (right, © Sesenlo Kath).

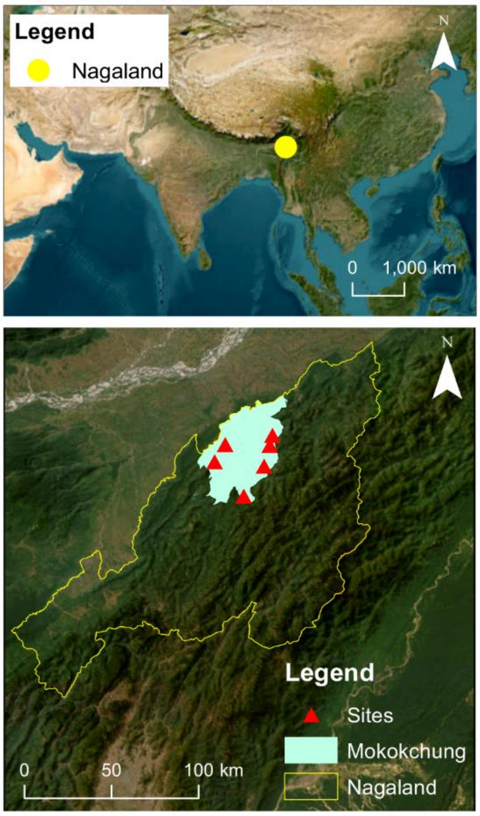


Figure II.2: Study area with sites of collected soil profiles.

Source of satellite image: ESRI, Maxar, Earthstar Geographics, and the GIS User Community.

The climate ranges from sub-tropical to sub-montane temperate. It is characterized by the Indian Summer Monsoon between mid-May and the end of September, making up over 85% of the total annual precipitation, which amounts to 1200-2500 mm (Jayahari and Sen, 2015; Government of Nagaland, 2019).

Soils in Nagaland comprise Inceptisols, Entisols, Alfisols, and Ultisols, with Inceptisols making up the highest share (66%) (Government of Nagaland, 2012), according to the USDA classification (Soil Survey Staff, 2014). Due to rainfall-related fast weathering processes and steep terrain, soils are relatively acidic (Bandyopadhyay et al., 2018). Soil loss tolerance has been reported as 10 t ha^{-1} $year^{-1}$ for most parts of the study area (Mandal and Sharda, 2011).

2.2 Data

2.2.1 Soil and site data

A pedological survey was conducted in 2014 on six soil profiles in Mokokchung district of Nagaland (Figure II.2). Five soil profiles belong to the soil order Inceptisols, one to Entisols. All sites were under current *jhum* cultivation or fallow land use during data collection. Soil samples from the different pedological horizons were manually collected with a spade, air-dried (at room temperature to constant weight), ground, and passed through a 2-mm sieve to exclude litter, roots, and coarse particles. For all horizons, depth-wise soil analysis was conducted using standard procedures. The percentage of silt, sand, and clay was determined using the pipette method as described by Piper (1966). Bulk density was estimated by the core method as described by Blake and Hartge (1986). Wet-oxidation method described by Walkley and Black (1934) was used to determine the SOC content. Hydrological soil groups were derived based on soil textures according to the USDA-NRCS Hydrologic Soil Group Classification (NRCS, 2007). Besides soil data, altitude information and geo-coordinates were collected for model input. Physical soil properties and site information used as model input are provided in Table II.1.

Table II.1: Site and physical soil properties of collected samples.

		P01	**P04**	**P06**	**P08**	**P12**	**P14**
Longitude		94.537	94.319	94.408	94.4	94.262	94.228
Latitude		26.216	26.148	26.337	26.305	26.308	26.254
Elevation (m)		490	774	614	889	445	504
Slope (%)		5	30	10	30	5	33
Soil order		I	I	I	I	E	I
Soil hydrologic group		C	D	C	C	B	B
Number of horizons		4	5	5	4	5	5
Per horizon	Depth to bottom of horizon (cm)	20	25	20	24	7	9
		40	44	50	37	41	45
		60	97	90	67	68	55
		90	135	117	130	101	72
			144	150		125	104
	Bulk density (g cm^{-3})	0.81	0.9	0.88	0.86	1.06	1.13
		0.84	0.91	1.04	0.92	1.06	1.21
		0.96	0.93	1.09	0.9	1.06	1.11
		0.99	1.13	1.16	0.98	1.23	1.16
			1.03	1.18		1.09	1.08
	Sand (%)	44.8	12.85	53.5	36.7	70.3	68.9
		42.55	16.65	44.85	34.25	69.85	71.85
		35.35	23.05	35.8	44.55	71.85	70.15
		32.52	41.4	42	43.1	92.45	57.95
			25.25	42.7		71.0	46.7
	Silt (%)	28.65	30	15.8	28.5	11.4	13.95
		26.15	28	20.7	28.45	12.55	11.2
		29.1	24.95	27.05	16.05	12.35	10.95
		26.05	24.55	26.8	20.35	6	5.1
			43.95	31.65		21.3	18.6
	Organic carbon (%)	1.96	2.67	1.85	1.86	0.89	1.29
		1.66	1.72	1.46	1.42	0.61	0.89
		1.24	0.89	0.54	1.04	0.41	0.95
		0.95	0.57	0.41	0.78	0.4	1.15
			0.53	0.38		0.32	0.01

Abbreviations: E, Entisol; I, Inceptisol.

2.2.2 Climate data

We used daily climate data on precipitation, maximum and minimum temperatures, relative humidity, solar radiation, and wind speed for a historical baseline (1985-2014), a near future (2021-2050), and a far future (2071-2100) period. The future climate projections include three scenarios from phase 6 of the Coupled Model Intercomparison Project (CMIP6), which combine Representative Concentration Pathways (RCPs) used for CMIP5 climate projections and Shared Socioeconomic Pathways (SSPs) derived from integrated assessment models (IAMs) (O'Neill et al., 2016). The scenarios used in our study include low-end (SSP126), medium-high (SSP370), and high-end (SSP585) scenarios of future forcing pathways. For all scenarios, we used bias-corrected and statistically downscaled climate data from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) (Lange, 2019a; Lange and

Büchner, 2021). Those climate data were available for five CMIP6 models: GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL, and IPSL-CM6A-LR. These models are structurally independent regarding their ocean and atmosphere components and are considered good representatives for the CMIP6 ensemble, as they contain models with low and high climate sensitivity (Lange, 2021). We downloaded the ISIMIP3b climate data in February 2022 from the ISIMIP repository (https://data.isimip.org/search/). The five climate models differ in their precipitation projections, mainly during the beginning and peak of the monsoon season. Particularly in the far future under the SSP370 and SSP585 scenarios, precipitation projections diverge, with UKESM1-0-LL projecting the highest increases and GFDL-ESM4 a slight decrease in precipitation during the peak of the monsoon season. At the beginning of the monsoon season, most models predict, to varying degrees, increases in precipitation, whereas precipitation projections of MPI-ESM1-2-HR fall below historic precipitation (Supplementary material A Figure 3). To account for differences among climate models, we applied climate data from all five models in our study.

2.3 Model

2.3.1 Environmental Policy Integrated Climate model

We used the Environmental Policy Integrated Climate (EPIC) model, originally called Erosion Productivity Impact Calculator, and developed to simulate interactions between soil erosion and soil productivity in the Unites States (Williams et al., 1984). While EPIC is not the only erosion model recommended for use in Asia (Guo et al., 2019), it was selected because expertise for this model was already available among the authors. Consisting of different physically based components, including hydrology, erosion, nutrient cycling, and plant growth, the model is capable of simulating various environmental processes resulting from interactions between climate, topography, soils, crops, and management. For details on model parameters and equations regarding the above processes, the reader is referred to Sharpley and Williams (1990) and Williams (1995). Since 1981, the model has been under continuous development, improved and tested for diverse regional and management conditions (Izaurralde et al., 2006), and applied in numerous studies on soil erosion (Benson et al., 1989; Favismortlock et al., 1991; Richardson and King, 1995; Lee et al., 1996; Izaurralde et al., 1997; Lee et al., 1999; Bhuyan et al., 2002; van Zelm et al., 2018; Carr et al., 2021). Besides, the model has been proven suitable for crop-fallow rotation systems, as applied in Gaiser et al. (2010) and Srivastava et al. (2012). In this study, we used the EPIC model version 0810.

The EPIC model captures soil erosion by water using the basic equation (II.1)

$$Y = R \cdot K \cdot LS \cdot C \cdot P \tag{II.1}$$

where Y is soil erosion (t ha^{-1} yr^{-1}), R the erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS the slope length and steepness factor (dimensionless), C the soil cover and management factor (dimensionless), and P the conservation practice factor (dimensionless). The calculation of the erosivity factor R depends on the specific erosion equation selected by the user, who can choose from seven equations. While the R-factor in the erosion equation USLE and its revisions (RUSLE, RUSLE2) is mainly driven by precipitation intensity, in MUSLE, MUST, and MUSS, it is driven by runoff variables, whereas the Onstad-Foster equation applies a combination (Williams, 1995; Carr et al., 2020). The K-factor is computed based on sand, silt, clay, and organic carbon contents of the top soil horizon at the beginning of each simulation year, using the equation provided in Williams (1995). The LS-factor is calculated from slope steepness and slope length using the equation from Wischmeier and Smith (1978). The C-factor is computed for all runoff-occurring days and is based on simulated above ground biomass and residues, as further explained in Williams (1995). EPIC calculates biomass growth based on Monteith's approach (Monteith and Moss, 1977) from photosynthetic active radiation, a crop parameter for converting energy to biomass, and day length. Photosynthetic active radiation is determined by solar radiation and leaf area index (LAI). LAI is a function of heat units, crop development stages, and crop stress based on stress factors for water, temperature, nutrients, and aeration. Heat units refer to daily average temperatures exceeding the base temperature, which is a crop-specific minimum temperature required for growth. Accumulated daily heat units that are needed to reach crop maturity are defined as potential heat units. They can be entered by the user or computed by the model from daily temperatures between planting and harvesting dates. Further information on biomass growth is given in Sharpley and Williams (1990). The P-factor of the erosion equation refers to the ratio between soil loss under the applied management and soil loss without this management (Morgan, 2005) and has to be supplied to the model by the user.

2.3.2 Model setup

To set up the model for the topographic conditions of the study region, we tested all of the above erosion equations and found that RUSLE provided the lowest and most realistic soil loss, which is consistent with the findings by Carr et al. (2020). We also tested several combinations of exponential coefficients in the RUSLE C-factor equation and applied the best-performing combination as given in supplementary material A (A.4). As P-factor, we chose the mean value (0.38) for contour bunds, which are mostly applied on *jhum* fields in the study region (unpublished survey carried out in April 2022) from Morgan (2005). We opted against a slope-specific P-factor value because these were unavailable for the entire slope range analyzed in this study. Using a mean P-factor value, we also attenuate the effect that EPIC typically overestimates soil erosion on steep slopes (Carr et al., 2020).

To represent shifting cultivation in the model, we implemented a rotation consisting of a 2-year cropping phase and a fallow period of one to 20 years length (see section 2.3.4 for details). Due to its importance in local shifting cultivation systems, we chose rice as the crop for the cultivation phase. Rise is planted at the beginning of March by manual broadcasting at a plant density of 250 plants m^{-2}. For field preparation, traditional contouring practices using rocks and wood are applied; no tilling occurs. During the growing period, neither fertilization nor irrigation takes place. Manual weeding, typically carried out between April and July, was not considered in our simulations, as field observations showed only marginal effects on erosion (Ziegler et al., 2007). Rice harvesting starts at the beginning of September and is done by manual cutting (at 50 mm above ground). Crop residues, including rice stalks, remain on the field. After 2 years of rice cultivation, herbaceous fallow vegetation starts growing. As fallow vegetation, we selected Johnson Grass, a weed that is widely distributed over India on cultivated and abandoned fields and well adapted to subtropical climates with warm and wet summers. Albeit fallow areas typically have scrub vegetation and trees growing up after a certain period of time, we limited fallow vegetation in our simulations to grass vegetation for simplicity. This approach is appropriate for erosion studies, as previous research has shown that grass vegetation has the most important effect on erosion; hence, the additional effect from secondary vegetation types can be considered marginal (Chen et al., 2018). We did not implement any fallow management except the burning of vegetation at the end of the fallow period, which is in line with the common shifting cultivation practice.

We used two spin-up simulations to compute potential heat units (PHU) required for the maturation of the rice crop and to approximate soil parameters not included in the measurements, which are mostly chemical soil properties relevant for yield predictions but less decisive for erosion. This is in line with the common procedure as outlined in Sharpley and Williams (1990). For further information on model setup, including scenario-specific CO_2

concentrations (Meinshausen et al., 2020) applied per simulation period, we provide detailed documentation in supplementary material A (A.1-A.4).

2.3.3 Model evaluation

To evaluate the model performance, we compared soil loss of the historical baseline simulations (1985-2014) to the measured soil loss range of a reference study. As a reference study, we selected Saha et al. (2011), to our knowledge, the only study that measured soil erosion under shifting cultivation in Northeast India over an extended period of time. The study was carried out in Meghalaya, a neighboring state of our study area with comparable climate and topographic conditions. To increase the comparability of our simulations with the reference study, we selected two points (P01, P08) with similar top soil horizon characteristics and slope inclination and management closest to the described conditions (Table II.2). Figure II.3 shows that the simulated soil erosion for P01 and P08 corresponds to the range of the reference study. The marginally higher soil loss can be explained by the slightly higher slope inclination and annual precipitation in our simulations. For completeness, simulated erosion for the other sites is also given in Figure II.3.

We further compared soil loss in our simulations to the land use and seasonal pattern reported in previous studies. Our simulations showed that mean soil erosion during rice cultivation was between four and six times higher than during fallow when the average of all stages within a 3-year fallow period is considered (Supplementary material A Figure 1). This is consistent with previous findings from Gafur et al. (2003). Also, our model simulations reproduced the bi-modal seasonal pattern of soil erosion during cultivation reported in Mishra and Ramakrishnan (1983), with the first erosion peak in spring between April and May and the second in September (Supplementary material A Figure 2). These are associated with a reduced soil cover before and after sowing, as well as after harvesting.

As the historic annual soil erosion of our simulations matches the measured soil loss range of the reference study and is consistent with land use and seasonal patterns found in previous studies, we presume that our simulations provide an adequate picture of soil erosion dynamics in the region.

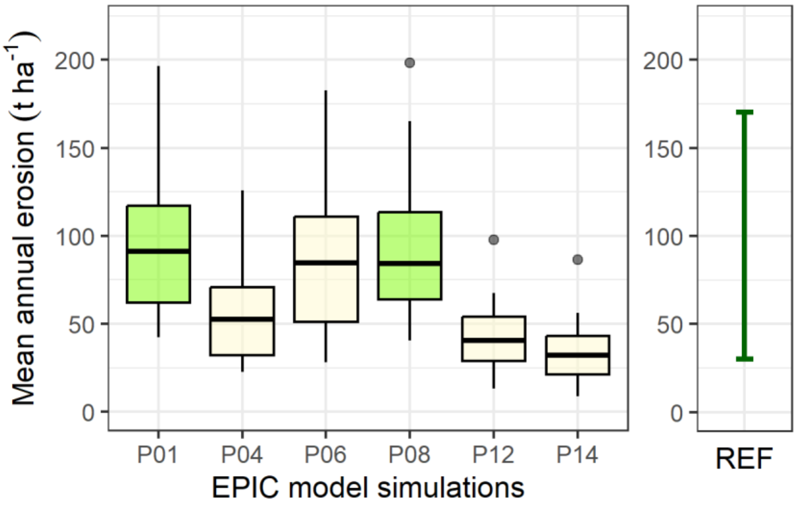


Figure II.3: Simulated historic soil erosion compared with reference study.

Note: Mean annual erosion (y-axis) for six different sites (x-axis) is shown.
Abbreviation: REF, measured erosion range in reference study (Saha et al., 2011).

Table II.2: Characteristics of simulated sites and reference study site used for model evaluation.

	P01	P08	REF
Time period	1985-2014	1985-2014	1983-2011
Land use	SC	SC	SC
Fallow length	3 years	3 years	3 years
Mean field slope	40%	40%	38.2%
Mean annual rainfall	2793 mm	2518 mm	2439 mm
Texture [a]	sandy clay loam	clay loam	clay loam
Annual soil loss [b]	42.40 - 196.56	40.39 - 198.36	30.20 - 170.20
Method	EPIC Model	EPIC Model	Multi-slot divisor

Detailed information on soil properties, including particle size distribution, SOC, and bulk density is given in Table II.1 (P01, P08) and Saha et al. (2011) (REF). Abbreviation: REF, reference study site; SC, shifting cultivation. **[a]** *= refers to top soil horizon;* **[b]** *= in t ha^{-1} yr^{-1}*

2.3.4 Model simulations

We simulated future soil erosion for three different climate scenarios, namely SSP126, SSP370, and SSP585, and two 30-year time horizons, from 2021 to 2050 (near future) and from 2071 to 2100 (far future). To examine the effect of slope inclination and fallow length on erosion dynamics, we simulated erosion for various slopes and fallow lengths, considering field slopes between 5% and 70% steepness (in 5% steps) and fallow lengths between 1 and 20 years. Previous studies and our model evaluation have shown that soil erosion behaves differently between the first and second years of cultivation and the fallow period. To avoid distorting this pattern due to inter-annual weather variations, we simulated each year of a simulation period with all three land uses (first year of rice cultivation, second year of rice cultivation, fallow). To achieve this, we started each simulation at a different point in the rotation and repeated this process until all points in the rotation had occupied the starting position. For example, for the shortest rotation we considered, rice-rice-fallow (fallow length 1 year), we started the simulation three times, once in the order of rice-rice-fallow, once in the order of rice-fallow-rice and once in the order of fallow-rice-rice. For each sequence, we prepared one operation file (see Figure II.4 for the resulting number of operation files). To analyze the results, we computed average values from all sequences.

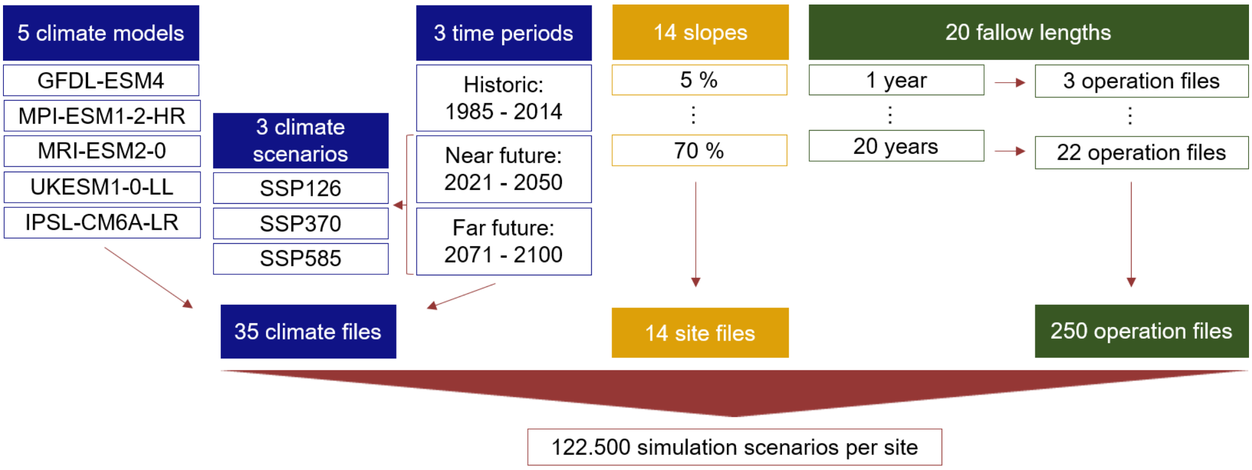


Figure II.4: Setup of simulation scenarios.

SSP, Shared Socioeconomic Pathways, describing low-end (SSP126), medium-high (SSP370), and high-end (SSP585) scenarios of future greenhouse gas emissions.

3 Results

3.1 Annual soil erosion rates under climate change

Our simulations indicate increases in mean annual soil erosion for the far future under all climate scenarios. This increase is particularly strong under the SSP370 and SSP585 scenarios, for which our simulations indicate a mean increase by a factor of 2.2 and 3.1 compared to the reference period, resulting in an average annual soil erosion of 85 t ha^{-1} and 120 t ha^{-1}, respectively (Figure II.5). Under the SSP126 scenario, we estimate mean erosion to increase by a factor of 1.2, corresponding to an annual soil erosion of 45 t ha^{-1}. Our simulations also indicate changes in mean annual soil erosion for the near future; however, these are less pronounced and inconsistent between climate scenarios (Figure II.5). On average, our results indicate annual soil erosion rates of 44 t ha^{-1}, 40 t ha^{-1}, and 42 t ha^{-1} for the near future of SSP126, SSP370, and SSP585, respectively, compared to 38 t ha^{-1} estimated for the historical baseline.

Although all applied climate models agree on a sharp increase in annual soil erosion during the far future under the SSP370 and SSP585 scenarios, erosion estimates vary depending on the underlying climate model used in the simulations (Figure II.5). For the far future, the highest soil erosion rates were simulated for UKESM1-0-LL (all scenarios) and the lowest for GFDL-ESM4 (SSP126, SSP585) and MPI-ESM1-2-HR (SSP370), while results for IPSL-CM6A-LR and MRI-ESM2-0 rank intermediate (all scenarios). Under SSP585 and SSP370, the difference between the highest and lowest soil erosion estimated for the far future is quite large, with 82 t ha^{-1} and 58 t ha^{-1}, respectively. Differences in erosion projections for the different climate models can be explained by differing precipitation projections during the beginning and mid of the monsoon season (Supplementary material A Figure 3).

Differences between projected precipitation and hence erosion are the result of diverging global warming levels projected by the different climate models (Figure II.6). As climate sensitivity and hence global warming levels are much higher for UKESM1-0-LL than for the remaining climate models of this study, erosion estimates for UKESM1-0-LL turn out to be higher as well. We derive a significant nonlinear relationship between erosion rates and global warming levels ($p < 0.001$, $R^2 = 0.88$), indicating an increase in erosion by more than 60% when global warming levels increase from 1.5 to 3.0 °C. We conclude that increases in soil erosion in Northeast India will depend significantly on future global warming levels.

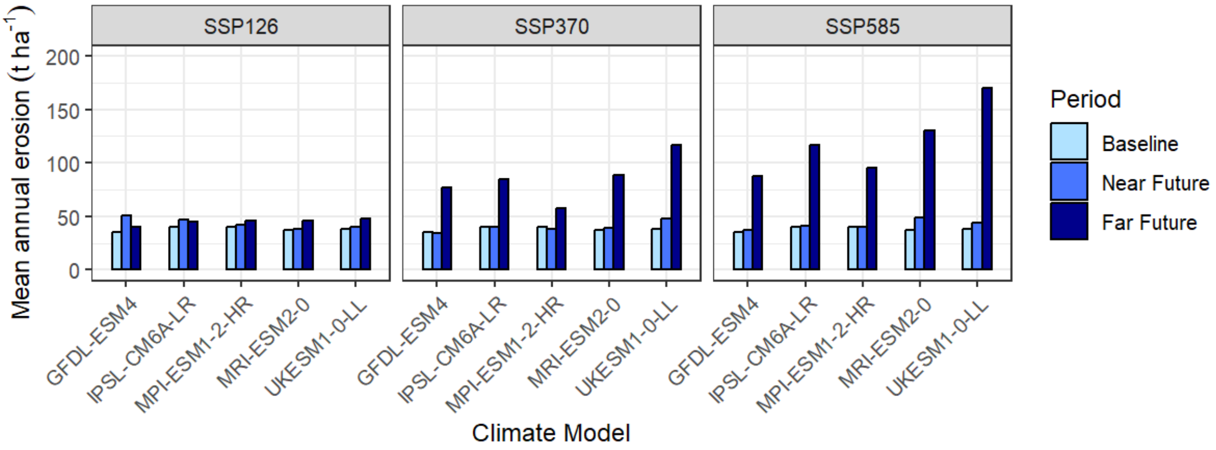


Figure II.5: Mean annual soil erosion rates for SSP126, SSP370, and SSP585 for five climate models.

Results show mean values of all simulated slopes and fallow lengths.

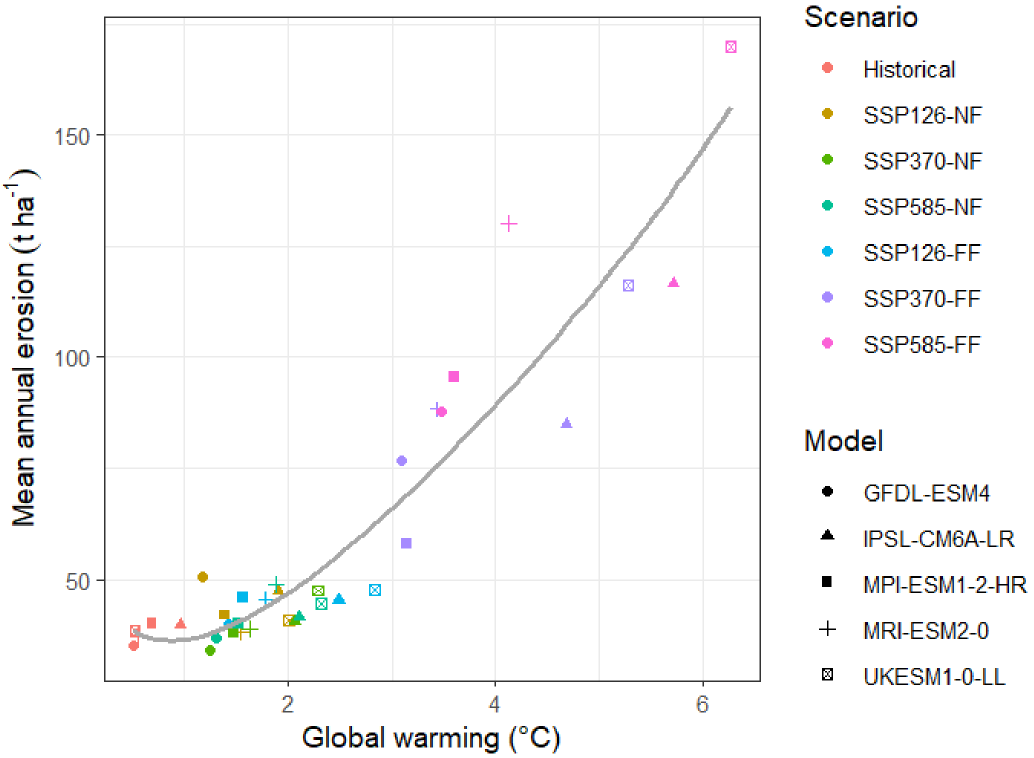


Figure II.6: Mean annual soil erosion rates in relation to global warming.

The model is described as $f(x) = 76.31 + 45.91x + 0.01\ exp(x) - 85.81\sqrt{x}$ *with* $p < 0.001$ *and* $R^2 = 0.88$. *The model is applicable for warming levels between 0.52 and 6.27 °C. NF, near future; FF, far future.*

3.2 Future intensity and seasonality of erosion

The simulated increase in annual soil erosion can be attributed to an increase in high-intensity erosion events. While during the historical baseline, in all near-future scenarios and the SSP126 far future, erosion per day rarely exceeds 0.3 t ha^{-1}, far-future scenarios of SSP370 and SSP585 indicate a clear increase of days with soil losses between 0.3 and 2.0 t ha^{-1} (Figure II.7a). Under these scenarios, days with erosion exceeding 0.3 t ha^{-1} constitute more than 50% of all erosion days. Increases in high-intensity erosion days are also determined by slope and fallow periods. With rising slopes and decreasing fallow periods, the share of erosion days above 0.5 t ha^{-1} and 1 t ha^{-1} clearly increases for the SSP370 and SSP585 far future, respectively. (Figure II.7b, c). We conclude that climate change-induced increments in annual erosion are largely due to an increase in high-intensity erosion events, while the quantity of days with lower erosion intensities (< 0.2 t ha^{-1}) shows slight decreases.

Our results further indicate that the increase in erosion intensities will mostly occur in the pre-monsoon season between March and April and the high-monsoon season between July and September. Figure II.8 shows that all erosion peaks, except the spring peak under fallow, are substantially higher under the SSP370 and SSP585 far futures. For the autumn peak under fallow, this increase is extreme. In addition, maximum erosion in spring and increases in erosion during summer occur about 1 month earlier under both rice and fallow under these scenarios. Changes in the magnitude and timing of erosion can be related to an increasing precipitation intensity during the early and high monsoon season. Particularly during the pre-monsoon season between the mid of March and the beginning of June, four out of five climate models indicate substantial increases in precipitation (Supplementary material A Figure 3). However, a simple translation from precipitation to erosion increases would fall short, since the latter also depends on other factors, such as the distribution of rainfall across days and changes in vegetation cover.

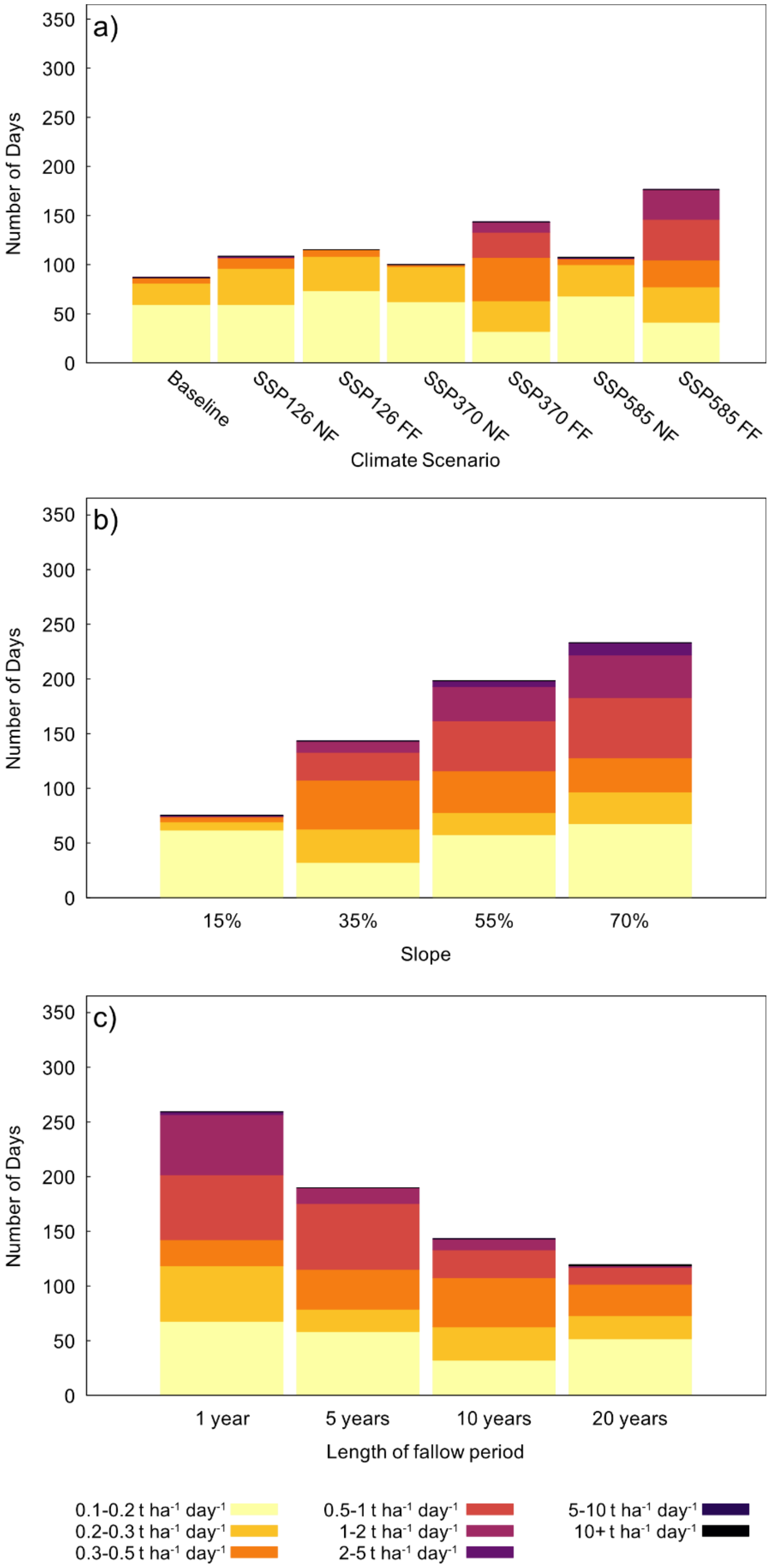


Figure II.7: Frequency of different daily soil erosion intensities per a) climate scenario and time period, b) 15%, 35%, 55%, and 70% slope steepness, c) 1-year, 5-year, 10-year, and 20-year fallow regimes.

Values for (a) are based on 35% slope steepness and a 10-year fallow regime. Values for (b) are based on the SSP370 far future and a 10-year fallow regime. Values for (c) are based on the SSP370 far future and 35% slope steepness. Results show the mean values of the five climate models.
FF, far future; NF, near future.

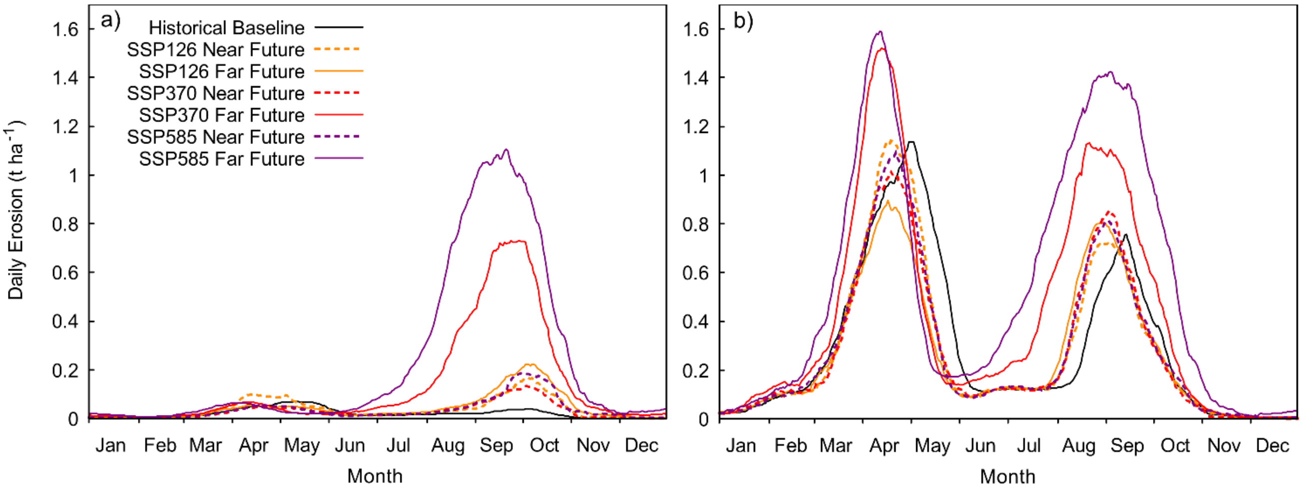


Figure II.8: 31-day moving average of intra-annual soil erosion dynamic for (a) fallow and (b) rice cultivation.

The x-axis indicates the month; the y-axis indicates erosion per day in t ha^{-1}*. Results were averaged over the five climate models and 30 simulated years per period and are based on 35% slope steepness and a 10-year fallow regime. The 35% slope was selected because this slope range contains the most shifting cultivation areas; the 10-year fallow regime corresponds to the mean simulated fallow period.*

3.3 Future soil erosion for different slopes and fallow periods

Our results reveal a negative relationship between fallow period length and soil erosion, which is stronger during the fallow period itself than during rice cultivation (Figure II.9a). During cultivation, the relation is linear, while it is nonlinear during fallow. This pattern can be explained by the fact that soil erosion during fallow is highest during the early years after rice cultivation. The shorter the fallow period, the higher the share of erosion-prone years at the beginning of the fallow phase. With increasing fallow length, the share of less erosion-intensive years increases, hence overall erosion during the fallow period decreases. When the fallow periods are longer than 10 years, the strength of the relationship diminishes. Considering the fallow-erosion relationship for the entire system, soil erosion is 1.6 times higher under a 1-year compared with a 5-year fallow regime and even 2.2 times higher when compared with a 10-year fallow regime.

Our results confirm the expectable distinct, positive linear relation between slope and soil erosion, which is more pronounced during rice cultivation than during fallow (Figure II.9b). During rice cultivation in the far future, annual erosion increases by 4.9 t ha^{-1} per each additional percent slope. Rice cultivation on slopes of 20% steepness hence leads to annual erosion rates more than twice as high as on slopes of 10% steepness (79 t ha^{-1} and 32 t ha^{-1}, respectively). Under fallow, erosion increases per additional percent slope are still prominent but with 2.1 t ha^{-1} less strong.

Our results show that erosion under shifting cultivation is influenced not only by the slope gradient but also by the length of the fallow period, and suggest that short fallow periods favor erosion for two reasons: First, frequent cultivation cycles result in poor physical characteristics of the soil, and second, the proportion of highly erosion-prone fallow years within the total cycle is larger when fallow periods are short.

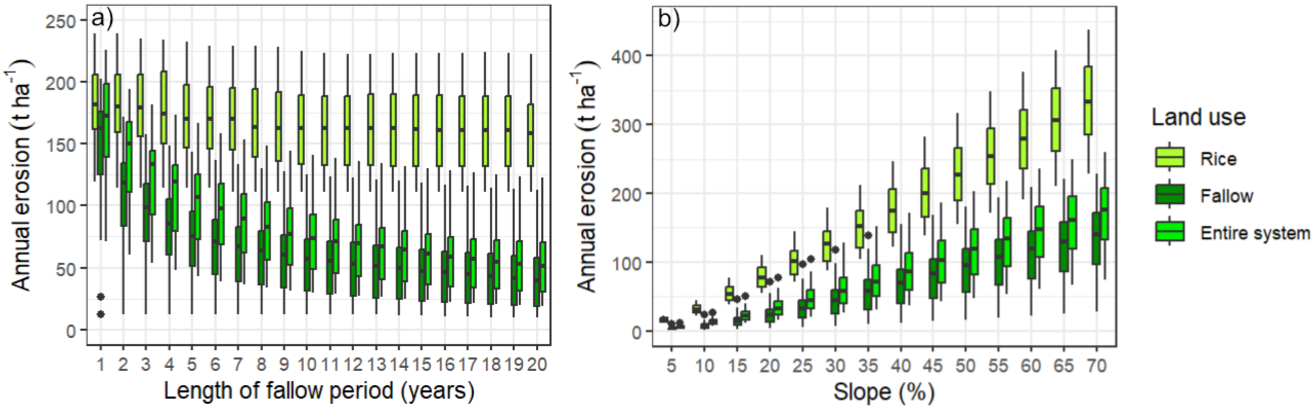


Figure II.9: Relationship between (a) fallow period length and erosion and (b) slope and erosion for the far future.

Boxplots show median, first and third quartile, and the range of values excl. outliers. Outliers are indicated by points. The average of SSP126, SSP370, and SSP585 scenarios of five climate models is shown.

3.4 Combined effects of slope inclination, fallow period, and climate change

Our results indicate that climate change will reduce the sustainable possibility space for shifting cultivation toward the end of the century, particularly under the SSP370 and SSP585 scenarios (Figure II.10). Under these scenarios, the same slope inclinations will require longer fallow periods than during the first half of this century when erosion rates are to remain largely unchanged.

When the often used soil loss tolerance of 10 t ha^{-1} year^{-1} is taken as a reference value not to be exceeded, shifting cultivation during the far future of SSP370 and SSP585 would require minimum fallow periods of 4 (SSP370) and 7 years (SSP585) on a 5% slope, and 11 (SSP370) and 17 years (SSP585) on a 10% slope. Under the far future of SSP126, 5% and 10% slopes could be cultivated under a 2 and 5-year fallow regime, respectively, while slopes of 15% and 20% would require fallow periods of at least 10 and 16 years, respectively. On slopes steeper than 20%, mean annual soil loss would exceed 10 t ha^{-1} year^{-1} under all fallow periods and far future scenarios.

In the near future, slopes of 5% and 10% could be cultivated under a 2 and 5-year fallow regime under all scenarios. Slopes of 15% and 20% would require a minimum fallow length of 10 and 16 years, respectively, under both SSP126 and SSP585, while under SSP370, 9 and 14 years would be required.

We conclude that an increase in the slope gradient from 5% to 10% multiplies the required years of fallow period by a mean factor of 2.5; hence, increasing the length of the fallow period can, albeit to a limited extent, compensate for cultivating steeper slopes. In the far future of the medium-high and high-end emission scenarios, a soil loss tolerance of 10 t ha^{-1} year^{-1} would already be exceeded at 10% slope gradients when fallow periods of 11 and 17 years, respectively, are not met. We note that the soil loss tolerance of 10 t ha^{-1} year^{-1} is used here only as an example, without claiming that losses below this threshold would be sustainable.

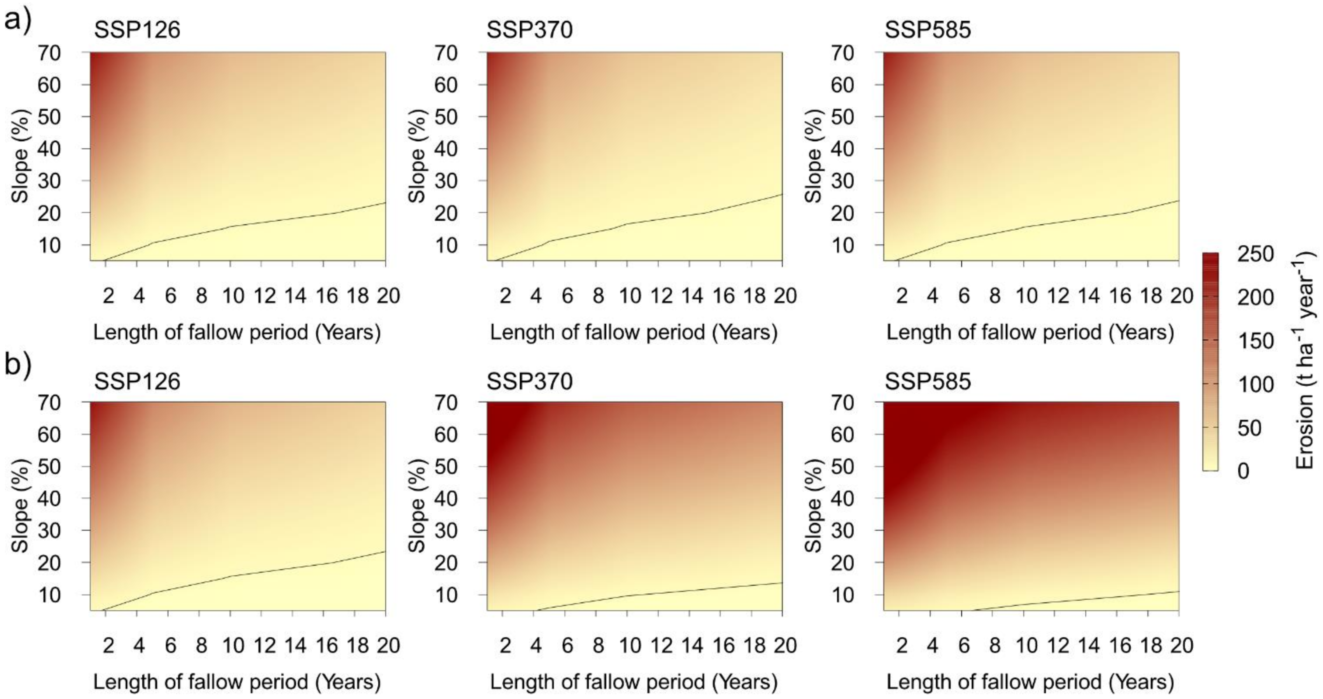


Figure II.10: Combined effects from the slope inclination and fallow period on erosion for the (a) near and (b) far future of SSP126 (left), SSP370 (center), and SSP585 (right) scenarios.

The average erosion values (in t ha^{-1} year^{-1}) of five climate models are shown. The number of fallow years is indicated on the x-axis. Slope values (in %) are given on the y-axis. The black line indicates the soil loss tolerance of 10 t ha^{-1} year^{-1} given for Nagaland in Mandal and Sharda (2011).

4 Discussion

4.1 Future changes in soil erosion

This is, to our knowledge, the first study estimating future soil erosion for shifting cultivation systems. Through comprehensive scenario simulations consisting of 14 slopes, 20 fallow periods, three climate scenarios, and two future periods, we assess the combined effects of climate change and agricultural intensification on future erosion dynamics of traditional smallholder production systems in the Himalaya region.

Our results indicate substantial increases in soil erosion at the field scale towards the end of the century, which are particularly strong under the SSP370 and SSP585 scenarios. For these scenarios, our study suggests increasing erosion intensities and slight seasonal shifts, which have not yet been shown by other studies. Our results highlight the dependence of future erosion increments on global warming rates and show that exceeding global temperature targets will have significant consequences for hillside agriculture. Under a 3 °C warmer world, annual erosion in shifting cultivation in Northeast India will increase by more than 70% from 38 t ha^{-1} to about 66 t ha^{-1}, while erosion increases can be limited to 5% if the 1.5 °C global warming scenario as aimed for in the Paris Agreement is reached.

Several previous studies have indicated reduced fallow periods as a reason for increased soil erosion, suggesting depletion of organic carbon and impaired physical soil properties (e.g., soil porosity and aggregate stability) due to short fallow cycles leading to increased soil erodibility (Mishra and Ramakrishnan, 1983; Ziegler et al., 2009; Grogan et al., 2012; Prokop and Poreba, 2012). However, we are not aware of a study that systematically analyzed the relationship between fallow length and erosion. Our research fills this gap, showing that short fallow periods indeed increase erosion rates of shifting cultivation systems and that a 10-year fallow system could potentially halve erosion compared with a 1-year fallow regime.

Our simulations confirm the significant positive relationship between slope inclination and erosion reported in many previous studies from diverse contexts (Elhassanin et al., 1993; Mondal et al., 2016; Setyawan et al., 2019; Shen et al., 2019). With rice showing a stronger slope-erosion correlation than fallow, our study is likewise in line with previous studies indicating the relationship to be land cover dependent (El Kateb et al., 2013; Sun et al., 2014).

By linking the slope-erosion with the fallow-erosion relationship, we could demonstrate that long fallow periods can compensate to a limited extent for steep slopes, which previous studies did not consider. Beyond that, our modeling approach allowed the analysis of potential, hypothetical future scenarios, such as highly unsustainable management on steep slopes and under extremely short fallow cycles, which cannot be found yet but might eventually evolve in the future, for example, as a consequence of increasing demographic pressure. That way, our analysis revealed not only the realistic but the entire possibility space of future soil erosion.

Our findings complement previous studies on climate change effects in India, suggesting an increasing trend in soil erosion that has already been predicted for other places and land uses in the country (Mondal et al., 2015; Gupta and Kumar, 2017; Khare et al., 2017; Chakrabortty et al., 2020; Rajbanshi and Bhattacharya, 2021; Kumar et al., 2022; Choudhury et al., 2022; Sooryamol et al., 2022). However, concerning the magnitude of soil erosion increases, our estimates can hardly be compared with previous studies, as these were carried out at the entire watershed scale instead of the field scale for different regions and/or land uses, and sometimes earlier-generation climate change scenarios. Still, our findings are in line with previous studies regarding slight changes in soil erosion in the near future, while our estimated increases for the late 21st century exceed those of previous studies (Mondal et al., 2015; Gupta and Kumar, 2017; Choudhury et al., 2022; Sooryamol et al., 2022). On a global level, our results are consistent with many other case studies, together indicating a wide range of soil erosion increases between 1.2% and 1614% during the 21st century when compared with the late 20th century (Li and Fang, 2016).

4.2 Implications for land degradation and management

Future increases in soil erosion will accelerate land degradation and thus productivity losses in uphill regions. Soil erosion and degradation processes are strongly interlinked, as erosion leads to a reduction in root zone depth and displacement of the nutrient and carbon-rich top soil, thus diminishing soil water availability and plant growth (Lal, 2001, Sidle et al., 2006; Zhang et al., 2021). Although quantification of the soil erosion–fertility relationship has proven to be difficult due to its dependence on the experimental methodology (Bakker et al., 2004) and its nonlinear shape (Zhang et al., 2021), previous studies have confirmed the organic matter and nutrient depletion due to erosion under shifting cultivation (Gafur et al., 2003) and estimated substantial associated reductions in crop productivity for Nagaland and other mountainous regions of India (Sharda et al., 2010). Based on these and our findings, we expect substantial declines in the productivity of uphill farming systems under climate change, particularly where steep slopes combined with short fallow periods will boost increasing soil erosion.

Lestrelin et al. (2012) have claimed that the effect of carbon and nutrient depletion due to intensified management could be more important for productivity declines than soil erosion. We argue that soil erosion plays an essential role in this process chain, as erosion exacerbates the loss of SOC, thereby promoting soil erodibility, further organic carbon depletion, and degradation. Moreover, we assume that the contribution of soil erosion to degradation processes will rise in the future, not only because of likely increments in erosion but also because of cumulative effects over time. While a certain amount of soil loss in 1 year may not significantly affect productivity, cumulative erosion over several years may significantly influence soil fertility. This assumption is supported by findings from Zhang et al. (2021), who reported crop yields drop significantly once a critical top soil depth has been eroded.

To limit adverse effects on future soil productivity, our study recommends maintaining sufficiently long fallow periods, which should be longer on steeper than on shallower slopes. In addition, a wide application of soil conservation measures is advised. Besides contouring practices, previous research recommends measures that provide a continuous soil cover, such as cover crops and mulching (Sidle et al., 2006; Kaye and Quemada, 2017; Ngangom et al., 2020; Anantha et al., 2021), intercropping, and a change in crop mix from upland rice to maize and soybean (Singh et al., 2011; Sharma et al., 2017). Further research will be needed on sustainable management practices for uphill shifting cultivation.

4.3 Implications for policies

This research contributes to the ongoing political debate on agricultural intensification in South and Southeast Asia, where population growth and the propagation of settled agriculture through various government programs and initiatives have recently increased land competition, resulting in intensified cultivation cycles and expansion of cultivation to steeper slopes (Lestrelin et al., 2012; Castella et al., 2013; Fox et al., 2014; Nongkynrih et al., 2018, Feng et al., 2021).

Our research shows that (1) the increasing competition and scarcity of cultivable lands will lead to significant erosion increments due to the combined effects from cultivation expansion on steeper slopes and decreasing length of fallow periods and that (2) these dynamics will intensify under increasing global warming scenarios. Under these scenarios, land degradation in uphill areas will proceed at an increasing pace, thereby further pushing land scarcity, ultimately leading to a reinforcing cycle of migration of tribal farmers to barely cultivable lands and land degradation. To break this cycle, our research recommends, on a global level, limiting increasing climate forcing as much as possible and, on a regional level, avoiding increasing competition among land uses in future development plans. Therefore, further studies will be needed to investigate the possibilities of integrating shifting cultivation with other land uses, thus reducing land competition and further displacement of tribal farming communities.

4.4 Limits and uncertainties

While providing important insights into future erosion dynamics of uphill agricultural systems, several limitations of our approach should be noted. First, we only represented one crop and fallow plant in our simulations and not the entire plant diversity, which is typical for shifting cultivation systems.

Further, we note that because this research was conducted at field scale, the outlined dynamics refer specifically to erosion processes at the sloping field, such as gully and interrill erosion; hence, estimated erosion is higher than if measured at the catchment scale. A simple aggregation of our results to the catchment scale should therefore be avoided, also because sedimentation processes were not captured in this study.

Our results depend strongly on future precipitation patterns and, thus, on the projected climate data used for the simulations. As the future occurrence of high-intensity precipitation events is uncertain, the magnitude of future erosion outlined here remains uncertain as well. However, by applying a combination of five bias-corrected and statistically downscaled climate models and three climate scenarios, we were able to present a range of possible future erosion pathways, accounting for the uncertainties related to future climate.

As soil property analyses are time-intensive, costly, and rarely available, our study was limited to six soil profiles, which cannot represent the full diversity of soils in the region nor the range of slopes implemented in the model. Future studies could extend this research to additional sites.

Lastly, we emphasize that this research focuses on a case study region; thus, the applied modeling approach was tailored to the specific conditions of this region. We expect that our results on the general dynamics between slope steepness, fallow periods, and erosion will be similar in other uphill shifting cultivation regions, but recognize that the analyzed relationships depend on the soil, climatic, and management conditions. In particular, climate change will manifest differently in distinct mountain regions; hence, climate change effects on upland soil erosion presented here should not be extrapolated to other regions.

5 Conclusion

This study identifies possible future trends in soil erosion for uphill shifting cultivation systems. Our results demonstrate that slope cultivation under short fallow cycles and climate change will lead to increasing soil erosion in the Himalayas. Increases will be particularly strong under the medium-high (SSP370) and high-end (SSP585) climate change scenarios, leading to mean erosion increases by a factor of 2.2 and 3.1 towards the end of the century, respectively, compared with the historical baseline (1985-2014). These increases occur especially between March and April and between July and September and are associated with a rising number of high-intensity erosion events. We conclude that an increase in global average temperatures by 3 °C will increase erosion rates by more than 60%, compared with erosion rates when the 1.5 °C goal of the Paris Agreement is reached.

Our results further show that, in order to maintain tolerable erosion rates, steeper slopes require longer fallow periods. An increase in slope inclination from 5% to 10% multiplies the minimum fallow period length by a mean factor of 2.5 when a soil loss tolerance of 10 t ha^{-1} $year^{-1}$ is taken as a reference. When erosion rates above this soil loss tolerance are to be avoided in the far future, shifting cultivation under medium-high and high-end climate change scenarios should reach fallow periods of at least 4 and 7 years, respectively, for slope inclinations of 5%, and 11 and 17 years, respectively, for slope inclinations of 10%. From our findings, it follows that climate change limits the possibility space of future shifting cultivation in terms of the cultivable slope range and the required fallow period lengths.

In order to prevent increasing land degradation of uphill regions in Northeast India and other places in South and Southeast Asia, we recommend (1) on a global level, to limit warming to the 1.5 °C temperature target of the Paris Agreement; (2) on a regional level, to avoid an increasing competition among land uses resulting in the displacement of tribal farmers to higher altitudes and/or the shortening of fallow periods; and (3) on a field scale, to adopt diverse soil conservation practices.

For future studies, our findings reveal the need to investigate options for sustainable integration of shifting cultivation with other land uses. Also, upcoming studies could focus on the potential of soil conservation measures to reduce erosion in shifting cultivation systems, particularly on the steeper slope range.

This is the first study analyzing soil erosion of shifting cultivation systems under climate change. Our results contribute to increasing the understanding of uphill land degradation dynamics, revealing impacts on erosion resulting from the interplay of climate change and agricultural intensification.

Article 2

III Managing uphill cultivation under climate change - an assessment of adaptation decisions among tribal farmers in Nagaland state of India

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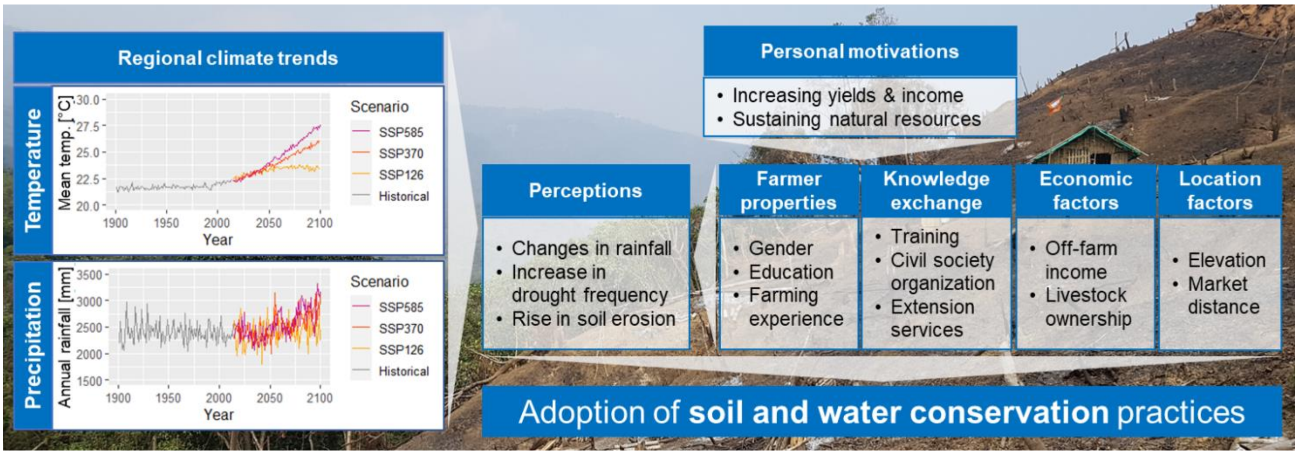
This chapter is published in *Journal of Environmental Management* under the DOI: https://doi.org/10.1016/j.jenvman.2023.119473



Graphical abstract 2

Abstract

Tribal farmers in the Himalayas are vulnerable to climatic changes, as their rain-fed cultivation systems, practiced on steep, sloping terrain, are susceptible to changes in rainfall while at the same time being the primary means of livelihood. Soil and water conservation practices (SWCP) can improve the resilience of these cultivation systems to adverse climatic conditions. However, little is known about adaptation within these tribal farming communities. This is the first empirical study on the adaptation decisions of tribal farmers in the Himalayan uplands of Northeast India. Starting from the analysis of future climate risks, we surveyed 372 tribal farmers in Nagaland state to analyze perceived climate and environmental changes in relation to socio-demographic factors. We estimate current adoption rates of SWCP together with farmers' goals and values and employ a binary logit model (BLM) to quantify the influence of diverse factors on adaptation decisions. Our results show that increases in temperatures and crop diseases were the most perceived changes by tribal farmers. Climate projections indicate that precipitation amount and intensity, along with temperatures, will increase towards the end of the century, underlining the importance of SWCP. However, all considered SWCP were employed by less than half of the tribal farmers. Adoption probabilities for all practices were significantly increased when farmers participated in agricultural training. After that, participation in a civil society organization, livestock ownership, high-altitude locations, and perceived increases in droughts were found to increase adoption probabilities significantly, while socio-demographic factors were of only minor importance. If the most effective factor was employed to all farmers, average adoption rates of SWCP could at least double. Adoption decisions were mainly motivated by improving livelihoods, sustaining natural resources, reducing workload, and preserving cultural aspects of cultivation. This research contributes to understanding adaptation decisions of tribal farmers and quantifies the untapped potential for climate change adaptation of marginalized and climate-vulnerable farming communities in mountain regions.

Keywords

adaptation decisions, climate change, Northeast India, soil and water conservation, tribal farmers, upland agriculture

1 Introduction

While negative impacts from climate change on productivity have been reported for many regions of the world, severe impacts are expected in mountain ecosystems and agriculture (IPCC, 2022b). Due to projected changes in hazards and the water cycle in mountain regions, particularly in south and central Asia, the IPCC has recently emphasized the importance of adaptation for warming rates above 1.5 °C (IPCC, 2022b). Besides the changing climate and difficult topographic conditions, political and social marginality have made mountain communities highly vulnerable (FAO, 2015).

In the Himalayas, warming rates are higher than the global average, while steep topographies and shallow, nutrient-poor soils favor erosion-caused land degradation (ICIMOD, 2010; Pepin et al., 2015). In addition, farming communities in the Himalayas are often marginalized, show high poverty levels, low literacy rates, and poor access to resources, markets, and off-farm employment, thus depending on subsistence agriculture (FAO, 2015; Ghosh-Jerath et al., 2021; Rana et al., 2021). Because of their climate-sensitive production systems and low adaptation capacities, Himalayan farming communities are particularly vulnerable to climate change (Rai et al., 2019).

These characteristics apply in particular to the indigenous tribal farming communities in Northeast India, designated as Scheduled Tribes by the Indian government (Ghosh-Jerath et al., 2021). Their centuries-old rain-fed, low-input, and thus purely organic production systems play a key role in securing local food supply and preserving the culture and traditions of the tribal population (Pandey et al., 2020). Climate change puts these production systems at risk because of their strong dependence on timely rainfalls and intact fertile soils.

The application of soil and water conservation practices (SWCP) has been advised to reduce the vulnerability of tribal farming communities to increasing climatic risks in the Himalayan region (Schröder et al., 2023; Xuan Minh et al., 2017). This raises the question of what internal and external factors influence farmers' decisions to adopt or not adopt such practices. Knowledge about how climate change perception, farmers' values, but also socio-demographic, economic, and location factors influence adaptation decisions may improve agricultural policies to support smallholder adaptation to climate change.

A wide academic literature has discussed socio-demographic and economic determinants of farmers' adaptation to climate change in diverse geographic contexts. It was found that gender, age, education, household size, and access to credit can significantly affect adaptation (Ahmed et al., 2021; Jin et al., 2016; Marie et al., 2020; Mwinkom et al., 2021). However, many factors have been proven to be context-dependent, with studies from Ethiopia identifying access to extension services, climate information, and household income as relevant (Adego and Woldie, 2022; Bryan et al., 2009; Deressa et al., 2009; Eshetu et al., 2021), while studies from Pakistan observed farm size (Abid et al., 2015; Ali and Rose, 2021; Amir et al., 2020; Khan et al., 2020), and from Vietnam membership in a local community organization as influential factors for adaptation (Huong et al., 2017; Truong et al., 2022; Vo et al., 2021). Consequently, findings from one geographical setting can hardly be transferred to other contexts where climate, environmental, and socio-political dynamics differ, thus making adaptation research focusing on the context of Himalayan tribal farmers necessary (Ghosh-Jerath et al., 2021).

A few studies on climate change perception and adaptation in the Himalayas have been conducted already; however, they did not focus on soil conservation (Rymbai and Sheikh, 2018; Singh et al., 2017), which will be increasingly important with changing rainfall regimes. Also, these studies did not address farmers' values and related goals and preferences in the adaptation process, nor was their research linked to established theories of adaption behavior (Bhalerao et al., 2022; Datta and Behera, 2022a; Jha and Gupta, 2021; Lone et al., 2022).

Due to the particular vulnerability of Himalayan tribal farming communities, this study seeks to close this research gap. We conducted a large-scale quantitative survey with tribal farmers from Nagaland State in Northeast India, the state with the second largest share of tribal population and the highest amount of families practicing shifting cultivation, a typical uphill farming system in the Himalayas (Government of India, 2015). Based on this survey and climate model projections, our research seeks to answer the following questions: 1.) Which climate futures can be expected for the region? 2.) Which climate and environmental changes do tribal farmers perceive, and how are they connected to socio-demographic factors? 3.) What are the current adoption rates of SWCP, which factors influence adoption, and to what extent can adoption rates be increased? 4.) Which personal values do tribal farmers consider in the adaptation process?

2 Theoretical framework

This research builds on established theories of adaptation behavior, namely the Model of Private Proactive Adaptation to Climate Change (MPPACC) (Grothmann and Patt, 2005) and the Values Beliefs Norms Theory (VBN) (Stern, 2000). MPPACC defines a two-stage process preceding the adaptation decision, which consists of a “climate change risk appraisal” and an "adaptation appraisal". Based on the Protection Motivation Theory (PMT) (Rogers et al., 1983), MPPACC assumes that adaptation presupposes the perception of climatic risks, thereby accounting for cognitive biases, heuristics, and social discourses on climate change, influencing people's perception of risk and adaptive capacity. The model also considers the effect of past experiences on risk perception and an objective adaptive capacity, including, e.g., economic and social constraints that enable or impede people from turning adaptation intentions into actions. VBN assumes a similar causal chain leading to pro-environmental behavior but emphasizes the role of personal values and norms in the risk perception and adaptation process. Our research builds on these theories with regard to three aspects: First, we analyze how climate change perception is shaped among tribal farmers and how these perceptions influence the adoption of SWCP. Second, we address the objective adaptive capacity by identifying other factors supporting or constraining adaptation. Third, we assess which values and norms of tribal farmers are relevant in the adaptation process. Thereby, we assume that personal values not only influence the risk evaluation but also the goals and preferences of farmers. A schematic illustration of the resulting theoretical framework is provided in Figure III.1.

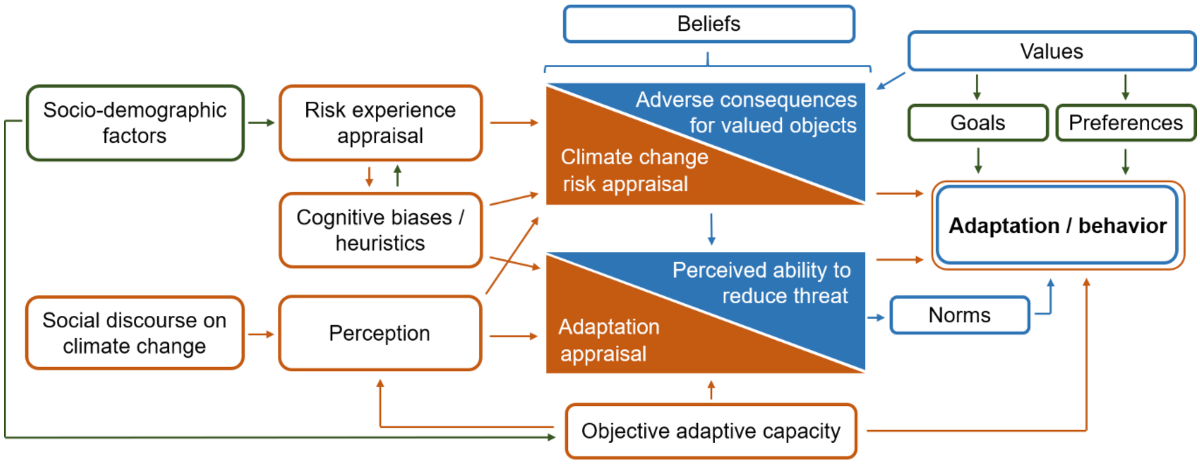


Figure III.1: Theoretical framework.

Orange elements relate to the MPPACC (Grothmann and Patt, 2005), blue elements relate to the VBN Theory (Stern, 2000). Elements in green were added to the framework by the authors. MPPACC and VBN Theory are shown in a simplified and reduced way; for the original theories the reader is referred to Grothmann and Patt (2005) and Stern (2000).

3 Material and methods

3.1 Study area

We selected Nagaland state of Northeast India as a study area for our research because it has one of the largest proportions of tribal population (87%) relying on traditional farming practices such as shifting cultivation, an extensive, uphill, subsistence farming system. While the distribution of shifting cultivation in many tropical regions has decreased over the last decades because of political and economic pressures (van Vliet et al., 2012), in Northeast India, particularly Nagaland State, the practice is still widely distributed, with approximately 116,000 families being engaged in the practice (Government of India, 2015).

Located in the Himalayas' foothills, Nagaland is traversed by mountain ranges. About 98% of the state is mountainous (Jayahari and Sen, 2015), with altitudes ranging from 194 to 3840 meters above sea level (Government of Nagaland, 2019). Accordingly, steep slopes dominate the region, with 63% of the area having slopes steeper than 30% and even 26% steeper than 50% (NASA SRTM, 2013). Because of its steep topography, Nagaland is especially threatened by soil erosion.

The climate of Nagaland ranges from sub-tropical to sub-montane temperate. It is characterized by high rainfall intensities during summer, with 85% of the total annual precipitation being recorded during the Indian summer monsoon between mid-May and the end of September. Total annual precipitation is 1200-2500 mm (Government of Nagaland, 2019; Jayahari and Sen, 2015).

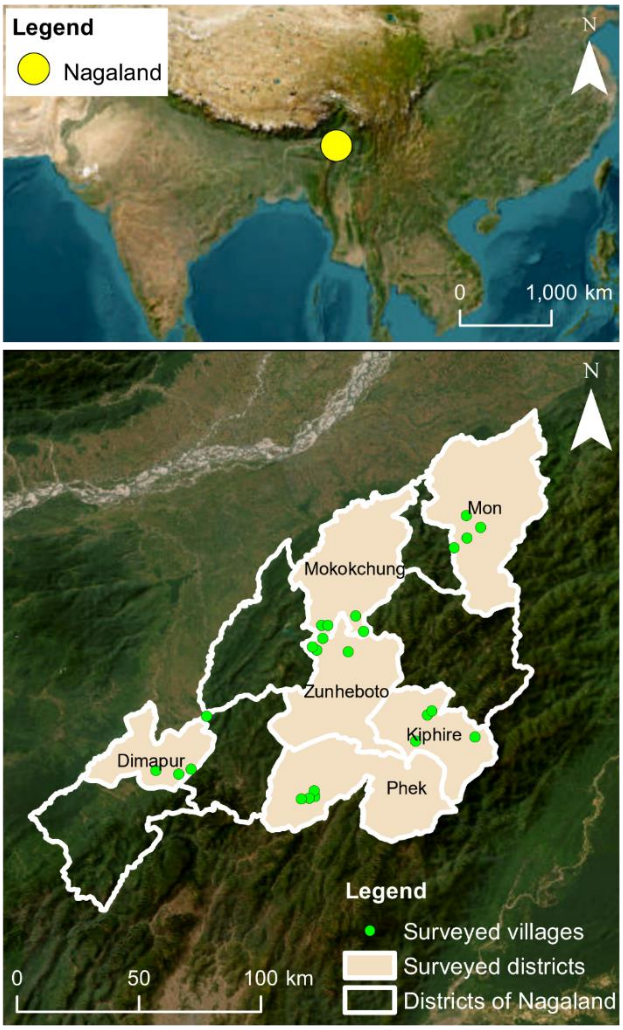


Figure III.2: Study area with surveyed villages.

Source of satellite image: ESRI, Maxar, Earthstar Geographics, and the GIS User Community.

3.2 Data

3.2.1 Farmer survey

To investigate farm-level management strategies, we surveyed Nagaland state between November 2021 and April 2022. We first selected six districts using simple randomization. In a second step, we selected four villages per district with a suitable number of families actively engaged in cultivation and available for interviews during our field visit (Figure III.2). Extension officers from the local Krishi Vigyan Kendras (KVK) supported the identification of these villages. From each village, all households actively involved in cultivation activities during our field visit and willing to participate were interviewed using a fully structured questionnaire on diverse socio-demographic, economic, and network variables, as well as farming practices, perceptions, and opinions (Supplementary material B.2).

From the collected data, we included only those data entries that were complete regarding the variables used in the final analysis. We excluded all data entries with logical errors. After data cleaning, 372 farmer interviews remained for the statistical analysis, with 41-88 entries per district and 6-25 per village (Supplementary material B. Table 1).

3.2.2 Climate data

To identify climatic trends in the study region, we used daily climate model data from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) (Lange, 2019a; Lange and Büchner, 2021). ISIMIP3b climate data are available for three climate scenarios, a low-end (SSP126), a medium-high (SSP370), and a high-end (SSP585) future forcing scenario as well as five models of phase 6 of the Coupled Model Intercomparison Project (CMIP6): GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL, and IPSL-CM6A-LR. ISIMIP3b data were statistically downscaled to a 0.5° spatial resolution and bias-adjusted by Lange (2019a) using the EWEMBI dataset (Lange, 2019b) with a global coverage at 0.5° spatial resolution (see also Frieler et al. (2017) for a detailed description of the EWEMBI dataset). We downloaded the ISIMIP3b climate data in February 2022 from the ISIMIP repository (https://data.isimip.org/search/). We intersected the ISIMIP grid with the locations of the surveyed villages using ArcGIS software and extracted daily maximum and minimum temperatures and precipitation for the six remaining ISIMIP grid cells. For further analysis, daily mean values over the six grid cells were derived. We computed daily mean temperatures by taking the average of daily maximum and minimum temperatures. To address rainfall intensity, we computed the rainfall peak volume, which we defined as the total precipitation of the ten wettest days per year. We defined drought frequency during the growing period from March 1st to September 1st as the number of non-overlapping periods with at least ten consecutive days without rainfall. To assess long-term climatic trends, we computed annual mean values for temperature, rainfall amount, rainfall peak volume, and drought frequency for a historical period from 1901-2014 and the three climate scenarios between 2015 and 2100. All computations and plotting operations were carried out in R software.

3.3 Statistical model

We applied a binary logit model (BLM) to estimate influencing factors of farmers' management strategies. BLMs describe the binary decision of farmers on whether to adopt a certain strategy or not based on various factors, which can include both categorical and continuous variables. The model allows for analyzing different adaptation strategies independently, thus providing a suitable method for contexts where farmers apply multiple management strategies simultaneously (Abid et al., 2015; Ali and Rose, 2021). Further, it provides a clear interpretation via the odds ratios, which can inform targeted interventions and policy recommendations. Lastly, using a BML is not restricted by assumptions of linear regressions, such as normality, linearity, and homoscedasticity (Ali and Rose, 2021). Because of these capabilities, the model has already been applied in various similar studies and has yielded valuable insights into farmer adaptation behavior, i.e., in Bangladesh (Ahmed et al., 2021), China (Jin et al., 2015; Jin et al., 2016), Vietnam (Huong et al., 2017; Thoai et al., 2018; Vo et al., 2021), Pakistan (Abid et al., 2015; Khan et al., 2020; Ali and Rose, 2021), and Ethiopia (Sertse et al., 2021). By utilizing a consistent and established methodology, we build upon existing research and facilitate comparisons with prior findings.

The model can be specified as

$$Y_{ij} = \alpha + \sum X_k \beta_k + \varepsilon_{Yij} \tag{III.1}$$

where Y_{ij} is the dichotomous dependent variable with subscript i referring to the farmer, who is taking the management decision, and j representing the management strategy. X_k is a vector of various factors influencing farmers' management decisions, with subscript k referring to the specific independent variable, whereas β_k indicates a vector of binary coefficients. α shows the model intercept, and $\mathcal{E}_{Yij}$ denotes the error term (Ali and Rose, 2021; Sertse et al., 2021).

We focused our statistical analysis on adaptation measures conserving soil and water resources, including cover crops, mulching, intercropping with legumes, manure, and rainwater harvesting (RWH). Both cover crops and mulching protect soils from high-intensity precipitation by providing soil coverage. Cover crops also stabilize soil aggregates through their roots, while mulching recycles nutrients and improves the soil water balance by increasing infiltration and reducing evaporation (Kaye and Quemada, 2017; Ngangom et al., 2020). Intercropping with legumes improves soil fertility through nitrogen fixation and reduces soil loss by providing additional soil cover (Sharma et al., 2017). The application of manure increases soil productivity by delivering nutrients and organic matter and can likewise act as a protective cover, reducing soil detachment and thus erosion (Ramos et al., 2006). Lastly, RWH increases water resources available for irrigation, thus potentially improving the soil water balance when rainfall is absent.

Similar to previous studies (Abid et al., 2015; Amir et al., 2020; Datta and Behera, 2022a; Deressa et al., 2009), we based the choice of explanatory variables on literature review and the specific characteristics of the study area, as also suggested by Dang et al. (2019). In contrast to many previous studies, we opted against the integration of gender in the statistical model, as in our study area management decisions are typically made by the entire farming household. Perception variables were reduced to those directly relevant for the analyzed SWCP, including an increase in temperatures and drought frequencies, any change related to rainfall, and an increase in erosion. Continuous variables were tested on linearity with log odds. Where possible, the non-linearity of independent variables and log-odds was solved by converting continuous into categorical variables (farming experience, elevation, distance to market), while others had to be excluded from the set of input variables (age, family size, total cultivated area). Lastly, all variables were tested on multicollinearity. As in Jin et al. (2015) we computed the “tolerance” (TOL) and “the variance inflation factor” (VIF) indices for multicollinearity diagnosis. Strong multicollinearity is indicated by TOL values below 0.1 and VIF values greater than 10 (Jin et al., 2015; Menard, 2002). In our models, TOL values ranged from 0.3 to 0.9 and VIF values from 1.1 to 3.0, confirming low multicollinearities for all models. We provide a detailed explanation of all independent variables used in the final model in Table III.1. In addition to the listed variables, we initially also included a perceived increase in temperature and erraticness of rainfall and the reception of financial support but excluded them in the final model as their coefficients for all management strategies turned out to be statistically insignificant. We run all tests and models in R software.

Table III.1: Summary statistics of variables included in the BLM.

	Variable	Description	Occurrence*
Dependent	Cover crops	Dummy 1 if adopted, 0 otherwise	14%
	Mulching	Dummy 1 if adopted, 0 otherwise	40%
	Intercropping	Dummy 1 if adopted, 0 otherwise	46%
	Manure	Dummy 1 if adopted, 0 otherwise	29%
	RWH	Dummy 1 if adopted, 0 otherwise	31%
Independent	Training	Dummy 1 if farmer received training, 0 otherwise	Figure III.6
	Extension contact	Dummy 1 if farmer has regular (at least yearly) contact to governmental extension worker, 0 otherwise	75%
	Civil society organization	Dummy 1 if farmer participates in a civil society organization, 0 otherwise	87%
	Off-farm income	Number of non-farming household income sources: 0 = no income sources; 1 = one income source; 2 = more than one income source	$\bar{x} = 1.0$ $\sigma = 0.7$
	Livestock ownership	Dummy 1 if farmer rears livestock, 0 otherwise	76%
	Rainfall quantity decrease	Dummy 1 if farmer perceived decrease in rainfall quantity, 0 otherwise	57%
	Drought frequency increase	Dummy 1 if farmer perceived increase in frequency of droughts, 0 otherwise	40%
	Rainfall intensity increase	Dummy 1 if farmer perceived increase in rainfall intensity, 0 otherwise	9%
	Rainfall quantity increase	Dummy 1 if farmer perceived increase in rainfall quantity, 0 otherwise	7%
	Erosion increase	Dummy 1 if farmer perceived increase in soil erosion, 0 otherwise	50%
	Farming experience	Dummy 1 if farming experience is at least 20 years, 0 otherwise	64%
	School education	0 = no schooling; 1 = primary; 2 = secondary; 3 = above secondary	$\bar{x} = 1.1$ $\sigma = 0.8$
	Elevation	Dummy 1 if elevation of village is above 1000 m, 0 otherwise	42%
	Market distance	Dummy 1 if distance to nearest market is at least 10 km, 0 otherwise	57%

** Occurrence within sample is given. For binary variables, the percentage of farmers where the variable takes the value 1 is shown, for other categorical variables, mean ($\bar{x}$) and standard deviation (σ) are given.*

4 Results

4.1 Climatic trends for Nagaland

Climate model data indicate a steady increase of temperatures in the study region during the end of the 20th and beginning of the 21st century (Figure III.3). Compared to the beginning of the 20th century, temperatures increased by at least 1° Celsius until 2014. By contrast, precipitation data do not reveal systematic changes for this period. Despite substantial interannual variability in annual precipitation, neither precipitation amount nor intensity, described by peak volume, has shown a clear trend until 2014. However, the frequency of droughts, here defined as 10-day periods without rainfall during the growing season, reveals a slightly decreasing trend.

Until the end of the 21st century, ongoing increases in temperatures are projected (Figure III.3). These will be particularly high for the medium-high (SSP370) and high-end (SSP585) emission scenarios, under which daily mean temperatures will exceed 26 °C, compared to approximately 22.5 °C in 2014. Likewise, increases in the amount and intensity of precipitation can be expected, particularly during the second half of the century and for the higher emission scenarios. In line with increasing precipitation, drought conditions are projected to decrease slightly without considerable differences between the scenarios.

Although these climate data are subject to large uncertainties and inaccuracies related to their spatial resolution and the complex terrain of the study region, they reveal relevant general climatic trends with important implications for upland cultivation in the region. Due to increases in temperatures and hence potential evapotranspiration, plant-available water might decrease even under increasing total annual precipitation. Since precipitation intensities are projected to increase simultaneously, runoff and hence soil erosion will most probably increase as well, making SWCP increasingly important.

4.2 Perceived climatic and environmental changes

While climate model data quantify objective, large-scale trends, surveys allow to understand subjectively perceived climatic and environmental changes at the local scale. Our survey results show that temperature increase is the most important change observed by farmers (Figure III.4). Over 80% of all respondents perceived an increase in temperatures, with slightly higher perception rates among farmers with at least secondary education. There are no notable differences between male and female farmers and those with longer and shorter farming experience. Most farmers (57%) also perceived a decrease in rainfall, which was more often observed among farmers with longer farming experience (64%). In follow-up discussions with farmers, we found that this decrease in rainfall was particularly observed in the months of February and March, suggesting a shift in the monsoon season, as observed by 16% of all respondents. An increase in the frequency of droughts is the third most noticeable climatic change, which was clearly more often perceived by female (50%) than by male (34%) farmers and by farmers with secondary education (49%). However, perception rates of increased drought frequencies drop again among farmers with post-secondary education. All other changes, including those related to increasing rainfall quantity or intensity, were clearly less often perceived.

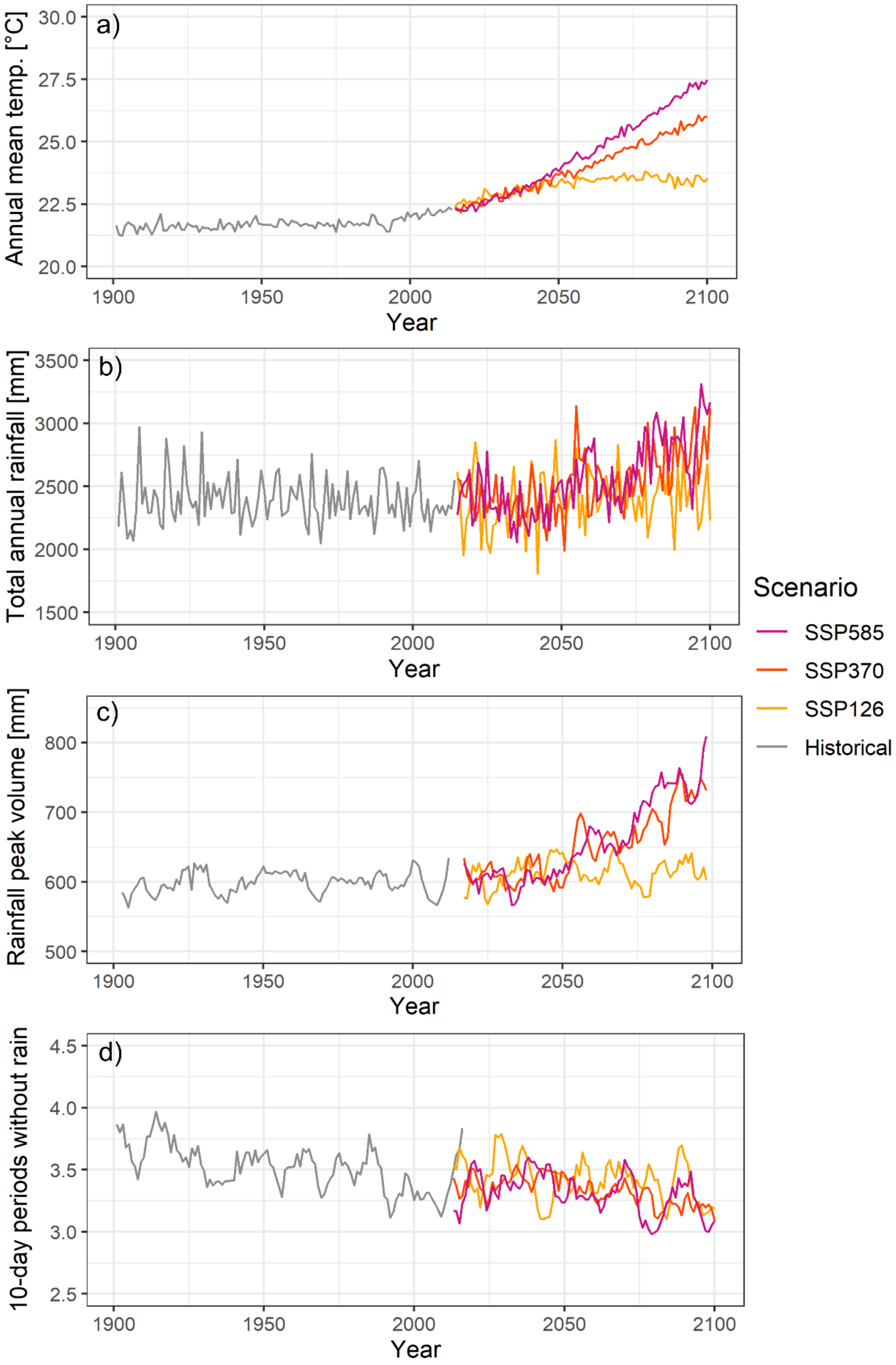
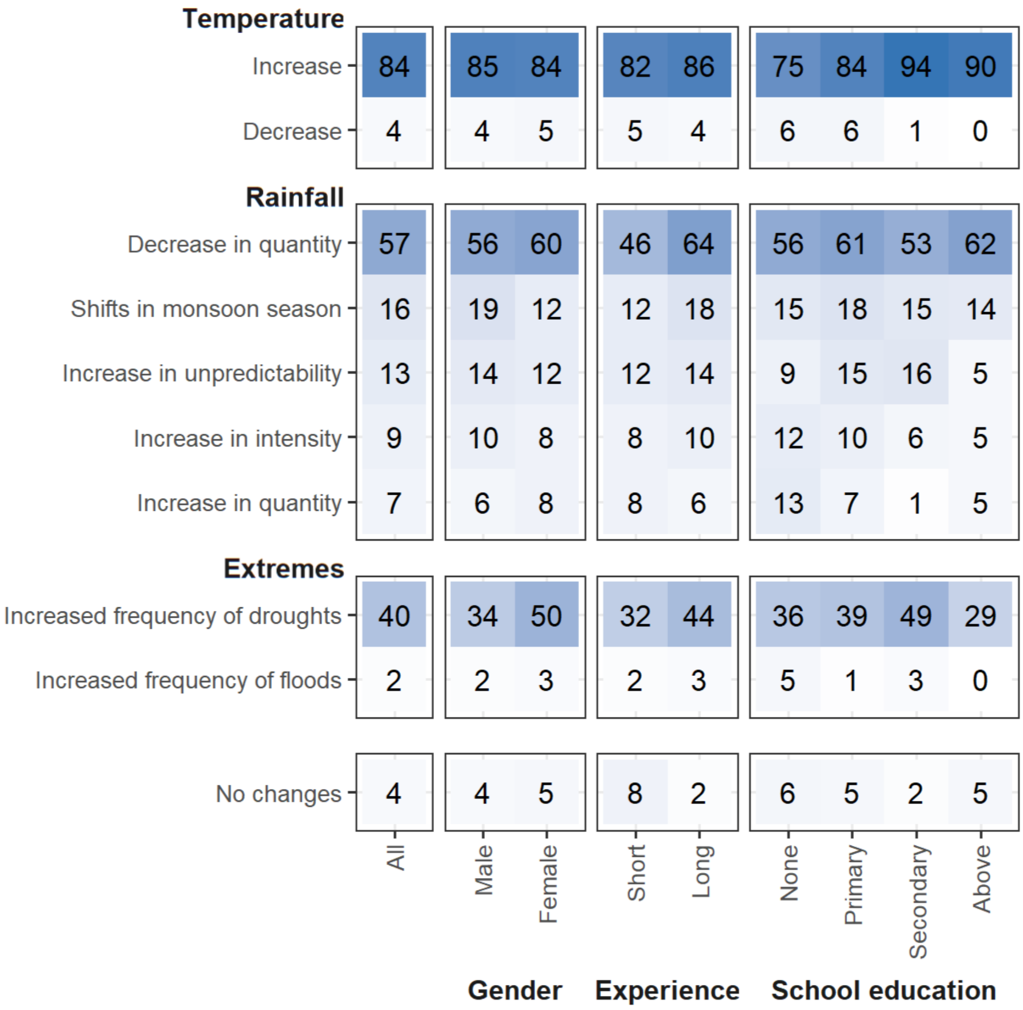


Figure III.3: Historical and future climatic trends of Nagaland under SSP126, SSP370, and SSP585 scenarios.

Figure shows a) annual mean temperatures in °C, b) annual precipitation in mm, c) rainfall peak volume in mm, defined as the cumulative precipitation of the ten wettest days per year as a proxy for rainfall intensity, d) number of non-overlapping periods with at least 10 rain-free days during the growing season (March 1st – September 1st) as a proxy for drought occurrence. For c) and d), a 5-year moving average is shown for readability.
Data source: ISIMIP3b (Lange and Büchner, 2021)



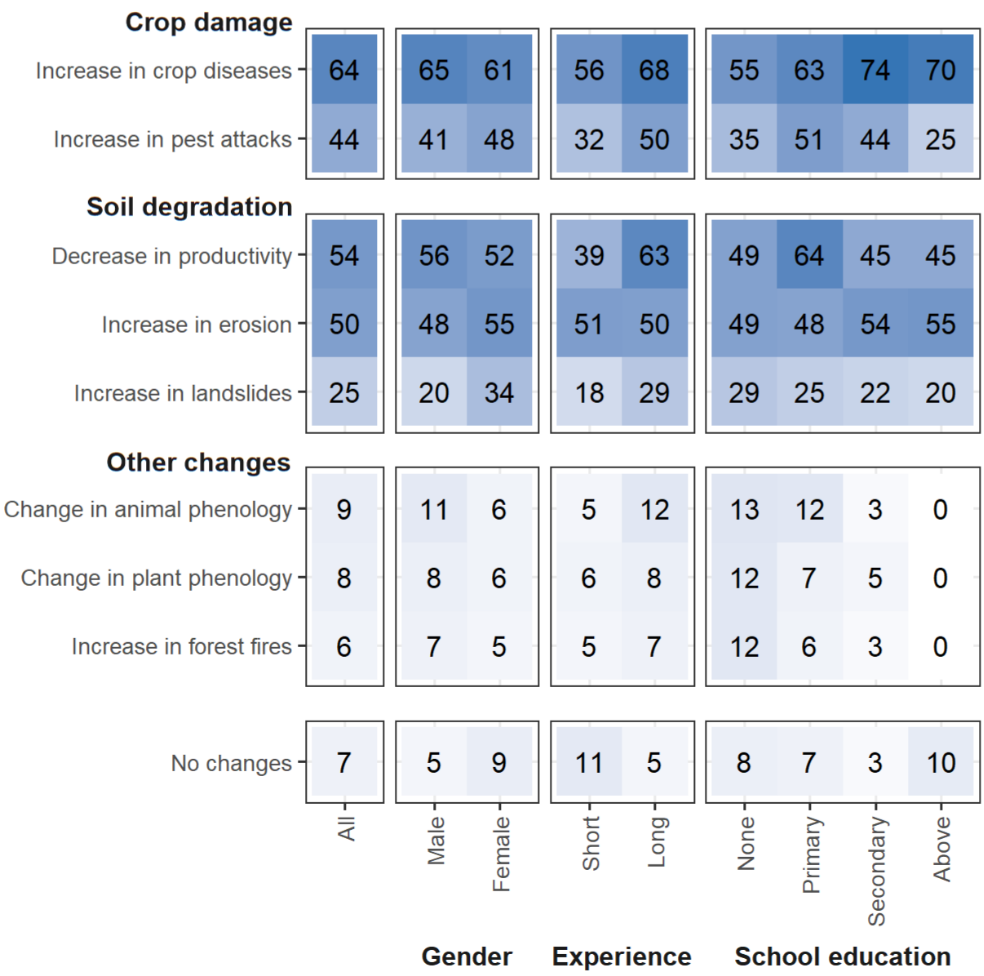
	All	Male	Female	Short	Long	None	Primary	Secondary	Above
Temperature									
Increase	84	85	84	82	86	75	84	94	90
Decrease	4	4	5	5	4	6	6	1	0
Rainfall									
Decrease in quantity	57	56	60	46	64	56	61	53	62
Shifts in monsoon season	16	19	12	12	18	15	18	15	14
Increase in unpredictability	13	14	12	12	14	9	15	16	5
Increase in intensity	9	10	8	8	10	12	10	6	5
Increase in quantity	7	6	8	8	6	13	7	1	5
Extremes									
Increased frequency of droughts	40	34	50	32	44	36	39	49	29
Increased frequency of floods	2	2	3	2	3	5	1	3	0
No changes	4	4	5	8	2	6	5	2	5

Figure III.4: Climatic changes perceived by farmers.

Values indicate the percentage of farmers who perceived the changes given on the y-axis. The leftmost column ("All") shows the percentage of all respondents who perceived the changes on the y-axis; the other columns show the percentage of farmers within individual groups, differentiated by gender, farming experience, and school education, who perceived a change. Short and long experience is defined as a farming experience of below and at least 20 years. School education refers to the level of schooling attained by farmers.

Among the environmental changes perceived by farmers, an increase in crop diseases is the most important, which was perceived by 64%, particularly by the more experienced and more educated farmers (Figure III.5). Crop diseases and climatic changes seem to affect productivity adversely. Productivity declines were perceived by 54% of all farmers and 63% of those with longer farming experience. In addition, risks related to soil instability were perceived as an increasing problem, with 50% of all farmers perceiving an increase in erosion and 25% an increase in landslides. Lastly, 44% of all respondents perceived an increase in pest attacks. Other changes, such as in animal or plant phenology or increases in forest fires, were only rarely reported.

We conclude that farmers were particularly concerned about increasingly dry conditions, which large-scale climate model data do not suggest in the first place. In addition, increasing incidents of crop diseases, pests, and erosion events seem to have already adversely affected productivity.



		Gender		Experience		School education			
	All	Male	Female	Short	Long	None	Primary	Secondary	Above
Crop damage									
Increase in crop diseases	64	65	61	56	68	55	63	74	70
Increase in pest attacks	44	41	48	32	50	35	51	44	25
Soil degradation									
Decrease in productivity	54	56	52	39	63	49	64	45	45
Increase in erosion	50	48	55	51	50	49	48	54	55
Increase in landslides	25	20	34	18	29	29	25	22	20
Other changes									
Change in animal phenology	9	11	6	5	12	13	12	3	0
Change in plant phenology	8	8	6	6	8	12	7	5	0
Increase in forest fires	6	7	5	5	7	12	6	3	0
No changes	7	5	9	11	5	8	7	3	10

Figure III.5: Environmental changes perceived by farmers.

Values indicate the percentage of farmers who perceived the changes given on the y-axis. The leftmost column ("All") shows the percentage of all respondents who perceived the changes on the y-axis; the other columns show the percentage of farmers within individual groups, differentiated by gender, farming experience, and school education, who perceived a change. Short and long experience is defined as a farming experience of below and at least 20 years, respectively. School education refers to the level of schooling attained by farmers.

4.3 Adoption of conservation practices

Tribal farmers in Nagaland have embraced various SWCP; however, overall adoption rates remain relatively low (below 50%; see Table III.1). Among the considered measures, intercropping with legumes is the most widely applied (46%), followed by mulching (40%), herein meaning covering the soil with biological material, e.g., crop residues. RWH and application of manure show similar adoption rates, with 31% and 29%, respectively. Cover crops have the lowest adoption rate, with only 14% of all interviewed farmers using them.

Model results indicate significant determinants for adoption probabilities (Table III.2). We divide the independent variables into five groups: Variables related to the formal or informal exchange of information, economic variables, variables related to the perception of specific changes, as well as socio-demographic and location variables.

Information exchange

We analyzed the effect of measure-specific training, civil society organizations, and extension services on adopting conservation practices. Our results clearly show that participation in training was the most important variable, positively influencing the adoption of all five measures at a 1% significance level. This finding is also supported by Figure III.6, showing that the three practices on which most farmers participated in a training, namely mulching, intercropping with legumes, and RWH, corresponded to the most widely used practices. Participation in a civil society organization had a significant positive effect on three out of five measures, namely mulching, intercropping, and RWH. Among the civil society organizations, self-help groups were the most important, with over 50% of all farmers indicating their participation (Supplementary material B Figure 1). Besides these, religious institutions and village councils, with 30% and 28% participation, respectively, played an important role in connecting farmers and supporting information exchange. Our results also indicate a highly significant ($p < 0.01$) influence of regular contact with extension services; however, the direction of the effect depends on the adaptation measure, being positive for cover crops and RWH, and negative for mulching, intercropping, and manure.

Economic variables

Among the economic variables, off-farm income sources and livestock ownership showed a significant effect on adaptation. Adoption probabilities of cover crops and intercropping increased significantly when farm households had access to at least two off-farm income sources. Owning livestock significantly increased the adoption probability of mulching, intercropping, and manuring. Having received financial support didn’t have a significant effect on adaptation.

Perceptions

Perceived changes have influenced the adoption of SWCP in diverse ways. Most importantly, a perceived increase in droughts has affected adaptation, showing a significant, positive correlation with the adoption of cover crops, intercropping, manure, and RWH, while the latter was also positively influenced by a perceived decrease in rainfall quantity. Interestingly, a perceived increase in rainfall intensity increased the adoption probabilities of intercropping and RWH, while a perceived increase in precipitation quantity did not, highlighting again the positive influence of extreme events on adaptation. The perception of an increase in soil erosion significantly and positively influenced the adoption of cover crops and mulching. Perceived temperature rises and increasingly erratic rainfalls did not show a significant effect.

Socio-demographic factors

The socio-demographic variables' effect on adaptation was relatively small. Farmers with at least 20 years of farming experience were more likely to adopt mulching ($p < 0.05$). As farming experience is typically strongly connected to the farmers' age, our results suggest that older farmers were, by tendency, more likely to use mulching. We also tested the effect of different education levels and found that education levels above secondary significantly and positively influenced the adoption of RWH ($p < 0.1$).

Location factors

Our results show that farmers situated at elevations above 1000 m were significantly more likely to adopt cover crops, intercropping, and rainwater harvesting. This suggests that physical factors related to elevation, such as slope gradients, soil properties, and weather conditions, significantly affect adaptation, most likely because they make the application of SWCP more necessary. On the other hand, a market distance of 10 km or more negatively influenced the adoption of cover crops and intercropping, underlining the importance of market accessibility in the adaptation process.

Table III.2: Coefficients from the BLM indicating significant influencing factors of adoption decisions for five different conservation practices.

	Variables	CC	MU	IC	MA	RWH
INF	Training	1.475***	2.133***	1.822***	2.201***	1.358***
		(4.370***)	(8.438***)	(6.182***)	(9.033***)	(3.889***)
	Extension contact	3.051***	-2.824***	-1.576***	-3.609***	1.742***
		(21.145***)	(0.059***)	(0.207***)	(0.027***)	(5.707***)
	Civil society organization	-0.804	1.401**	0.970*	0.392	1.424**
		(0.448)	(4.059**)	(2.639*)	(1.481)	(4.153**)
ECN	Off-farm income (1)	1.334*	-0.136	0.158	-0.422	0.038
		(3.797*)	(0.873)	(1.171)	(0.656)	(1.039)
	Off-farm income (2)	2.799***	-0.166	1.196***	-0.455	0.638
		(16.423***)	(0.847)	(3.305***)	(0.634)	(1.892)
	Livestock ownership	0.646	1.402***	1.562***	2.821***	-0.463
		(1.907)	(4.065***)	(4.768***)	(16.786***)	(0.629)
PCP	Rainfall quantity decrease	-0.65	-0.299	-0.072	-0.029	1.235***
		(0.522)	(0.742)	(0.931)	(0.971)	(3.438***)
	Drought frequency increase	0.876**	0.542	0.691**	1.075***	1.415***
		(2.400**)	(1.719)	(1.996**)	(2.930***)	(4.117***)
	Rainfall intensity increase	0.71	0.341	1.062**	0.329	1.012*
		(2.034)	(1.407)	(2.892**)	(1.39)	(2.751*)
	Rainfall quantity increase	-1.912	0.075	-0.977	-3.554***	0.064
		(0.148)	(1.078)	(0.376)	(0.029***)	(1.066)
	Erosion increase	1.196***	0.654**	-0.286	0.281	0.411
		(3.306***)	(1.923**)	(0.751)	(1.325)	(1.509)
SCD	Farming experience	0.218	0.865**	0.112	-0.022	-0.423
		(1.244)	(2.375**)	(1.118)	(0.979)	(0.655)
	School education (3)	-0.948	0.729	1.022	0.37	1.171*
		(0.388)	(2.074)	(2.777)	(1.448)	(3.225*)
LOC	Elevation	0.937**	-0.282	0.613*	0.311	0.938***
		(2.552**)	(0.754)	(1.847*)	(1.365)	(2.554***)
	Market distance	-1.513***	-0.56	-1.127***	-0.162	-0.354
		(0.220***)	(0.571)	(0.324***)	(0.85)	(0.702)
	Constant	-6.198***	-1.936***	-2.084***	-1.955**	-5.928***
		(0.002***)	(0.144***)	(0.124***)	(0.142**)	(0.003***)
	Observations	372	372	372	372	372
	Log Likelihood	-105.003	-166.869	-179.539	-132.278	-162.422
	Akaike Inf. Crit.	246.006	369.738	395.078	300.555	360.844
	Pseudo R^2	0.294	0.336	0.300	0.407	0.294

****, **, * are significant at 1%, 5%, and 10%, respectively.*

Positive coefficients indicate a positive effect on adaptation, negative coefficients a negative effect. The magnitude of the effect is given by odds ratios, indicated in brackets. Odds ratios were computed by $OR = exp(coef(model))$*. They define the ratio between the probability of adopting a conservation practice when the value of the independent variable is increased by one unit compared to the probability of adoption if it's not. This means for binary variables, e.g., if a farmer participated in a training on cover crops, (s)he is 4.4 times more likely to adopt cover crops than if (s)he did not participate in a training, keeping all other variables constant. The independent variables are further explained in Table III.1.*

Abbreviations: INF = Variables related to the exchange of information; ECN = Economic variables; PCP = Perception variables; SCD = Socio-demographic variables; LOC = Location variables

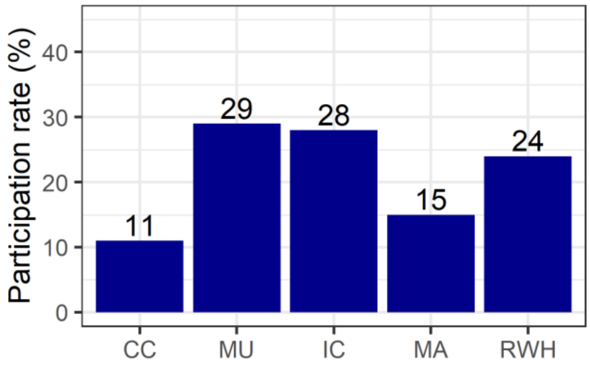


Figure III.6. Percentage of respondents who participated in training on different management practices.

Abbreviations: CC = Cover crops; MU = Mulching; IC = Intercropping with legumes; MA = Manure; RWH = Rainwater harvesting

4.4 Predicted adaptive capacities under different scenarios

Our results reveal large unused potentials for the adoption of SWCP (Figure III.7). Model-based predictions under five different scenarios show that adoption rates of all measures could be at least doubled when exposure to effective influencing factors was improved.

Adoption of cover crops could increase to above 60% when all farming households had access to at least two off-farm income sources. Participation in a training could improve adoption rates of mulching to more than 80%. Likewise, intercropping with legumes could be applied by over 80% of farmers when they received the appropriate training or were involved in livestock rearing. Participation in a training and livestock ownership could also triple the application of manure. Adoption rates of RWH could reach about 60% if all farmers participated in a training or were engaged in a civil society organization. If all farmers had above-secondary education levels, RWH adoption rates could be doubled. Figure III.7 demonstrates that participation in a training increases the adoption probability of all practices by a factor of 2 (e.g., intercropping, mulching, RWH) to 5 (e.g., cover crops).

Our results show that even changing a single factor can have a significant impact on adaptation probabilities.

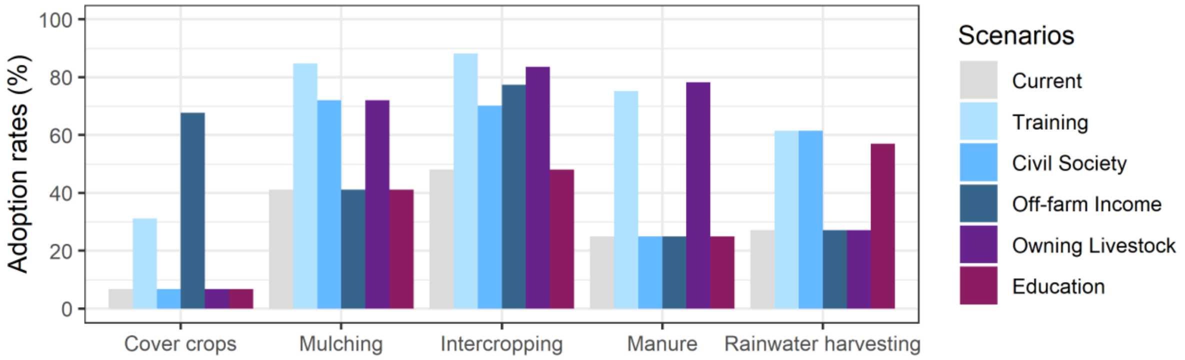


Figure III.7: Estimated adaptation potential from BLM for different scenarios.

Adoption rates were computed from probabilities and odds ratios (see Table III.2). Estimated adoption rates are given for current conditions and five scenarios: The training scenario assumes that all farmers participated in a measure-specific training; civil society scenario assumes that all farmers participate at least in one civil society organization; off-farm income scenario assumes that all farming households have at least two income sources in addition to farming; owning livestock scenario assumes that all farming households are also engaged in livestock rearing; education scenario assumes that all farmers have above secondary education levels. For each scenario, only the given variable was changed, while all other model variables were kept constant.

4.5 Goals and values of tribal farmers

While the BLM provides a picture of the factors influencing adaptation decisions, it doesn't answer the question of which personal values and, thus, goals, norms, and preferences drive these decisions. To answer this question, we asked farmers why they decided to implement adaptation practices. Specifically, we asked farmers how much they agreed that the six goals suggested in Figure III.8 were the motivation for implementation.

Increasing yields of food crops and family income were the most important motivations for tribal farmers in making adaptation decisions (Figure III.8). Thereof, increasing food crop yields was slightly more important than income, although both are strongly interlinked. The subsequent motivating factors varied slightly across practices but generally included efforts to sustain natural resources, diversify livelihoods, and cut down on work hours. Increasing social status was clearly of the least importance for tribal farmers.

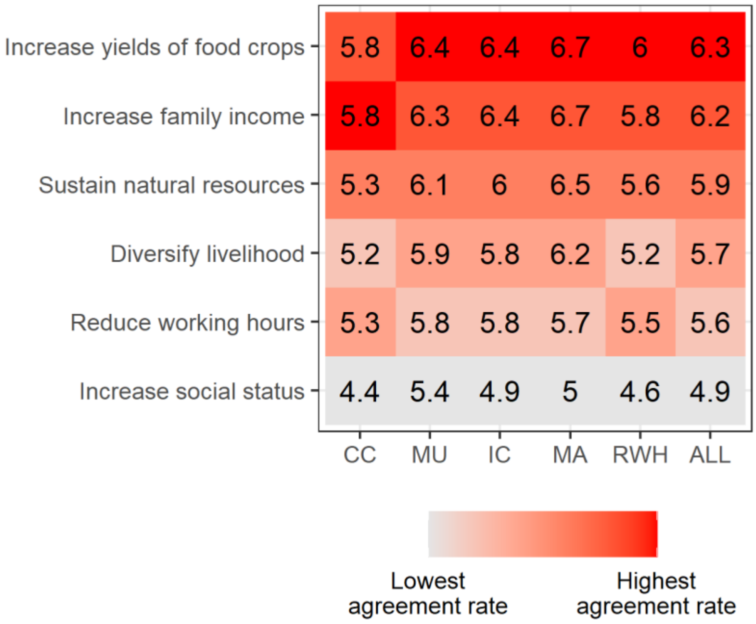
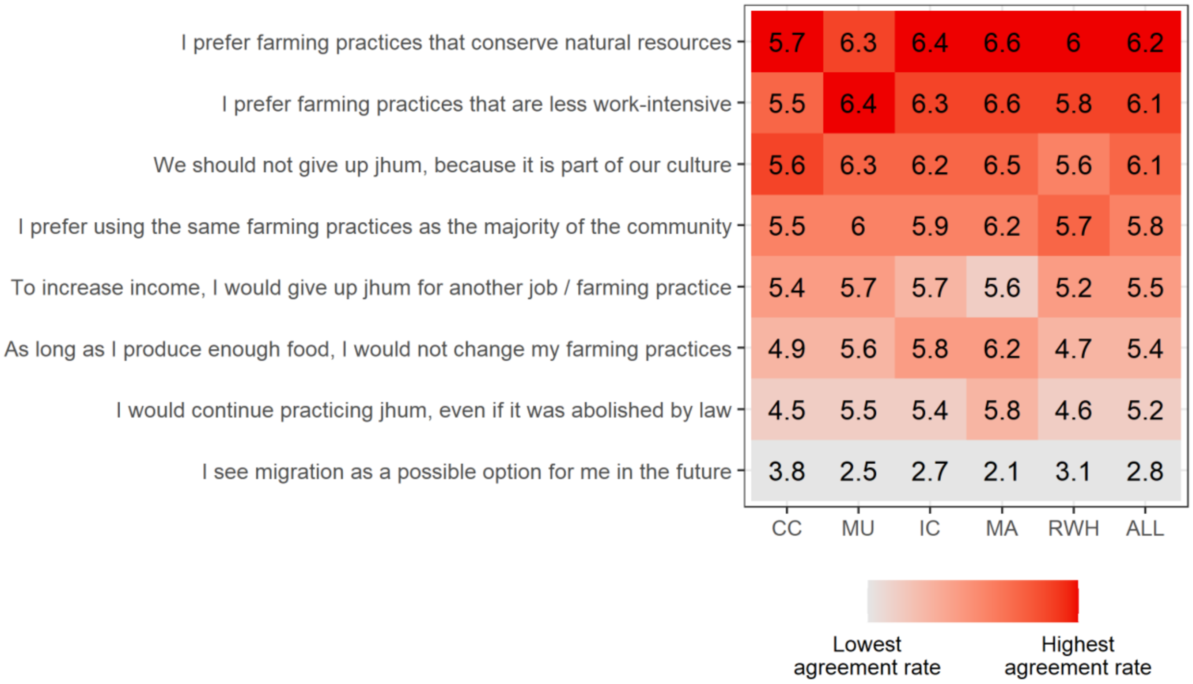


Figure III.8: Agreement of farmers to goals in adaptation.

Note: Figure shows agreement rates of farmers that the suggested goals on the y-axis were the reason for adaptation. Values inside the boxes indicate the average rate of agreement among respondents on a scale from 1 (strongly disagree) to 7 (strongly agree). Respondents were grouped into farmers who applied cover crops (column 1), mulching (column 2), intercropping with legumes (column 3), manure (column 4), rainwater harvesting (column 5). Farmer groups are shown on the x-axis. The last column ("ALL") includes all respondents. For each farmer group on the x-axis, goals have been ranked according to the received agreement rates; red indicates the highest agreement rate, grey the lowest.

In addition, we asked farmers to indicate their level of agreement with different norms and preferences regarding cultivation and adaptation (Figure III.9). As shifting cultivation, locally called *jhum*, is the dominant cultivation practice of the region, we also asked farmers about their motivations to continue this type of practice.

Our results reveal that most farmers prefer management practices that conserve natural resources. Also, farmers prefer practices that are less work-intensive, possibly because the available workforce for farming in tribal communities is limited to family members, mostly to the older generation, while the younger population tends to leave farming for education or off-farm employment. Our results further underline the relevance of cultural and social values in farming decisions. Respondents strongly favored a continuation of shifting cultivation because of its cultural value and farming practices that are employed by the majority of the village community. In contrast, migration was not one of the preferred adaptation options, as evidenced by the relatively low agreement scores it received.



	CC	MU	IC	MA	RWH	ALL
I prefer farming practices that conserve natural resources	5.7	6.3	6.4	6.6	6	6.2
I prefer farming practices that are less work-intensive	5.5	6.4	6.3	6.6	5.8	6.1
We should not give up jhum, because it is part of our culture	5.6	6.3	6.2	6.5	5.6	6.1
I prefer using the same farming practices as the majority of the community	5.5	6	5.9	6.2	5.7	5.8
To increase income, I would give up jhum for another job / farming practice	5.4	5.7	5.7	5.6	5.2	5.5
As long as I produce enough food, I would not change my farming practices	4.9	5.6	5.8	6.2	4.7	5.4
I would continue practicing jhum, even if it was abolished by law	4.5	5.5	5.4	5.8	4.6	5.2
I see migration as a possible option for me in the future	3.8	2.5	2.7	2.1	3.1	2.8

Figure III.9: Agreement of farmers to attitudes in cultivation and adaptation.

Figure shows agreement rates of farmers to the suggested norms and preferences on the y-axis. Values inside the boxes indicate the average level of agreement among respondents on a scale from 1 (strongly disagree) to 7 (strongly agree). Respondents were grouped into farmers who applied cover crops (column 1), mulching (column 2), intercropping with legumes (column 3), manure (column 4), rainwater harvesting (column 5). Farmer groups are shown on the x-axis. The last column ("ALL") includes all respondents. For each farmer group on the x-axis, norms and preferences have been ranked according to the received agreement rates; red indicates the highest agreement rate, grey the lowest. Jhum is the local term for shifting cultivation.

5 Discussion

5.1 Modeled and perceived climatic trends

Our results have shown that climate change in the study region, on a larger spatial scale, will most probably increase precipitation intensities and the total precipitation amount per year, while periods without any rainfall during the growing season are expected to decrease slightly. With this, we show for the first time that the dominant risk of precipitation changes in the region stems from increasing intensities, which may result in rising crop damages and soil erosion, rather than from decreasing rainfall quantity, even though there may be varying trends on smaller spatial scales.

With regard to historical trends, climate data have shown similarities but also discrepancies with farmers' observations. While there is a large agreement with regard to rising temperatures, certain inconsistencies exist for rainfall trends. There may be several reasons for this: First of all, the topography of the region is complex; hence, the spatial and temporal distribution of climate variables, particularly rainfall, is complex as well. There may be strong variations in rainfall even at small spatial scales (Shrestha et al., 2017) that are not represented by climate models operating at larger spatial scales and relying on scarce observational data, typically from mountain valleys. Resulting uncertainties in climate simulations and observations demand the integration of social science methods in climate research (Dhakal et al., 2020). However, people's perceptions of climatic factors are likewise influenced by inherent biases and heuristics (Dhakal et al., 2020). For example, perceptions largely rely on recent experiences; hence, dry spells in the year of the survey or preceding years, even if only related to the inter-annual variability of precipitation, might have disproportionately influenced farmers' perceptions of climatic trends (Hasan and Kumar, 2020a). This assumption is supported by a previous survey conducted in 2017, which found over 70% of farmers from Northeast India had perceived an increase and only 25% a decrease in rainfall quantity (Bhalerao et al., 2022). A meaningful comparison between farmers' perceptions and climate data can hence only be made for short-term trends (Hasan and Kumar, 2020a). In addition, perceptions might be influenced by other biotic and abiotic factors, such as perceived temperatures by humidity (Dhakal et al., 2020), and by social discourses on climate change (Grothmann and Patt, 2005), e.g., when climate change in the social discourse is predominantly associated with water scarcity, this might steer farmers' climate change perceptions accordingly.

Surprisingly, although only 9% of farmers perceived increasing rainfall intensities, increases in erosion and landslides were perceived by 50% and 25% of the respondents, respectively. This suggests that recent soil loss could be rather linked to intensified land use than to climate change. Except for Bhalerao et al. (2022), we are not aware of any previous study in India that has considered the perceived risk of increasing land degradation outlined by our study.

Farmers' perceptions of increasing temperatures, crop diseases, pest attacks, and decreasing productivity were also reported by other studies from northern India and can thus be considered the biggest challenge of recent changes (Bhalerao et al., 2022; Datta and Behera, 2022b; Sharma et al., 2020; Shukla et al., 2016).

5.2 Adoption of conservation practices

Our results revealed large unused adaptation potentials among tribal farmers in Northeast India, showing for the first time that adoption rates of SWCP could be at least doubled when the most influential factor per practice was fulfilled. Thereby, the current adoption rates of 14 - 46% could theoretically be increased to 62 - 88%.

Observed adoption rates were relatively low compared to previous studies on the Himalaya region, which found that a majority of farmers had adapted to climate change (Datta and

Behera, 2022a; Lone et al., 2022; Rymbai and Sheikh, 2018). This difference in observed adaptation rates might be because of the specific regional and social context of the farming communities studied here or because previous studies focused on other adaptation practices, such as changes in crop types, cropping calendars, and irrigation, while we assessed specifically those practices that conserve soil and water resources.

To increase adoption rates of SWCP, our findings emphasized the outstanding importance of agricultural training. Though some previous studies have already indicated a positive effect of training on adaptation (Asfaw et al., 2019; Thoai et al., 2018), none has found a similarly dominant role of training in the adaptation process as our study. This could be either explained by the specific regional context of this study or by the methodological reason that this study asked for training received on the specific management practice, while previous studies analyzed access to or attendance in an agricultural or climate change training in general. Considering the low participation rates in training (Figure III.6), we suggest that increasing participation in measure-specific training might considerably accelerate climate change adaptation. This assumption is supported by Bhalerao et al. (2022), who found that a lack of training poses a major barrier to climate change adaptation in Northeast India.

Besides training, we found participation in a civil society organization to have a significant positive influence on adaptation, which is in line with previous findings (Panta et al., 2020; Vo et al., 2021). Presumably, local organizations provide a space for farmer-to-farmer interactions where experiences, knowledge, and information are shared, thus encouraging adaptation decisions, as also suggested by Zamasiya et al. (2017). The relevance of information exchange among farmers for adaptation was also pointed out by Abid et al. (2016). Moreover, it can be assumed that farmers who participate in local organizations have a better social network than others and consequently improved access to diverse forms of support (institutional, labor, financial, etc.).

Surprisingly, we did not observe a clearly positive effect of regular contact with extension services on the adoption of SWCP, even though most farmers indicated relatively frequent contacts (Supplementary material B Figure 2) and mentioned extension workers as their main source of information on adaptation measures (Supplementary material B Figure 3). While many previous studies found a positive effect of extension services on climate change adaptation (Abid et al., 2015; Adeagbo et al., 2021; Bryan et al., 2009; Khanal et al., 2018; Sertse et al., 2021; Zamasiya et al., 2017), our results confirmed this effect only for two out of five practices, namely cover crops and RWH. By contrast, the adoption of the three other practices was negatively associated with regular contact with extension services. A possible explanation could be that the focus of discussions with extension officers is limited to specific practices, while other practices are less promoted. Since the ambiguous influence of extension contacts on climate change perception and adaptation was also found in other studies (Hasan and Kumar, 2020b), further research is needed to identify the role of extension officers in farmers' adoption or non-adoption of conservation practices.

Concerning economic determinants, our results confirmed previous findings from India (Jha and Gupta, 2021) and other places of the world (Adeagbo et al., 2021; Bryan et al., 2013; Koç and Uzmay, 2022) showing that off-farm income has a significant positive effect on adaptation. Previous studies indicated that among these income sources, remittances from migrated family members are of particular importance for the adoption of new agricultural technologies (Datta and Behera, 2022a; Jha and Gupta, 2021), which make up 17% of all off-farm income sources in our study area (Supplementary material B Figure 4). The positive effect of livestock on adaptation is likewise in line with previous studies and was associated with flexibility regarding financial resources facilitating climate change adaptation (Jha and Gupta, 2021).

The predominantly positive effect of perceived climatic changes on adaptation is in line with previous studies (Hasan and Kumar, 2019; Jin et al., 2016; Khan et al., 2020) as well as established adaptation theories, postulating that adaptation decisions are influenced and preceded by a risk or threat appraisal stage (Grothmann and Patt, 2005; Rogers et al., 1983).

We also found relationships between socio-demographic factors and adaptation; however, these were clearly less important than the above factors related to information exchange, economic characteristics, and perceptions. The positive effect of education on adaptation, observed in numerous previous studies from diverse countries, including Nepal (Adhikari et al., 2022; Khanal et al., 2018), Pakistan (Abid et al., 2015; Ali and Rose, 2021; Amir et al., 2020), China (Jin et al., 2016), and India (Jha and Gupta, 2021; Lone et al., 2022), was herein only found for the adoption of RWH, while the relationship for all other practices was insignificant. In a follow-up discussion with farmers, we found that the educated, mostly younger community members often migrate to urban areas to pursue studies or non-farm jobs, so they are no longer involved in farming.

For farming experience, previous studies observed a positive relationship with adaptation (Abid et al., 2015; Huong et al., 2017; Jin et al., 2016; Lone et al., 2022), suggesting that the more experienced farmer has a broader observation-based knowledge of farming practices and climate change, thus increasing adaptation likelihood (Dang et al., 2019). However, our study found this relation only for mulching.

The negative effect of longer market distances on adaptation found in this study is in line with Huong et al. (2017), suggesting that spatial proximity to local markets facilitates the purchase of needed inputs, the sale of produce, and the search for off-farm employment, providing opportunities for additional household income generation and thus supporting adaptation (Huong et al., 2017).

5.3 Goals, norms, and preferences of tribal farmers

Only a few studies have analyzed farmers' personal values in adaptation; hence, this research tackles an important research gap to understand the driving motivations behind the adaptation of tribal farming communities. Our findings revealed that sustaining livelihoods was the most important goal in adaptation among tribal farmers. This is not surprising, as Zobeidi et al. (2022b) found that adaptation is, in the first place, an economic undertaking. According to the authors, normative considerations associated with climate change adaptation are only of secondary importance. Nevertheless, it’s worth noting that tribal farmers preferred increasing yields of food crops over income as a strategy for sustaining livelihoods. This indicates a skeptical attitude of tribal farmers about the reliability of markets to secure local food supplies and underscores the importance of uphill cultivation for local food security. In contrast to previous studies, our findings additionally emphasized sustaining natural resources as the second most important value, after sustaining livelihoods, within the adaptation process. We interpret this as a specific characteristic of tribal farming communities in the Himalayas, which have a particularly strong appreciation of the natural environment (Pandey et al., 2020). Our results also showed that the preservation of cultural aspects of cultivation was important for tribal farmers. This extends findings from Warner (2016), who identified the preservation of personal identity as an important goal of smallholder farmers by the aspect of a common cultural identity. Low agreement levels for migration as a potential adaptation option were also found by Dang et al. (2014) for Vietnam. Nevertheless, one has to consider that those farmers who emigrated already were not captured in the survey; thus, a certain bias cannot be ruled out.

5.4 Relation to adaptation theories

Our research shows that farmers' probability of adopting SWCP was significantly increased when they had perceived increases in soil erosion and changes in rainfall. In accordance with the ‘risk experience appraisal’ in MPPACC (Grothmann and Patt, 2005), we confirm that the past experience of a risk positively influences the risk appraisal and thus the adaptation intention. Further, our research adds to the ‘climate change risk appraisal’ of Grothmann and Patt (2005) that the perception of climatic and environmental changes is influenced by socio-demographic variables, such as gender, education, and farming experience. While the importance of personal characteristics in the ‘adaptation appraisal’ appears evident, we show that these already play a role in the initial stage of risk perception. As outlined in section 5.1, our research further suggests that cognitive biases, heuristics, and social discourses may affect the perception of climatic changes, as also considered in Grothmann and Patt (2005).

Besides the perception of climatic and environmental changes, the adoption of SWCP is significantly increased by diverse forms of resources, such as off-farm income, livestock, and, even more importantly, information provided by civil society organizations and agricultural training. This confirms the importance of an ‘objective adaptive capacity’ as conceptualized by Grothmann and Patt (2005) in the adaptation process.

Finally, our study reveals shared values among tribal farmers regarding cultivation, with natural resource conservation being most important after the improvement of livelihoods. Based on Stern (2000), it can be expected that a serious threat to soil resources, e.g., through increasing erosion, when perceived by farmers, will activate pro-environmental behavior. As shown above, a significant link between the application of SWCP and perceived increases in rainfall intensities and erosion was observed, supporting the VBN theory (Stern, 2000).

We conclude that our findings on perceptions, influencing factors, and values in the adaptation process of tribal farmers are largely consistent with established theories of adaptation behavior.

5.5 Study limitations

While this study offers valuable insights, it also has certain limitations that should be acknowledged. Due to limitations of the available climate data, this study only looked at large-scale general climatic trends without considering small-scale spatial variations. Likewise, we focused on long-term trends; therefore, climate variables were aggregated annually. As a consequence, seasonal changes, including potential shifts in the monsoon precipitation, were not analyzed.

Another limitation is the sampling bias resulting from the selection of only tribal families actively engaged in farming, which may affect the generalizability of the findings and the study’s representation. In addition, the lack of randomization in village selection and reliance on extension officers raise concerns about potential biases.

The statistical model applied in this study can only reveal relationships between a limited number of independent and dependent variables, but it cannot prove causality. Due to the limited number of variables considered, we might miss out on other relevant factors. For instance, we could not consider the specific influence of soil properties, slope aspect, and inclination on adaptation probabilities due to limited data availability and partially unknown field locations. Likewise, we could not parameterize neighborhood effects in the model. The role of neighboring farmers and villages in information flows is instead indicated in the Supplementary material (see Supplementary material B Figure 3). As this study applied a binary logit model, potential interdependencies between the analyzed conservation practices were not considered. The application of a simultaneous equation model and seemingly unrelated regressions in further studies is suggested to assess whether these provide additional valuable insights. We also point out that the adoption of SWCP is not necessarily a reaction to climate change. In fact, farmers adapt their management in a complex ecological-social-economic environment (Dang et al., 2019); hence climate change is one but not the only driver for changes in the agricultural system.

Lastly, the execution of this survey was impeded by the COVID-19 pandemic and had to be postponed and interrupted several times. Due to entry restrictions, supervision of local staff during data collection was possible only to a limited extent. Hence, in spite of intensive data quality checks by the authors, which led to the exclusion of almost 50% of the collected data from the final dataset (as explained in section 3.2.1), some uncertainties related to the collection procedure cannot be ruled out completely.

Despite these limitations, the study provides valuable information and insights into climate change perceptions and adaptation decisions of tribal farming families.

6 Conclusion

Tribal farmers in Northeast India have experienced various climatic and environmental changes. Among the environmental changes, more than half of the farmers perceived increasing crop diseases and productivity declines, while among the climatic changes, increased temperatures, decreased precipitation quantity, and increased frequency of droughts were the most reported.

For the future, our analysis showed that, along with rising temperatures, total annual precipitation and precipitation intensities are likely to increase in the region, amplifying the need for SWCP. However, our study showed that current adoption rates of SWCP ranged only between 14% and 46%, which were relatively low compared to other contexts. By applying a BLM, we showed that the adoption probabilities of all analyzed conservation measures were significantly increased by participation in measure-specific training. In addition, participation in a civil society organization, livestock ownership, high-altitude residence, and perceived increases in droughts had significant, positive effects on at least three out of five SWCP. Surprisingly, regular contact with extension services was significantly negatively correlated with the adoption of a majority of the analyzed practices. Thus, contacts with extension workers outside of a training context appear to be less effective in promoting adaptation. The widely reported positive effect of education on adaptation was observed only for RWH but not for the other practices. Our findings revealed large unused adaptation potentials for all analyzed practices, which could more than double the current adoption rates. Adaptation decisions among tribal farmers were mainly driven by the goal of increasing food crop yields and income; however, sustaining natural resources and cultural identity were also highly valued by farmers.

This study contains important insights for regional authorities and identifies strategies for a more sustainable adaptation of uphill tribal farming systems to climate change. Particularly, effective strategies include improving farmers' awareness of future changes in precipitation patterns and increasing training programs on SWCP to exploit unused adaptation potentials of all analyzed practices. Lastly, our results suggest that future research is needed to identify current deficits and future potentials of extension services in the propagation of SWCP. This research contributes to a better understanding of the adoption processes towards more sustainable farming practices among tribal Himalayan farmers, thereby identifying unused potential for climate change adaptation for marginalized and climate-vulnerable farming communities in mountain regions.

Article 3

IV Producers' perspectives on agricultural intensification in the Brazilian Amazon: Bridging behavioral theory, empirical evidence, and land use models

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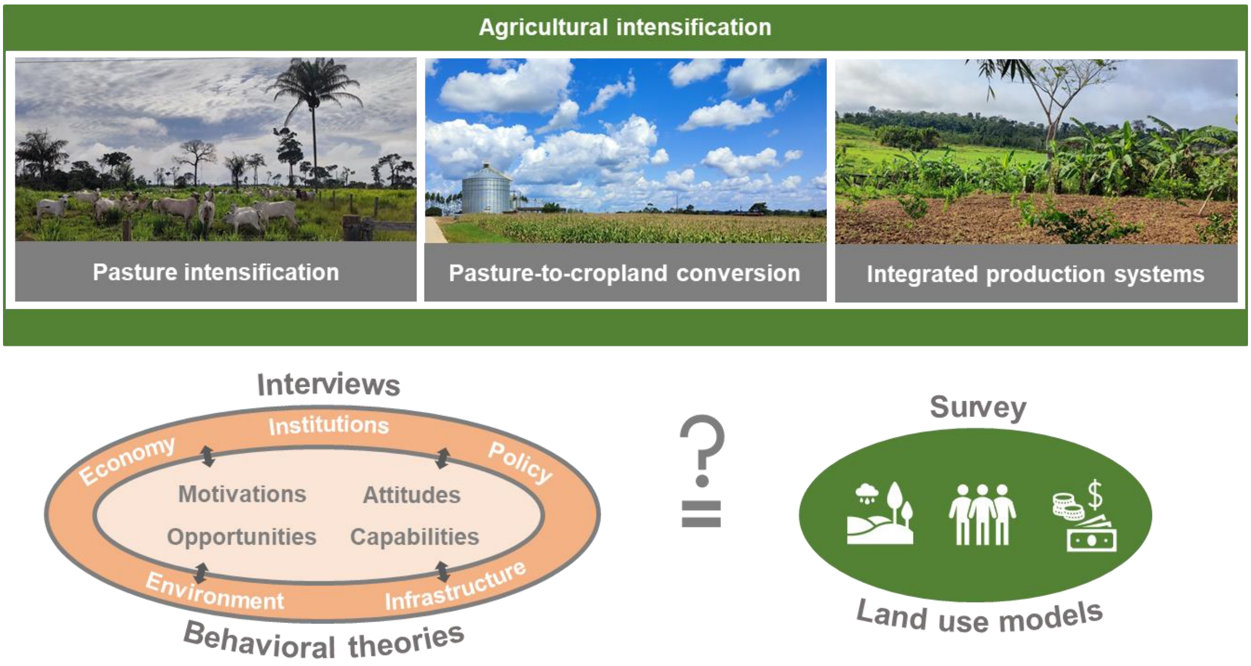

Graphical abstract 3

Abstract

Rising global pressure on land resources, particularly unfolding in agricultural frontiers, where expansion processes into natural habitats have led to substantial environmental impacts, has put the intensification of agricultural production on national agendas. However, agricultural intensification, depending on the land use decisions of producers, is a complex adaptation process with multiple perceived benefits and costs. This study analyzes agricultural intensification in an agricultural frontier of the Brazilian Amazon. We use semi-structured interviews embedded in behavioral theories to assess factors influencing producers' intensification decisions. We also conduct a standardized expert survey to analyze how these factors are considered in typical land-use assessment models. Lastly, insights on plausible agricultural developments in the region are derived based on producers’ perspectives. Our findings provide empirical evidence that perceived economic benefits motivate agricultural intensification but also reveal important constraints, including risk aversion, lack of knowledge, personal reluctance, limited access to resources, roads, and processing infrastructure, and biophysical and institutional barriers. While typical partial and general equilibrium models adequately represent market mechanisms, actor-specific motivations and constraints are usually neglected. Agent-based models, on the other hand, have these advantages and disadvantages in reverse but are limited to specific regions. Prevailing gaps in land use models encompass the depiction of risk aversion and infrastructure. Experts see the lack of comprehensive empirical data and integration of different models as the main obstacles in land use modeling. For the future agricultural development of the study region, further pasture-to-cropland conversions are expected, while producers express doubts about the uptake of integrated production systems. By revealing key drivers and limitations of agricultural intensification and their representation in land use models, this study offers important insights for development policies and land use research.

Keywords

agricultural intensification, Brazilian Amazon, cropland expansion, integrated production systems, land use decisions

1 Introduction

Land use decisions in agricultural frontiers are of global concern because they can have substantial adverse environmental impacts. These include the loss of forest carbon stocks and biodiversity, greenhouse gas (GHG) emissions, and soil degradation, with considerable effects on climate and food supply (Gil et al., 2018; Klink and Machado, 2005). Agricultural frontiers typically concentrated in the tropics, can be described as dynamic environments with rapid land conversions due to agricultural expansion with varying levels of primary forest loss (Eigenbrod et al., 2020; Schielein and Börner, 2018; Schiesari et al., 2013). In the context of climate change, the Brazilian Amazon agricultural frontier has increasingly become the focus of scientific and public discourses. This frontier region showed 17.600 km² of annual forest loss between 1988 and 2008, the highest deforestation rates in the world (Coy and Klingler, 2011), which were linked to the expansion of cattle grazing, modernized soybean cultivation, commercial logging, and extraction of mineral resources (Coy and Klingler, 2011). With growing pressure on global land resources due to rising food and feed demand (Fukase and Martin, 2020; Tilman et al., 2011), declining yield improvements (Blomqvist et al., 2020), and adverse impacts from climate change (Challinor et al., 2014), further shifts in the Amazon agricultural frontier seem probable.

To limit further shifts of the Amazon agricultural frontier, previous studies underlined the importance and potential of agricultural intensification in the region (da Silveira Bueno et al., 2021; Lapola et al., 2011). Besides cattle intensification through rotational grazing, re-seeding and fertilizing of pastures, and the application of supplementary cattle feed (Cialdella et al., 2015; da Silveira Bueno et al., 2021), the conversion of pasture to cropland, and the integration of different production systems were suggested to increase agricultural production while reducing adverse environmental impacts (Cohn et al., 2016; Gil et al., 2015; Gil et al., 2016). Pasture-to-cropland conversion refers to the transition from cattle pastures to industrial crop production, involving the use of machinery and increased inputs, such as seeds and fertilizers, which leads to an increase in food production by at least a factor of four (Gil et al., 2018). The integration of different production systems typically includes crop-livestock integration in various forms, e.g., the rotation of crop and pasture areas or the integration of pasture as a third crop in soybean-maize double cropping systems, and the integration of trees in pasture, crop or crop-livestock systems (Gil et al., 2015). Compared to cattle raising, conversion to soybean cultivation and integrated crop-livestock systems were shown to not only provide higher protein supply per land but also higher economic returns and lower GHG emissions per human digestible protein (Gil et al., 2018). Integration with forestry additionally showed positive effects on soil organic carbon (SOC) accumulation, contributing to the rehabilitation of degraded pasture lands (Gil et al., 2015; Oliveira et al., 2018). By increasing production and economic returns per unit of land while restoring soil fertility and reducing land demand and GHG emissions, pasture-to-cropland conversion and integrated systems have been advocated as suitable intensification strategies for Brazil, the latter forming a key element of Brazil's Low Carbon Agriculture Plan (ABC Plan) (Cohn et al., 2016; dos Reis et al., 2023; Ministry of Agriculture, Livestock and Food Supply, 2021).

Despite multiple benefits, agricultural intensification is not a straight-forward process. Previous studies have identified several constraints for producers to intensify their production in the Brazilian Amazon, such as poor infrastructure, limited resource endowments, and lack of labor force, using surveys and interviews (Cortner et al., 2019; Gil et al., 2015; Gil et al., 2016). However, these studies have rarely involved behavioral theory, a set of formal models from psychology and behavioral economics describing how individuals make decisions depending on their environment (Schlüter et al., 2017). Having entered the field of natural resource management, these models have been proven useful in analyzing and predicting adaptation behavior in agricultural contexts (Mitter et al., 2019; Zhang et al., 2020; Zobeidi et al., 2022a).

Also, previous research has barely assessed plausible future agricultural developments in the Amazon region. A few studies applied land use assessment models to propose different storylines on future land use development in the Brazilian Amazon (Gollnow et al., 2018; Schaldach et al., 2018; Schönenberg et al., 2017). However, these rely on vague assumptions about agricultural intensification and are mostly driven by idealized economic principles, such as welfare maximization, lacking empirical evidence. This potential oversimplification may result in implausible projections of land use change (Dalla-Nora et al., 2014).

This research analyzes agricultural intensification behavior in the Brazilian Amazon by linking producers' perspectives to behavioral theory. We aim to identify factors that motivate and restrict producers to intensify their production and analyze, in a second step, how these factors are represented in existing land use assessment models. Thereby, we analyze how consistent producers' decisions in the Brazilian Amazon are with economic principles and whether other factors are decisive for local land use transitions. Also, we seek to shed light on plausible future agricultural developments in the region. Our research questions are: 1.) Which internal and external factors motivate or constrain producers to intensify and expand agricultural operations in the Brazilian Amazon? 2.) How do land use assessment models represent motivations and constraints? 3.) Which plausible land use futures can be derived from producers' perspectives?

To answer these questions, we conducted semi-structured interviews with agricultural producers in the Brazilian state of Pará. These interviews aimed to understand producers' perspectives on past and future agricultural developments and identify factors motivating agricultural intensification and expansion that may inform the representation of producers' behavior in future land use modeling approaches. We analyzed the interviews using a qualitative content analysis and behavioral theories. Afterwards, we compared our findings to land use assessment models. Therefore, we conducted a survey with scientists from land use modeling on the representation of different factors in such models.

In the following, we present the study region and the conceptual framework of behavioral theories that guided our empirical work. Next, we provide details on the applied methods and interviewed producers. In section 3, we present results on factors motivating and constraining land use decisions, their representation in land use models, and plausible future agricultural developments in the study area. We then compare our findings to previous studies and discuss implications for land use projections in Brazil and future model development.

By analyzing land use decisions in the context of behavioral theories, we improve the understanding of agricultural intensification processes and shed light on producers' perspectives on future developments of an agricultural frontier region in the Brazilian Amazon. Thereby, we offer important insights not only for policymakers on barriers to agricultural intensification but also for researchers, as we provide empirical evidence of relevant factors in land use decision-making beyond those traditionally considered in land use models.

2 Methodology

2.1 Study region

The empirical field work of this study was conducted in Novo Progresso, a municipality of the Brazilian state of Pará. Characterized by a tropical monsoon climate with an average annual precipitation of approximately 2300 mm in Itaituba (Secretaria de Meio Ambiente e Sustentabilidade, 2023), Pará has evolved as the largest cattle producer in Brazil (Coy and Klingler, 2011). With the highest deforestation rates in the country (INPE, 2023) and the dominance of extensive cattle farming, often characterized by production intensities of below one cattle head per hectare (Hampf et al., 2020; Olimpio et al., 2022), Pará is becoming a focus of agricultural intensification.

Novo Progresso is located in the peripheral south-west of Pará on the route of the federal road and export corridor BR-163 (Figure IV.1). The municipality covers about 38,162 km² and contains more than 33,500 inhabitants (IBGE, 2023a). Of the working population, 18% are involved in agriculture (IBGE, 2022, 2023a), most of whom originate from southern states of Brazil, which have been attracted by emerging economic opportunities since the 1980s (Coy et al., 2016). As typical for the state of Pará, the majority of agricultural land in Novo Progresso is dedicated to cattle production, but crop cultivation is on the rise, with soybeans making up 73% of the total cultivated area (IBGE, 2023b). This early stage of agricultural intensification combined with high deforestation rates (INPE, 2023) makes Novo Progresso an interesting case study region for the aim of this research.

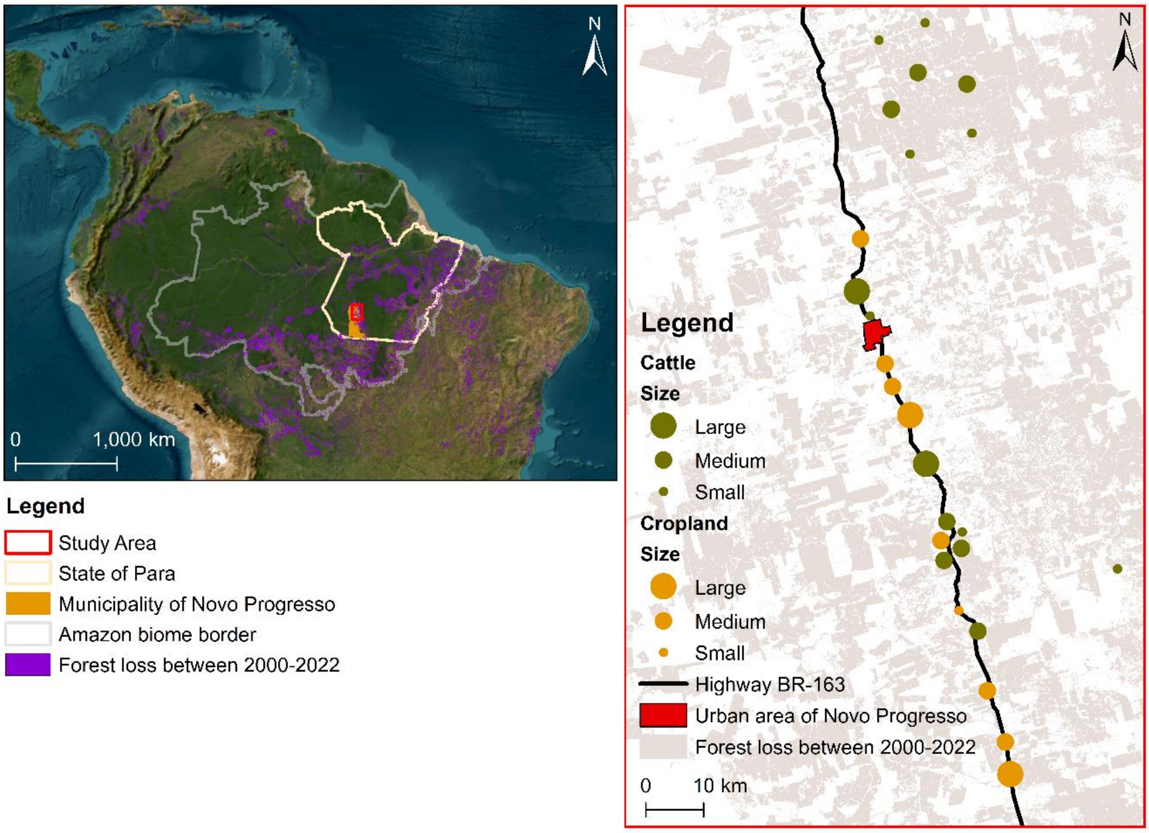

Figure IV.1: Study area with interviewed small, medium, and large cattle and crop producers.

Only approximate locations are shown for data protection. Farm size is defined as small ≤ 300 ha, medium ≤ 1125 ha, large > 1125 (Embrapa).

2.2 Conceptual framework

Our empirical work is based on components of established behavioral theories. Behavioral theories aim to explain human behavior through internal and external factors. Internal factors include the mental and physical state as well as cognitive processes of the individual, such as perception and evaluation (Schlüter et al., 2017). External factors refer to the environmental, economic, political, and institutional context in which individuals are situated and make decisions (Malek et al., 2019). A schematic illustration of these factors is provided in Figure IV.2. Behavioral theories suggest that behavioral options are perceived and evaluated differently depending on the mental and physical state of the individual (Schlüter et al., 2017). This mental and physical state is characterized by motivations, attitudes, capabilities, and opportunities.

Motivations energize and catalyze behavioral intentions. While they are herein defined as equivalent to goals, they may conceptually also include habitual processes or emotional responses (Michie et al., 2011).

Attitudes, understood as the individual's set of beliefs, may be influenced by the way past experiences were perceived and evaluated (Constantino et al., 2021) and shape behavioral preferences and priorities, as in the Values and Investments for Agent-based interaction and Learning in Environmental systems (VIABLE) framework (BenDor and Scheffran, 2019). We acknowledge that attitudes are also closely linked to personal values and norms, as specified in the Value-Belief-Norm Theory (VBN) (Stern, 2000), and emotions, as conceptualized in Constantino et al. (2021); however, these have not been assessed in this study. Our framework focusses on two types of attitudes, namely risk attitudes, as in the Prospect Theory (PT) (Kahneman and Tversky, 1979) and the Model of Private Proactive Adaptation to Climate Change (MPPACC) (Grothmann and Patt, 2005), and attitudes toward specific behavioral options, here agricultural practices, as in the Theory of Planned Behavior (TPB) (Ajzen, 1985).

Capabilities are defined as the individual's capacity to perform a specific behavior, including knowledge and skills, while opportunities include physical and social factors enabling the behavior (Michie et al., 2011). Physical and social opportunities are largely influenced by external factors.

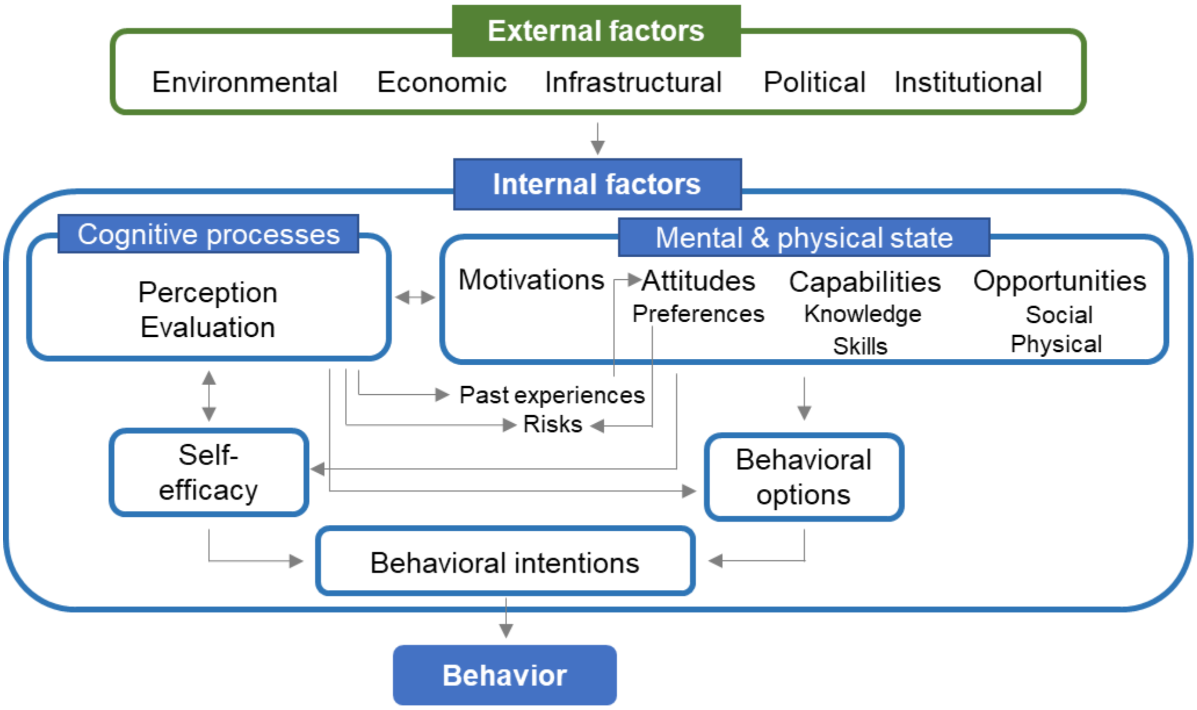

Figure IV.2: Conceptual framework based on behavioral theories.

Depending on the mental and physical state of the individual and the context in which it operates, not only behavioral options but also self-efficacy may be differently perceived and evaluated. Perceived self-efficacy stems from the Protection Motivation Theory (PMT) (Rogers et al., 1983) and describes, similar to the Perceived Behavioral Control in TPB, the way in which individuals feel themselves capable of performing a certain behavior. Behavioral intention, therefore, results from the perception and evaluation of behavioral options and the individual's subjective abilities.

This conceptual framework summarizes key components of selected behavioral theories and can thus be used as a starting point to collect and analyze individual behavior in dependence on external context factors. In the following, the conceptual framework will be used to assess producers' decisions on land use and management in the Brazilian Amazon, particularly concerning agricultural intensification and expansion.

2.3 Semi-structured interviews with farm managers

We conducted 25 face-to-face, semi-structured interviews with 31 farm managers in April and May 2022. Of these, 19 were single interviews, while the other 6 interviews were held with producer couples. We held 16 interviews with cattle ranchers and 9 with crop producers.

The interviews were prepared based on a literature review and the conceptual framework (section 2.2), which provided the basis for developing our interview guide. The interview guide was slightly adapted after five pre-testing interviews in the study region, which were not considered in the final analysis. The final interview guide contained five distinct sections related to 1) the producer's farming history, 2) current production and management system, 3) perceived challenges in production, 4) future plans and visions, specifically with regard to agricultural intensification strategies and related obstacles and chances, 5) socio-economic and farm structural data including age of farmer, farm size, and land ownership. While sections 1, 2, and 5 provided background information on the producers, sections 3 and 4 were tailored to our research questions. For example, we asked about specific plans to intensify production to collect information on attitudes toward different intensification strategies. We also asked about barriers to intensification to identify external environmental, economic, and political factors influencing the producer's opportunities and production behavior. In terms of agricultural intensification, we focused on land intensification strategies suggested by previous studies for the Amazon region (Cohn et al., 2016; da Silveira Bueno et al., 2021; Gil et al., 2015; Gil et al., 2016; Oliveira et al., 2018), including cattle intensification, pasture-to-cropland conversion, crop-livestock integration, and integration with trees, considering trees for fruit and wood production. During the pre-testing interviews, we found that land intensification in the region was closely entangled with expansion; hence, we also included agricultural expansion as a behavioral option in the interview guide. Each of the five interview sections included one opening question and a varying number of sub-questions. The questions were mostly open-ended to encourage the interviewees to elaborate on their experiences, perspectives, and opinions. The order of the sections was kept in most interviews, while the sub-questions were adjusted to the individual interview situation.

We aimed for maximal variation in the sample (Flick, 2014) of producers and therefore included cattle and crop producers of different ages and farm sizes and from different locations within the municipality. We could not retrieve information on the producers beforehand and selected interview partners based on visual inspection of and a few introductory questions on the landholding size, production type, and, if applicable, cultivated crops. The selection of interview partners was influenced by the geographic location, the availability of producers during our visits, and their willingness to participate.

We contacted most interviewees directly by visiting the farms and asking for the farm manager(s). In a few cases, snowball sampling was applied, as interviewees introduced us to other producers or recommended potential participants. Due to the exploratory design of this study and the in-depth nature of the communication (Crouch and McKenzie, 2006), we ended the sampling when we did not obtain any new information from the interviews, following the criterion of theoretical saturation (Glaser and Strauss, 1967), which was already applied in similar studies (Matousek et al., 2022; Mitter et al., 2019). All interviews were conducted in Portuguese by the first and second authors and recorded upon approval. Respondents were assured that participation was voluntary, that the interviews would be used only anonymously and for the purpose of the described study, and that the audio recordings would be permanently deleted at the end of the study. Quotations from the interviews provided in the results (section 3) were translated from Portuguese into English by the authors, and the names of interview participants were replaced by codes (given in front of the quotations) for anonymization purposes.

2.4 Characteristics of producers and production systems

All interviewed crop producers grew soybeans and maize in double cropping, with soybeans cultivated from September to January and maize from March to June. One crop farmer had integrated “off-season cattle” (Gil et al., 2015) in the rotation, planting Brachiaria grass with maize in parallel lines and introducing cattle to feed on the grass during the dry season after the maize has been harvested. Most of the dedicated cattle ranchers applied rotational grazing. They were typically involved in cattle breeding and raising but not in fattening, while integrated crop-cattle production included fattening of mature cattle. The average production area of cattle producers was about 200 ha (excluding one cattle producer with 1600 ha who was already in the process of changing to crop production), while the average production area of crop producers was more than twice as large at 415 ha. The average production intensity of cattle producers was 1.3 cattle per hectare. However, production areas and intensities are slightly uncertain because the interviewed producers were not always sure of their actual field or pasture areas and the current number of cattle and because the Brazilian unit of area, the "alqueire", was sometimes used inconsistently. The majority of the interviewed producers were male (73%). Cattle producers had an average age of 51 years (range: 28-70), and crop producers 44 years (range: 24-53). Only 4 cattle ranchers and 2 crop producers held a land title. Crop producers hired, on average, more employees, both permanent and seasonal, than cattle ranchers. 16 producers of the sample were located along the BR-163 highway, and 8 in nearby settlements without direct access to the highway (Figure IV.1).

2.5 Interview analysis

A qualitative content analysis of the word-by-word interview transcripts was carried out, following the content-structuring approach (Mayring, 2010; Schreier, 2014). We combined deductive and inductive coding to allow analytical flexibility as widely recommended (Gläser and Laudel, 2013; Kuckartz, 2018; Schreier, 2014). In the first step, we deduced main codes from our research questions, interview guide, and conceptual framework, such as “motivations”, “constraints”, and “preferences”. In the second step, we induced sub-codes from the interview transcripts (Schreier, 2014). For example, sub-codes of “motivations” were the behavioral options of producers in terms of intensification, such as “changing to agriculture”, with additional sub-codes such as “problems with pasture”, “fast income generation”, and “low cattle prices”. The code system was tested and further developed on the basis of 13 interviews by one researcher; thereby, codes were iteratively added, modified, and reorganized (Kuckartz, 2018). When no further changes were necessary, apart from adding some minor sub-codes, the entire interview material was coded in the original language (Portuguese) by a team of three researchers. Coding was preceded by a detailed introduction and discussion of the coding system to derive a consistent understanding of the coding system in the team. At least two researchers coded each interview, and discordances and ambiguities were recorded in the memo file of each interview and discussed within the coding team. Coding was carried out using MAXQDA software.

2.6 Standardized survey with land use modelers

Based on the results of the interview analysis, we prepared and conducted a standardized online survey with scientists from land use modeling. This survey aimed to identify strengths and gaps in current land use models with regard to the representation of the empirically identified driving factors in agricultural intensification behavior. The online survey (Supplementary material C.2), combining single- and multiple-choice with open-ended questions, was distributed among land use modeling experts in December 2023. Experts were identified from relevant scientific publications. In addition, the survey was distributed within different modeling communities through mailing lists and forums. In particular, we addressed experts in computable general equilibrium (CGE) models, agricultural sector models (ASM), and agent-based models (ABM).

Experts were asked to estimate how well six types of factors were represented in the model they were familiar with. Factors included market equilibrium (e.g., commodity prices), risk aversion, natural environment (e.g., soil, terrain, climate), infrastructure (e.g., roads, processing facilities), actor characteristics (e.g., age, knowledge), and access to resources (e.g., labor, financial assets). While market factors, such as commodity prices, were associated with motivations to intensify, risk aversion was associated with attitudes, actor characteristics with capabilities, and resource access with opportunities of producers. Environmental and infrastructural factors were related to external landscape variables influencing the producer’s opportunities.

In addition to the quality of representation, we asked experts if factors were implemented endogenously or exogenously and explicitly or implicitly. Experts were also asked how important they considered the appropriate representation of these factors and what restricts it. Lastly, we included open-ended questions to collect ideas on how the representation of the different factors could be improved in respective models. Initially, experts were asked to rate their familiarity with the model on a scale from 1 (not very familiar) to 5 (very familiar), whereby only participants with familiarity scores of 3 to 5 were included in the analysis.

From 40 survey participants, we excluded 1 participant with a familiarity score below 3. From the remaining participants, 6 worked with a CGE model, 15 with an ASM, and 14 with an ABM. Other models were excluded from the analysis due to an insufficient number of participants and included 2 System Dynamics, 1 geographical model, and 1 unclear model type. Results from the survey were analyzed using GAMS software.

3 Results

3.1 Internal factors in land use decisions

3.1.1 Motivations and attitudes

Agricultural intensification was largely motivated by economic incentives. In particular, pasture-to-cropland conversion was planned or implemented due to higher income prospects. As revenues for soybeans-maize rotation cropping are obtained twice a year, income generation is higher and faster than through cattle ranching.

Despite this, different attitudes limited conversion. In particular, risk aversion was found to discourage cattle ranchers from switching to crop production. Perceived risks were related to large upfront investments when entering crop production combined with the possibility of weather-related crop losses (see section 3.2.1), resulting in potentially significant financial burdens. We found indications that risk-averse attitudes were rather associated with older- than younger-generation producers and sometimes related to negative experiences with crop farming in the past:

> *R20: “I've been through it, I've suffered a lot with crops. It's very uncertain, because crop farming, apart from the weather, which is very risky, there's also the question of the market. The good thing is that [in cattle production] if you can't sell like you can now, when [the price] is low, you can leave it there. The time has come and you have to harvest, the time has come and you have to plant, and we, being small, don't have the structure to withstand any problems."*

On the other hand, cattle ranching was perceived as a safe and comparatively easygoing business, which is considered less risky, less complicated, and less work-intensive than crop production. Cattle ranchers who planned to stay in cattle production appreciated specifically the ease of liquidation of cattle and the limited dependence on the weather, or simply favored cattle ranching as an activity over mechanized agriculture out of personal preference.

> *R25: “I like the cow. I think it's easier and gives you a more secure income. If you put a cow there, you know it's going to give birth, but if you plant rice there, you don't know if it's going to produce.”*

However, we also found producers with passionate attitudes towards crop production, which were related to the perceived pleasure of caring for plants and watching them grow:

> *R06: “Cultivation is nicer, you see it growing and you harvest it again, you plant it again and it's always in motion. Crop farming is more beautiful.”*

While likewise providing economic incentives, crop-livestock integration was hindered by hesitant attitudes. Though being aware of the possibility of integrating cattle into the crop rotation between maize harvest and soybean sowing and recognizing the potential income benefit, crop producers associated “off-season cattle” with logistical and financial challenges. Acquiring cows at the right development stage, transporting and managing them was perceived as complicated and work-intensive, requiring additional employees or support. Also, profitability was perceived as uncertain, depending on the price of cattle at the time of sale and the available production area.

> *R14: “Cattle, their profitability is very low. And since our area is relatively small, it's not viable for us to have cattle here.”*

Negative attitudes were also found to limit the integration with forestry. Doubts were mostly related to the perceived uncertain future marketability of wood and the time lag between investment and income generation, which was mainly mentioned by older producers. Also, the need and viability of forestry in the region were generally questioned. Instead of forestry, producers expressed interest in engaging in fruit production, including lemon, papaya, cacao, or native fruits such as açaí, in order to diversify income sources.

> *R13: "Look, for now, the problem is security for us to invest in this. Security of purchase, security of sale, future price. This forestry system today has to be certain that it's going to be marketed, because […] in Brazil they're developing the pulp issue a lot, but for the time being, that's the problem."*
>
> *R06: "No, because I can't make any more money from it. My life is over. If I plant a tree, it takes 30 years to cut it down and I no longer have 30 years to live. […] For me, planting trees is not the future."*

Besides intensification, expansion intentions were driven by economic motives. Cattle and crop producers with expansion intentions associated these with future profits due to expected increases in land prices. Among the crop producers, however, we also found low-interest attitudes towards expansion. These producers saw higher gains from intensifying production on the existing area. We found more cattle than crop producers interested in expansion. This could be related to the fact that crop production is comparatively more work-intensive than cattle ranching, thus requiring expensive machinery and an adequate labor force that may compromise the benefit of additional land when such resources are limited. Besides that, we found a relation between the production area and the willingness to expand: Production areas of cattle and crop producers who were satisfied with the size of their land were considerably larger than the production areas of producers with expansion intentions. While smaller landholders associated additional land gains with increased prosperity, larger landholders were more reluctant due to limited labor and production capacities. Apart from the current land endowment, the producers' age seems to influence attitudes toward expansion, as we found younger producers to be more open to expansion than older ones. Particularly, producers close to retirement tended to be satisfied with the size of their land and feared the additional workload associated with expansion.

> *R07: "Because land is money. [...] It's increasing in value. [...] So, land today, whoever buys land never loses, that's what we think here."*
>
> *R17: "The more I produce in a hectare, the more my costs go down, the more I earn. [...] Sometimes you increase the area, but you harvest the same amount. Because you have to take care of everything, you can't plant on time, you can't harvest on time, you end up needing machinery, you need people, so seriously, the right thing is productivity, the more you produce in a hectare, the better."*

3.1.2 Capabilities and opportunities

Among the capabilities, lack of knowledge and experience were found to be important constraints of intensification, particularly pasture-to-cropland conversion. Converting was mostly considered by cattle ranchers who already had some experience in crop production from previous farms in their region of origin, cattle ranchers who received support from a relative with experience in crop production, or by the educated younger generation with (upcoming) degrees in agronomy or related fields. Thus, the conversion was often carried out after farm succession or planned by the farm successor.

> *R03: “For the time being, I'm going to stick to cattle because crop cultivation is just beginning, and we don't have much experience. Our business is cattle, so if we take all the capital we have from cattle and turn it into cultivation without knowing how it works, we could lose everything overnight.”*

Among the opportunities, we identified limited financial and land resources as important barriers. Limited financial assets constrain almost all intensification options, including cattle intensification through pasture renovation, fertilization, or supplementary alimentation, pasture-to-cropland conversion, and crop-livestock integration. Since crop cultivation requires land preparation and the purchase of expensive machinery and inputs, many producers cannot afford the transition to crop production. Likewise, limited financial resources prevent many producers from expanding their farmland. Limited land resources restrict, in particular, pasture-to-cropland conversion and crop-livestock-integration. As pointed out in 3.1.1, small farms raised doubts about the profitability of these intensification measures when the production area cannot be increased. We did not identify any social factors limiting the producers’ capabilities, except a lack of institutional support.

> *R07: “We're working with cattle, because for those of us who have little land, crop farming is not viable.”*

3.2 External factors in land use decisions

3.2.1 Environmental factors

Climate and climatic change

Climate showed an important but ambivalent effect on agriculture in the study region. On the one hand, the climate was perceived among cattle and crop producers as beneficial for production, especially because of the abundance and predictability of rain, attracting producers from the south.

> *R17: “The climate here is very good for plants. […] Lots of water, it rains a lot, even too much, let's put it that way. We have good soil, food for plants, light, lots of light and heat. So, there's everything the plant needs […]. So, the climate is very good, the land is good, but the climate.”*

On the other hand, heavy rainfall during the soybean harvest season was considered the biggest climatic risk for crop production. Soybeans must be harvested between the end of January and the beginning of March. Excessive rainfall during this period can lead to significant crop losses if machines cannot enter the swampy fields and soybeans rot. Consequently, while some producers were attracted to the region by the rainfall, this rainfall is also the most important constraint for pasture-to-cropland conversion, as cattle producers observe soybean harvest losses of neighboring crop producers, reinforcing the perception of crop production as a risky investment.

While rainfall during the harvest season is perceived as a risk and, hence, an intensification barrier, climate change is not. No producer mentioned to consider climate change in his/her production behavior; however, different perceptions of climate change were expressed:

> *R01: “Just like Dad was saying about the deforestation. It's never changed the climate at all. It's still raining as much as it used to. When we arrived, the same amount of sunshine, everything the same, it hasn't changed at all. All the same.”*

> *R02: “When I arrived here in the 1990s, it used to rain a lot for more than six months, rain that would drain the hills. For a few years now, it's been decreasing a little. It's the climate. Don't say it's because of deforestation, that's a lie. This year, it's the same as in the 80s and 90s, this year it rained a lot […]”*

Soils and terrain

Soil properties and terrain conditions were relevant for intensification, particularly pasture-to-cropland conversion. Many cattle producers claimed undulating terrain and rocky soils are significant constraints for crop production, as machines cannot operate in such areas. Due to this reason, soil and terrain conditions may also impede the restoration of degraded pastures to recover pasture productivity and permit a higher cattle production intensity.

Weeds and pests

Weeds and pests contribute to pasture degradation, which may accelerate agricultural intensification by catalyzing the conversion from cattle ranching to crop production. Several producers who switched from cattle to crops named invasive grass species (“capim louco”) and weeds as reasons for switching. Otherwise, they would have had to apply expensive herbicides or other pasture restoration measures, leading to noticeable income losses. Many cattle producers also reported problems with pests, requiring the application of costly pesticides to sustain pasture productivity. Mainly, producers mentioned leafhopper attacks on the Brizantha grass during the dry season and problems with caterpillars, which attacked the Mombaca grass and were perceived to be more challenging to control.

3.2.2 Economic and infrastructural factors

Market incentives were identified as an important motive for agricultural intensification. Thus, commodity prices evolve as relevant factors in producers’ intensification behavior. Besides higher returns from soybean production, producers mentioned low cattle prices as a reason for changing to crop production. At the same time, low market prices for cattle reduce producers’ willingness to integrate cattle in the crop rotation (see section 3.1.1). In that regard, cattle prices have an ambiguous effect on agricultural intensification, as they accelerate the conversion from cattle ranching to cropping but at the same time slow down the integration of crop and livestock production. In addition to price levels, price fluctuations have an effect on production behavior, as they influence producers’ risk perception (see section 3.1.1). As producers felt price fluctuations were easier to manage in cattle than in crop production due to the flexibility in the timing of the sale, unstable commodity prices seemed to slow down the spread of crop-based production systems.

Also, the current and estimated future marketability of products influences production behavior. We observed that the perceived limited marketability of wood (see section 3.1.1), fruits, and field crops other than soybeans and maize, such as rice, sorghum, canola, and sunflower, was a constraint for diversification and thus integration of different production systems.

> *R17: “I planted [sorghum] last year and I planted it this year, but the people in the region don't know it well. They don't know it well. So, if you want to sell it here, it's very little, to a farmer, a landowner. […] Then there are the feed mills here that, last year, I didn't even sell last year's, but it's still in storage. Because when I went to sell, there was no trade.”*

Besides commodity prices, we identified land prices as an important factor in agricultural land use decisions. Both cattle and crop producers mentioned high land prices as a major barrier to increasing the production area. This may have a mixed effect on intensification: On the one hand, impeded land expansion by the established producers might limit pasture-to-cropland conversions and crop-livestock integration, which were perceived to only pay off above a minimum land size. On the other hand, increasing land prices might promote land purchases by more affluent producers with higher financial capacities, which may stimulate capital-intensive intensification processes, such as pasture-to-cropland conversions.

In addition, infrastructure shapes agricultural land use. While crop producers mentioned the nearby construction of silos as an incentive for cultivating soybeans, cattle producers located in settlements away from the highway mentioned the inaccessibility of proper roads as a key obstacle to crop production. Likewise, limited access to machinery, inputs, and labor force was perceived as a constraining factor of agricultural intensification. While limited access to machinery and inputs was named as an obstacle to crop production, the perceived lack of labor force and high labor costs were reported as barriers to labor-intensive operations such as integrating cattle into the crop rotation or fruit trees in the production portfolio.

> *R13: "Fruits, I was interested in doing something with them, […], pineapples and things that are easy to handle. What is the main problem for those working in fruit growing? Labor. It's hard to find people willing to work, but everything involves a lot of work, so everyone is avoiding working with things that involve a lot of work effort and fruit growing unfortunately depends a lot on people to work."*

3.2.3 Political and institutional factors

Missing or inadequate land titles, bureaucratic hurdles, and environmental sanctions were named as the main obstacles in production. Producers claimed a missing land title and bureaucratic hurdles in obtaining it as a major barrier to investment, as credits are rarely provided to producers without proper documentation of land ownership. As a consequence, intensification processes related to larger investments, such as cattle-to-crop conversions, are prevented by the inaccessibility of financial support due to missing land documentation.

> *R03: "If you take all the areas in our region, not 10% have the documentation to get funds from a bank or other institution."*

Producers also perceive environmental sanctions, often enforced through embargos preventing the sale of products from areas with environmental violations, as a serious production risk. While this seemingly prevents producers from clearing forest inside the land holding, it also appears to be less worrisome for cattle than for crop producers:

> *R23: "Because today anyone who buys soy and maize here, the first thing they ask is if there's no problem with IBAMA*, and the region here is very good and there's a lot of area that's legal and there's no problem. But there are those that have a problem, and then it's an area that's usually used for cattle, because if there's any inspection or anything, cattle are something that [...] you can take away. That's why no one cultivates crops in an area that has a problem, because if you invest and plant crops and then someone comes along and tells you to kill the crops, the damage is huge. […] It's like this with cattle: if there's a problem, they give you a deadline to remove it, then you remove it, disappear with the cattle and that's it."*

**IBAMA is the Brazilian Institute for the Environment and Renewable Natural Resources and is responsible for the enforcement of environmental restrictions, e.g., through deforestation control and the imposition of fines and embargoes.*

The current political-institutional context in the Brazilian Amazon is perceived to favor cattle production while complicating crop-based production systems since 1.) credits needed by cattle ranchers to enter crop production are hardly provided due to unresolved issues concerning land titles, and 2.) environmental sanctions pose a greater financial risk to crop producers than to cattle ranchers.

3.3 Representation of factors in agricultural land use models

While operating at different spatial scales, many land use models rely on optimization. CGE models and ASMs typically cover the entire globe but may depict focus regions with a higher resolution (Supplementary material C Figure 1). A majority of ABMs operate at the farm level and rarely cover more than a subnational region. All CGE models and ASMs in our expert survey employ economic optimization as a driving mechanism of land use change (Supplementary material C Figure 2). Among the ABMs, more than 70% apply rules and heuristics as driving mechanism of land use decisions, and more than half include income maximizing behavior.

We asked modeling experts if factors (see section 2.6) were represented explicitly or implicitly and endogenously or exogenously, and how accurate they considered their overall representation. We found that market equilibrium is mostly endogenously and explicitly simulated in CGE models and ASMs (Supplementary material C Figure 3 – 6), and its representation is considered very accurate (Figure IV.3a). In ABMs, the representation of market equilibrium is considered poor and depicted rather exogenously and implicitly. Thus, commodity and resource price-based economic incentives, which were identified as the main motivation behind agricultural intensification, are better represented in CGE models and ASMs than in ABMs.

Actor characteristics such as knowledge, on the other hand, are represented fairly well and explicitly in ABMs but only poorly and implicitly in CGE models and ASMs. Likewise, ABMs outscored other modeling approaches in representing access to resources, such as financial assets and labor. It can be derived that farmers' capabilities and opportunities, which we identified to restrict agricultural intensification behavior, are more often considered in agent-based approaches than in other models. Risk aversion decelerating agricultural intensification was found to be poorly represented in all described models, revealing an important general gap in current agricultural models.

As far as the representation of landscape features is concerned, the focus is more on the natural environment than on infrastructure. While the representation of the natural environment, e.g., soil and terrain, was considered fairly well in ABMs and ASMs, roads and processing facilities are underrepresented in most models. Landscape factors are typically considered explicitly but exogenously.

In general, the representation of all factors was valued higher when the representation was explicit, while an endogenous representation did not necessarily lead to higher perceived performance scores (Supplementary material C Figure 7, 8).

Future improvements of land use models were indicated to be rather limited by the availability of data than by computing capacities (Supplementary material C Figure 9). This applies in particular to the representation of actor characteristics, risk aversion, and infrastructure, which was restricted by limited data availability in all model types. Data limitations were more often named as a constraint for CGE than for other models, probably due to their global scope and comprehensive depiction of economic sectors. Apart from data limitations, improving the representation of the analyzed factors in land use models was reported to be challenging due to the additional complexity and differences in spatial scales. The latter applies specifically to internal aspects of decision-makers, such as actor characteristics, risk preferences, and access to resources, which were perceived either irrelevant or difficult to implement in CGE models and ASMs operating at a global level with aggregated producers. Also, surveyed experts pointed to epistemic uncertainties regarding the effect of actor characteristics and risk attitudes on decision-making, requiring further research. Data and knowledge gaps were proposed to be overcome through empirical data collection, including representative surveys and field experiments, and the deduction of decision rules or behavioral equations, potentially also through the use of artificial intelligence. Increasing the spatial resolution and coupling of global models with sub-national, spatially-explicit models were proposed to improve the representation of the natural environment and infrastructure. Specific suggestions to enhance the representation of market equilibria include improving estimates on demand elasticities and price dynamics. Regarding risk aversion, the introduction of extra shadow costs and the explicit representation of producers were suggested. Infrastructure and access to resources were proposed to be improved by network analysis and linking different data sources.

In general, the representation of markets, the natural environment, and resource access were perceived as important in the majority of models, while the representation of infrastructure was considered less important (Figure IV.3b). Representing actor characteristics and risk aversion was considered important only for ABMs but not CGE models and ASMs, reflecting the conceptual focus of the different model types.

In summary, the survey with experts from land use modeling reveals a general awareness of the relevance of market forces, biophysical landscape characteristics, and resource constraints for plausible land use assessments, which are represented in the different model types to varying degrees. On the other hand, the relevance of risk aversion and infrastructural constraints remains mostly underestimated. The surveyed experts see a need to improve the empirical data base of land use behavior and increase efforts to integrate different model types to reduce existing limitations in model-based land use assessments.

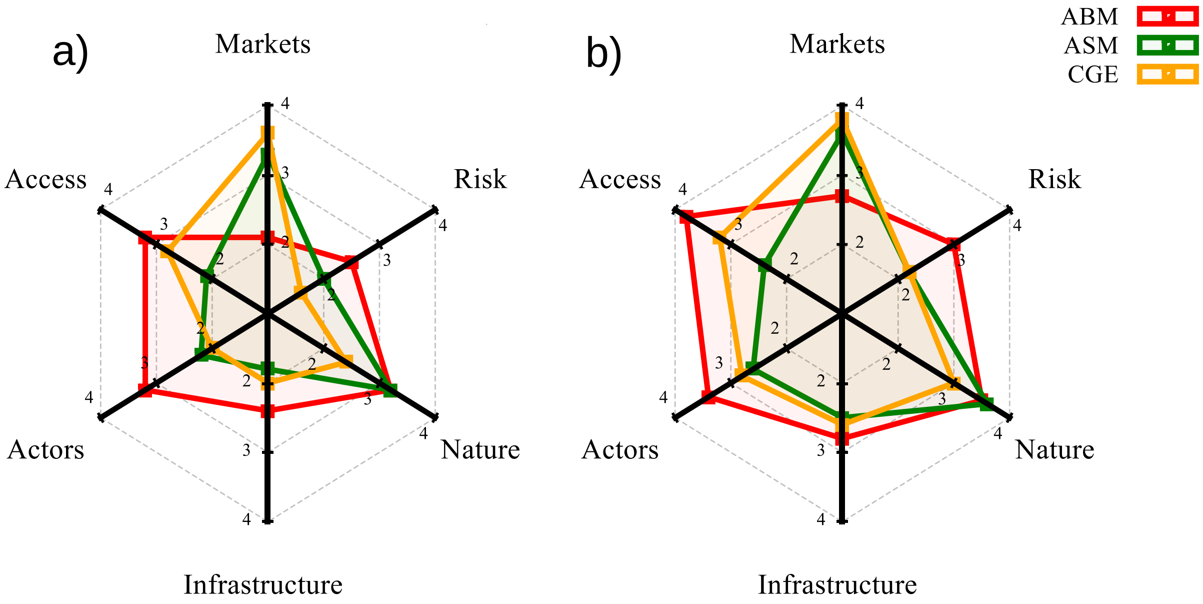

Figure IV.3: Estimated quality (a) and importance (b) of representation of factors in land use models.

Factors include market equilibrium, risk aversion, natural environment, infrastructure, actor characteristics, and access to resources. Average values for CGE models (yellow), ASMs (green), and ABMs (red) are given. Results were generated from survey among land use modeling experts. Values for quality of representation (a) indicate no representation (1), poor representation (2), fairly accurate representation (3), and very accurate representation (4) representation. Values for importance of representation (b) refer to not important (1), slightly important (2), quite important (3), and very important (4).

3.4 Producers’ outlook on regional land use futures

We noticed a large consensus that the cultivation of soybeans and maize is expected to increase in the region over the next 15 years. Many cattle producers assumed that this increase would happen, particularly in flat areas where cattle production would be displaced. Further, producers suggested that this increase would concentrate along the BR-163 highway and on legal production plots (plots compliant with environmental law) due to the importance of road connection for soybean production and the fact that crop production in illegal areas is perceived riskier than cattle ranching. Despite a decline in cattle production, producers assumed that cattle would not disappear from the landscape but would remain in the hilly areas where mechanized crop production is not feasible. Where cattle production is expected to stay, producers assume that grazing will be intensified.

While almost all producers expected an expansion of agriculture, only a few also expected an expansion of integrated crop-livestock systems. We assume this is because there were very few examples of integrated crop-livestock systems in the region at the time of the interviews. Thus, our interviewees might have been less aware of these than the pasture-to-cropland conversions, which every producer had already observed in their neighborhood. In line with the general skepticism toward forestry, none of our interviewees mentioned the integration with forestry as a potential future scenario for the region.

With ongoing cropland expansion, some producers expected further land appreciation and, thus, rising prices, coupled with a concentration of land in the hands of fewer but larger landholders. Also, cropland expansion was often associated with a general appreciation of the region, as it was expected to be accompanied by infrastructural development, including improvements of healthcare, roads, and production facilities. In this process, producers expected an increasing relevance of agriculture in the regional economy, while other sectors, including gold mining and timber production, might shrink. Some producers suggested that deforestation might decrease in the region but also expressed uncertainty about the future due to unregulated land tenure, environmental enforcement, and political developments.

> *R23: “I think that within five years this [city] […] is going to make a lot of progress, because every day people arrive from somewhere looking for land to plant and buy, so the trend here is going to develop a lot over the next five, ten, fifteen years, it's going to change for sure. It's going to bring a lot of improvements. In fact, today we have an axis that puts us on the line, this BR163 here, we're on the route, and I've never seen a town that's on the route and isn't developing. So, I say that in five- or ten-years’ time, it's going to grow a lot.”*

4 Discussion

4.1 Influencing factors in land use decisions

Our results on external and internal factors influencing agricultural intensification behavior are in line with findings from previous studies. Revealing market incentives as relevant drivers of agricultural intensification, this study confirms "potential higher income" as the most important motivation in intensification, as reported for the adoption of integrated production systems (Gil et al., 2015), and underlines the importance of global forces for regional land use changes (Lambin et al., 2001).

While market forces were found to promote intensification, internal factors, including restricted opportunities due to limited financial and land resources, as well as restricted capabilities due to a lack of knowledge and experience in crop production, hamper the intensification behavior of farmers. Our research suggests that landholding size is particularly critical for intensification steps with high upfront investments, where profitability after implementation depends on economies of scale, which is confirmed by previous research on integrated systems in Sao Paulo, Brazil (de Souza Filho et al., 2021). Besides landholding size, previous studies confirmed the critical role of financial resources (Cohn et al., 2016; Gil et al., 2015; Gil et al., 2016), which are particularly relevant for the expansion of crop- and forestry-based farming systems, as highest investment costs were reported for the introduction of forestry, followed by crops (Gil et al., 2015). Cohn et al. (2016) also pointed out that the limited financial resources of cattle farmers and high investment costs of cattle-to-cropland conversions often lead to conversions being preceded by land transactions, which is consistent with our findings and likely also applies to other intensification steps (Gil et al., 2015).

Opportunities of producers were additionally influenced by external factors, such as limited access to supply chain infrastructure and qualified labor, as also reported in previous studies (Cortner et al., 2019; Gil et al., 2015; Gil et al., 2016). Likewise, physical parameters such as soil and terrain characteristics were found to play a role in intensification, e.g., in pasture renovation and pasture-to-cropland conversion, as also observed previously (de Souza Filho et al., 2021). We could not yet identify any effect of climate change on intensification. Instead, climatic changes in the region were often denied, which contrasts climate observations from previous studies, indicating decreasing precipitation trends since the 1980s in older deforested regions of the southern Amazon (Dubreuil et al., 2017; Marengo et al., 2018; Mu and Jones, 2022). Decreasing precipitation trends could affect future agricultural intensification in the Amazon in multiple ways. On the one hand, a negative trend in rainfall during the soybean harvest season, as observed by Marengo et al. (2018), might favor conversion from cattle to soybean production. On the other hand, the profitability of double-cropping due to a shortened rainy season could decrease (Carauta et al., 2021a) and thus reduce cropping intensities.

Regarding capabilities, our results indicate that knowledge constraints in intensification may be overcome through farm succession by the younger, "college-educated" generation, which is in line with findings from Gil et al. (2016). As our conceptual framework suggests, restricted capabilities and opportunities constrain intensification behavior by adversely affecting the individual's perceived self-efficacy. This is in line with previous studies from similar contexts, which found perceived self-efficacy as an important factor in the uptake and maintenance of agroforestry in Bahia, Brazil (McGinty et al., 2008) and the use of improved natural grasslands in the Pampa biome, Brazil (Borges et al., 2016).

Besides perceived self-efficacy, our results underline the importance of risk aversion for agricultural intensification. Producers perceived diverse economic risks, including the risk of harvest losses due to excessive rainfalls, the risk of missing market outlets due to uncertain market developments, and legal risks due to the absence of land titles and potential environmental sanctions. Perceived commercialization issues, herein reported for wood products and hitherto uncommon field crops, were also observed by previous studies (Gil et al., 2015). The critical role of risk attitudes in agricultural production decisions was also observed in previous research on cropland expansion (Bragança and Cohn, 2019; Cohn et al., 2016) and crop-livestock integration (Gil et al., 2016) in Mato Grosso, Brazil. In that context, Gil et al. (2016) pointed to the relevance of farmers' geographic and cultural backgrounds, as origin and experience may explain variations in informal knowledge influencing farmers' attitudes towards risk and complexity. Previous studies further suggested that risk aversion might become more prevalent with age (König, 2021; Kurnianingsih et al., 2015), as observed for land conversion and intensification in New Zealand (Brown et al., 2019). We also found this tendency in our interviews, indicating an effect of the population's age structure on future agricultural development.

In addition to risk attitudes, this research reveals attitudes towards cultivation and cattle ranching to play a role in producers' intensification behavior, particularly concerning pasture-to-cropland conversion. This is supported by Cohn et al. (2016), suggesting that extensive cattle ranching is sometimes preferred over cultivation because of emotional attachment and a feeling of cultural and professional identity.

4.2 Implications for land use assessments

Our findings confirm that land use decisions in the Brazilian Amazon are driven by economic incentives, i.e., the magnitude and stability of income prospects from farming. Thus, empirical evidence of producers' intensification decisions justifies land use modeling based on economic principles, as implemented in diverse model applications for Brazil and the Brazilian Amazon. These encompass applications of the ASM Global Biosphere Management Model (GLOBIOM) (de Andrade et al., 2019; Havlík et al., 2011; Soterroni et al., 2018; Zilli et al., 2020), the CGE The Enormous Regional Model (TERM) (Ferreira et al., 2015; Horridge et al., 2005), and the agent-based software Mathematical Programming-based Multi-Agent Systems (MP-MAS) (Carauta et al., 2018; Carauta et al., 2021b; Schaldach et al., 2018; Schreinemachers and Berger, 2011), driven by maximizing economic surplus (GLOBIOM) or expected income (MP-MAS), or minimizing production and consumption costs (TERM).

However, our findings also underline the importance of considering producers' and landscape constraints when simulating agricultural land use change in the Brazilian Amazon, which are implemented in these models to varying degrees. Therefore, beyond ongoing model development, integrating different models is suggested to exploit the advantages of alternative approaches and thus increase the plausibility of land use projections. While TERM and GLOBIOM likely outperform MP-MAS in terms of market dynamics, MP-MAS explicitly represents the heterogeneity of producers, thereby also accounting indirectly for risk aversion through implementing innovation segments that describe the agents' willingness and ability to adopt new practices (Schreinemachers and Berger, 2011). For an integrated modeling framework, we further suggest aiming for a high spatial resolution of environmental characteristics, as average values over larger areas are typically associated with a loss of information, resulting in biophysical limitations no longer being adequately depicted, particularly in regions with complex topographic conditions.

The identified gaps in land use models have implications for the plausibility of previous model-based land use assessments in Brazil. Using an ASM and CGE model, pasture intensification, cropland expansion, and pasture-to-cropland conversions were estimated under scenarios of rising ethanol demand (de Andrade et al., 2019) and deforestation control (Ferreira et al., 2015; Soterroni et al., 2018). Broad pasture-to-cropland conversions and intensification of cattle ranching were expected to meet rising production demand with only marginal impacts on natural vegetation, at least under strong law enforcement. Considering that CGE models and ASMs rarely represent producers' capabilities, risk aversion, and opportunities limited by resource access and available infrastructure, barriers to intensification might be largely neglected, and thus, the speed of agricultural intensification processes overestimated. It follows that projected estimates of agricultural production and resulting land-sparing potentials might be overrated.

Likewise, our findings may be used to revise development storylines and resulting land use implications for the Brazilian Amazon region (Göpel et al., 2018; Schönenberg et al., 2017). Accounting for future perspectives of local producers, a reduction of cropland areas and a simultaneous increase in pastures along the BR-163 highway in Pará until 2030, as proposed in the ‘Trend’ storyline (Schönenberg et al., 2017), appears rather implausible. On the other hand, pasture-to-cropland conversions along this corridor, as suggested in the ‘Sustainability’ storyline (Schönenberg et al., 2017), are consistent with producers’ expectations, though potentially taking place at a slower pace due to various intensification barriers identified in this study.

It can be concluded that neglecting the identified internal and external factors influencing land use decisions in the Brazilian Amazon may prevent model-based assessments from comprehensively capturing local land use dynamics. Thus, the spread of agricultural intensification may be potentially overestimated, resulting in inaccurate projections of environmental impacts from production in the Brazilian Amazon and other regions.

4.3 Study limitations

Despite the application of the criterion of theoretical saturation and the qualitative design of the empirical data collection, a certain effect of sampling biases on our findings resulting from the limited number of interviews can not be ruled out. As the interviews were preceded by a time-consuming process of trust building and the atmosphere in the study region was politically heated due to the upcoming presidential elections in the same year and the global media attention on deforestation in the Amazon, the number of interviews that could be conducted within the designated data collection period was limited. It is possible that producers interested in being interviewed may have different attitudes and characteristics than those who declined to be interviewed, resulting in potential biases in our findings. In addition, the regional focus of this study on one specific municipality raises concerns about its generalizability.

Quantitative surveys building on the results of this study are suggested to be carried out in different locations of the Amazon agricultural frontier to determine the robustness and generalizability of our results. In addition, the expansion of this study to other frontier regions and rural areas with limited agricultural production intensities is suggested to further explore context-specific factors of agricultural intensification.

Moreover, a broader survey including additional land use models and a detailed breakdown of the various factors influencing agricultural land use decisions could help to gain a more comprehensive understanding of gaps and future potentials of land use models in projecting agricultural developments.

5 Conclusion

This study explored producers' decisions on agricultural intensification in the Brazilian Amazon, interpreting information from semi-structured interviews with the help of behavioral theory. We analyzed internal and external factors that influence cropland expansion and the integration of production systems and explored plausible land use futures for the agricultural frontier.

Our findings provide empirical evidence that agricultural intensification is driven by economic incentives. However, producers' attitudes, capabilities, and opportunities, influenced by environmental conditions and the political-institutional context, considerably restrict the speed of intensification. Particularly, pasture-to-cropland conversion is impeded by the individual's limited knowledge about crop cultivation, the perception of cattle ranching as a less complicated and less work-intensive occupation, limited access to roads and processing infrastructure, terrain and soil constraints, and land title issues; the latter potentially being particularly relevant in frontier regions with weak land institutions. Interestingly, pasture degradation may act as a catalyst for pasture-to-cropland conversions. Limited financial and land resources restrict not only the conversion of pasture to cropland but also the integration of crop and livestock systems. Availability and costs of labor were important constraints for crop-livestock integration and farm diversification with fruticulture. In addition, risk aversion restricts almost all intensification strategies. Perceived risks relate mainly to crop losses due to heavy rainfall during the soybean harvest, insecure investments due to weak land institutions, and uncertainty about the future marketability of alternative crops, fruits, and timber, the latter representing a major obstacle for the integration of forestry in the production portfolio.

Our empirical findings justify, to some degree, modeling approaches driven by market dynamics, i.e., as implemented in CGE and agricultural sector models, for predicting rural land use dynamics. However, an adequate representation of land use change also requires the consideration of crucial barriers at the producer and landscape level, which were found to be more commonly implemented in agent-based approaches. At the producer level, our study reveals gaps in the representation of risk aversion and technical knowledge of agricultural practices among most land use models. On the landscape level, proximity to roads and processing infrastructure remains mostly underrepresented. To increase the plausibility of model-based land use assessments, findings underline the importance of improving the empirical database on land use behavior and coupling of different model types, as relevant factors in land use changes address different spatial scales.

Regarding the future development of the agricultural frontier, producers expect a large-scale spread of soybean production, especially in flat and legal areas with good access to the highway, while they expressed doubts about the introduction of integrated production systems. Based on producers' perspectives, integration with forestry, in particular, can be considered implausible for the coming years. With ongoing cropland expansion, producers anticipated a further increase in land prices and a concentration of land in the hands of fewer but larger landowners. While this could resolve financial and land size-related barriers to intensification, concerns about the social implications and effects on future deforestation dynamics due to displacement processes may arise.

Besides revealing important barriers to agricultural development in frontier regions, our findings provide empirical evidence on relevant factors in land use decision-making that should be considered in future land use model development. Closing the identified gaps in land use assessment models will likely improve land use projections for diverse rural contexts beyond the Brazilian Amazon agricultural frontier.

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Appendix

A Supplementary material to article 1

Extended methodology

Here we present additional information on our model setup, including data applied in the operation, site, control, and parameter file.

1 Crop management (operation file)

A. Table 1: Management data as applied in the operation file.

Crop	Planting date	End of growing period	Plant population at planting (plants m^{-2})	Land use number
Rice	1 of March	1 of September	250	11
Johnson Grass	1 of January	31 of December*	100	1

** At the end of the growing period, Johnson Grass is burnt. Harvesting operations take only place for rice and are further specified in section 2.3.2 of chapter II.*

Potential heat units (PHU) for rice and Johnson Grass, applied in the operation files, depend on the applied climate model and were therefore adjusted before each simulation. PHU for rice were computed in EPIC through spin-up simulations (see Sharpley and Williams, 1990), in which rice was grown for a 30-year historical period (1985-2014). PHU for Johnson Grass were computed manually in R software by using equation (A1) for the calculation of heat units or growing degree days and equation (A2) for calculating PHU from total heat units of all growing seasons from 1985 to 2014.

$$Heat\ Units = \frac{T_{Max} + T_{Min}}{2} - T_{Base} \tag{A1}$$

$$Potential\ Heat\ Units = \frac{\left(\sum_{i=1985}^{2014}\left(\sum_{j=Planting\ Date}^{Harvesting\ Date} Heat\ Units_{i,j}\right)\right)}{30} \tag{A2}$$

2 Area and slope length (site file)

For all sites, we assumed a field size of one hectare. This corresponds to the rounded average field size of shifting cultivation fields in the study area, which we collected during a field survey in April 2022. From the field size and the slope steepness, we computed the slope length using equations (A3) and (A4). As slope length depends on slope steepness, we computed specific slope lengths for all simulated slope inclinations.

$$Field\ length\ (m) = \sqrt{Field\ size\ (ha) \cdot 10{,}000} \tag{A3}$$

$$Slope\ length = \frac{Field\ length\ (m)}{\cos(slope\ steepness)} \tag{A4}$$

3 Atmospheric CO2 (control file)

We considered scenario-specific CO_2 concentrations in our simulations. Therefore, we downloaded annual CO_2 concentrations from Meinshausen *et al.* (2020) (data access: 03/10/2022) and computed average CO_2 concentrations of the northern hemisphere for each climate scenario and future period. The resulting CO_2 concentrations were written in the EPICCONT file of each simulation scenario, and "constant atmospheric CO_2" was selected for ICO2.

A. Table 2: Average CO_2 concentrations.

Scenario	Historic	SSP126		SSP370		SSP585	
Period	1985 - 2014	2021 - 2050	2071 - 2100	2021 - 2050	2071 - 2100	2021 - 2050	2071 - 2100
Atmospheric CO2 (ppm)	370	448	461	476	757	482	940

Values were derived from Meinshausen et al. (2020).

4 RUSLE coefficients (parameter file)

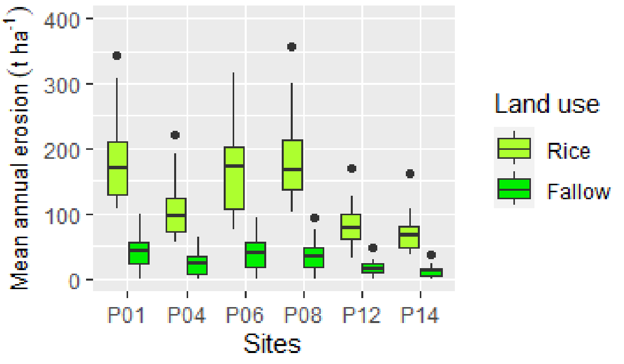
A. Table 3: RUSLE C-factor coefficients.

Exponential coefficient in RUSLE C-factor equation (0.5-1.5) used in estimating the residue effect.	1.5
Exponential coefficient in RUSLE C-factor equation (0.05-0.2) used in estimating the effect of growing plants.	0.05

The above values for RUSLE exponential coefficients have been defined to achieve the lowest possible C-factor. By reducing the C-factor, we reduced erosion and hence attenuated the effect that EPIC typically overestimates soil erosion on steep terrain (Carr *et al.*, 2020).

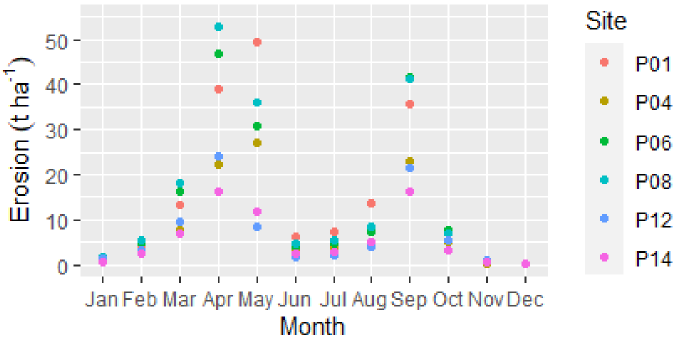
5 Model evaluation

Here we present additional information on the model evaluation, with Figure A1 showing simulated average soil erosion per year for rice and fallow and Figure A2 showing its seasonality for the six different sites during rice cultivation.



A. Figure 1: Mean annual soil erosion for 1985-2014 under rice and fallow land use.

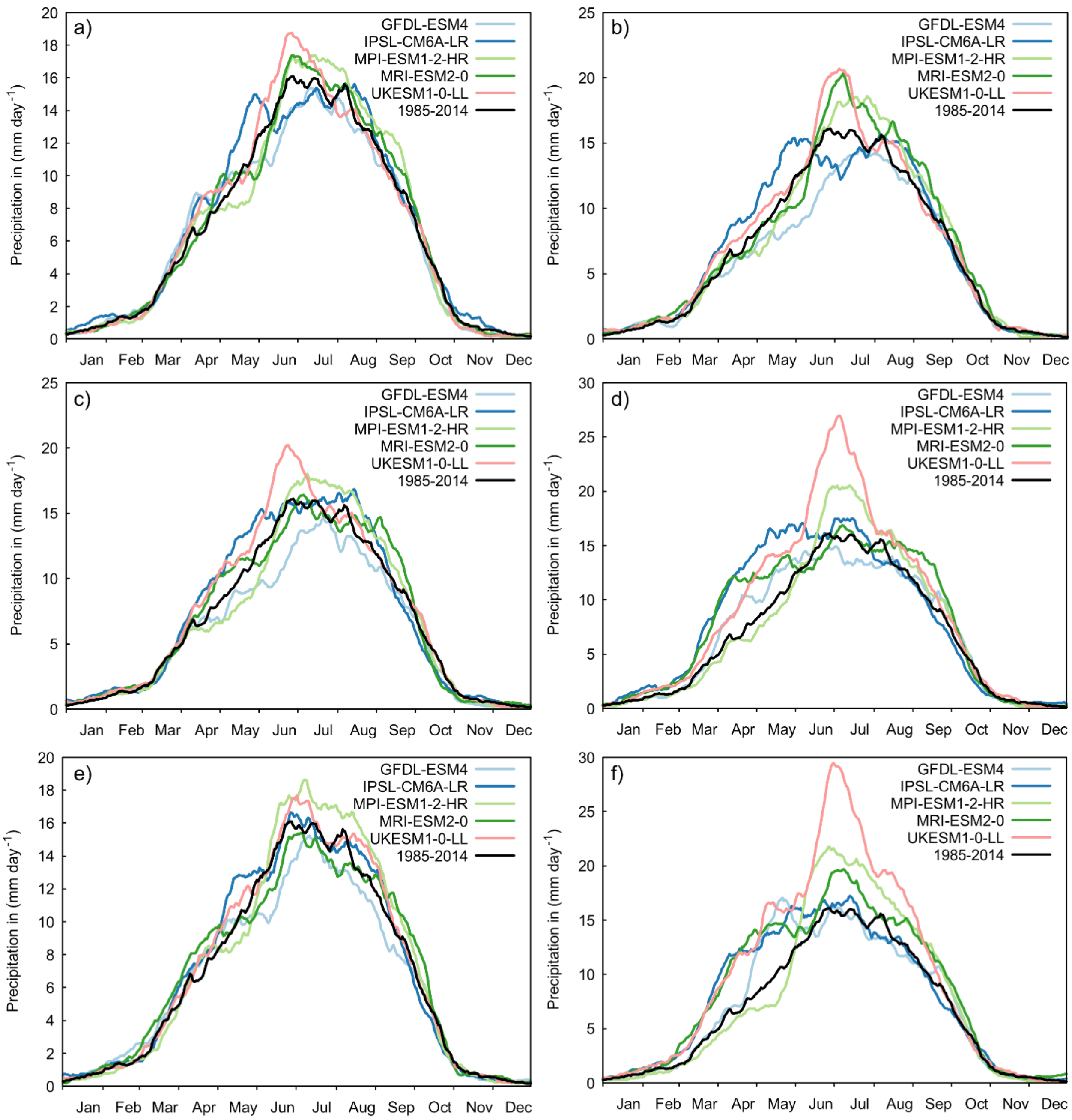
Erosion values are based on 40 % slope inclination and a 3-year fallow regime.



A. Figure 2: Monthly soil erosion during rice cultivation for 1985-2014.

Monthly erosion was averaged over all simulation years and is based on 40 % slope inclination and a 3-year fallow regime.

6 Seasonal precipitation projections from ISIMIP 3b climate data



A. Figure 3: 31-day moving average of precipitation under different climate models for the a) SSP126 near future, b) SSP126 far future, c) SSP370 near future, d) SSP370 far future, e) SSP585 near future, f) SSP585 far future scenario.

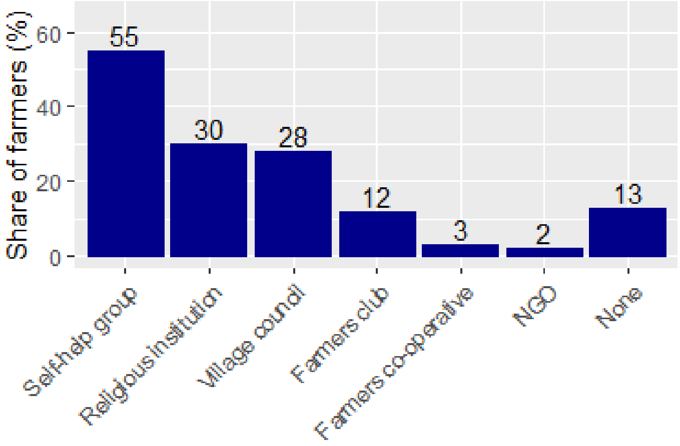
Mean precipitation from 2021-2050 (near future) and 2071-2100 (far future) is shown.

B Supplementary material to article 2

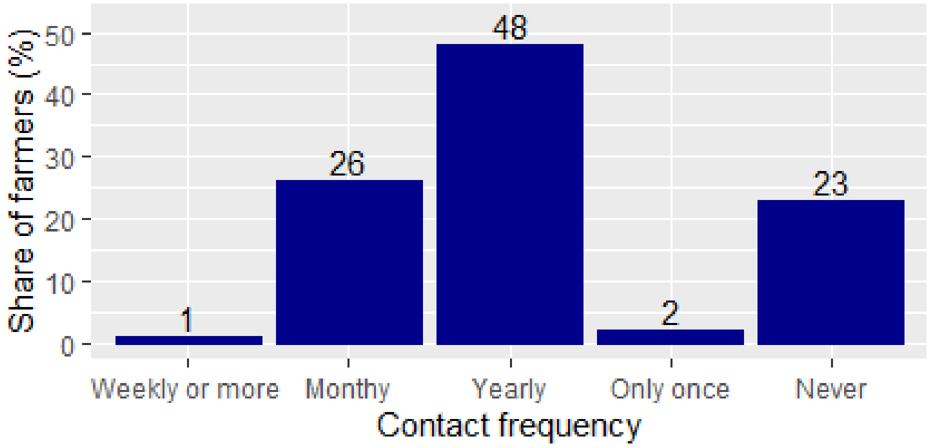
1 Extended methodology and results

B. Table 1: Number of samples per district and village.

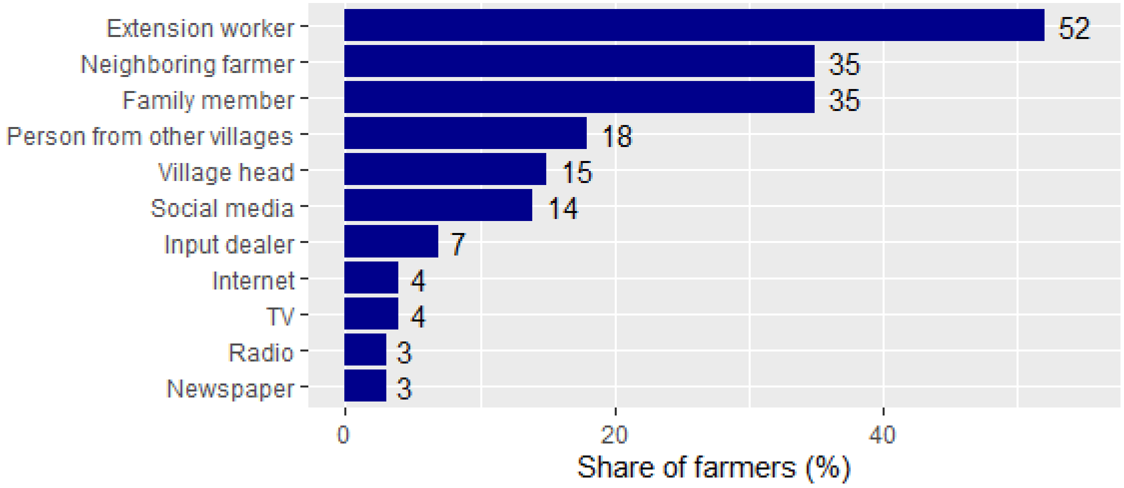
Village	Tribe	Count	District	Sum per district
Piphema	Angami	6	Dimapur	41
Ruzaphema	Angami	6	Dimapur	
Zhuikhu	Sema	14	Dimapur	
Zuheshe	Sema	15	Dimapur	
Lithsaoung	Sangtam	21	Kiphire	88
Phelungre	Sangtam	18	Kiphire	
Sangtsung	Sangtam	25	Kiphire	
Sanphure	Sangtam	24	Kiphire	
Alichen	Ao	12	Mokokchung	44
Chubayimkum	Ao	7	Mokokchung	
Longkum	Ao	17	Mokokchung	
Ungma	Ao	8	Mokokchung	
Langmeing	Konyak	18	Mon	71
Ngangching	Konyak	15	Mon	
Sowachangale	Konyak	17	Mon	
Totochinga	Konyak	21	Mon	
Gidemi	Chakhesang	17	Phek	69
Phola	Chakhesang	18	Phek	
Porba	Chakhesang	13	Phek	
Sakraba	Chakhesang	21	Phek	
Izheto	Sumi	21	Zunheboto	59
Litta New	Sumi	16	Zunheboto	
Litta Old	Sumi	11	Zunheboto	
Shichimi	Sumi	11	Zunheboto	



B. Figure 1: Percentage of farmers participating in civil society organizations.

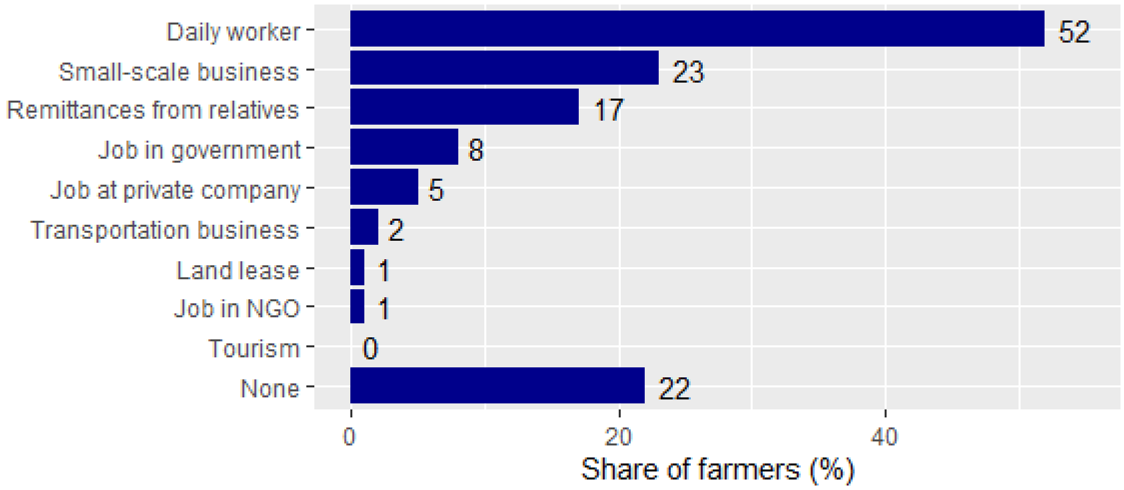


B. Figure 2: Contact frequencies of farmers to extension workers from government.



B. Figure 3: Percentage of farmers who learned about adaptation measures from different sources.

Different types of information sources are given on the y-axis. Proportions of farmers who learned about one or more adaptation measure(s) from a specific source are given on the x-axis. Adaptation measures refer to climate change adaptation measures in general and are not limited to SWCP.



B. Figure 4: Percentage of farmers receiving off-farm income from different sources.

2 Questionnaire

Village: **District:** **State:** Nagaland
Date: **Number of questionnaire:** **Interviewer:**

No.	**Part-A: Personal and socio-economic characteristics**		
101	Name (First name, surname)		
102	Age	Years	
103	Gender	① Male ② Female ③ No answer	
104	Tribe	① Angami ② Ao ③ Chakhesang ④ Chang ⑤ Dimasa Kachari ⑥ Khiamniungan ⑦ Konyak ⑧ Kuki ⑨ Lotha ⑩ Phom ⑪ Pochury ⑫ Rengma ⑬ Sangtam ⑭ Sumi ⑮Yimchungrü ⑯ Zeliang ⑰ ……………….….	
105	Education	① No schooling ② Primary ③ Secondary ④ Higher secondary ⑤ Under Graduate ⑥ Post Graduate and above	
106	Experience in farming	Years	
107	Total number of family members	Male:	Female:
108	Number migrated family members	Male:	Female:
109	Where did family members migrate? *(Multiple selections possible)*	① Rural area (uphill) ② Rural area (valley) ③ Nearby town ④ City in Nagaland ⑤ City in other NEI state ⑥ City outside NEI ⑦ ……….……………	
110	Why did family members migrate? *(Multiple selections possible)*	① Education ② Job ③ Better cultivation conditions ④ Better connectivity ⑤ ……………………….......….	
111	How much do you practice jhum?	① Full-time ② Part-time ③ Not every year	
112	Why do you practice jhum?	① Subsistence ② Cultural reasons ③ …...………	
113	What is your annual household income from jhum?	₹ (INR)	
114	Which other farming practices do you apply? *(Multiple selections possible)*	① Agroforestry ② Beekeeping ③ Livestock rearing ④ Fishery ⑤ Horticulture plantation ⑥ Mushroom cultivation ⑦ Tea plantation ⑧ Wet Terrace Rice Cultivation ⑨ None ⑩…………………………………	
115	What is your annual household income from these practices?	₹ (INR)	
116	Which other sources of income do you have? *(Multiple selections possible)*	① Daily worker ② Job in government ③ Job in NGO ④ Job at private company ⑤ Land lease ⑥ Tourism ⑦ Transportation business ⑧ Small-scale business ⑨ Remittances from relatives ⑩ None ⑪ …………	
117	What is your annual household income from these sources?	₹ (INR)	
118	During the last 10 years, has your jhum area changed in size?	① Decreased ② No change ③ Increased	

119	Current length of fellow period:	Years	
120	Has the length of fallow period changed during the last 10 years?	① Decreased by……..…… years ② No change ③ Increased by ……..…… years	
121	How much land do you cultivate?	(acre)	
122	How much land do you own?	(acre)	
123	Please indicate size of cultivated area per land use.	Area (acre)	Units (plots)
	Jhum – 1st year		
	Jhum – 2nd year		
	Jhum – 3rd year		
	Permanent horticulture plantation		
	Wet Terrace Rice Cultivation		
	Other		
124	Please indicate land ownership of cultivated area per land use.		
	Jhum	① Own land ② Leased land ③ Village land ④ Community land	
	Horticulture plantation	① Own land ② Leased land ③ Village land ④ Community land	
	Wet Terrace Rice	① Own land ② Leased land ③ Village land ④ Community land	
	Other	① Own land ② Leased land ③ Village land ④ Community land	

No.	**Part-B: Access to credit, market and information**	
201	Do you have access to local credit sources?	① Yes ② No
202	Did you receive credit from a local credit institution?	① Yes ② No
203	From where did you receive financial assistance? *(Multiple selections possible)*	① Govt. sources ② NGOs ③ Private bank ④ Relative / friend ⑤ Co-operative ⑥ …………
204	Do you regularly sell your products?	① Yes ② No
205	Which products do you sell? *(Multiple selections possible)*	
	① Cereals ② Vegetables ③ Fruits ④ Spices ⑤ Honey ⑥ Mushrooms ⑦ Livestock ⑧ Fish ⑨ Timber ⑩ Non-timber forest products ⑪ …………………………	
206	Whom do you sell your products?	① End consumer ② Middleman ③ ………….
207	What is the distance to the nearest market?	km
208	What type of transportation do you use? *(Multiple selections possible)*	① Bicycle ② Motorcycle ③ Four-wheeler vehicle ④ Bullock cart ⑤ Horse ⑥ Hand-pulled cart ⑦ Bus ⑧ Other ⑨ None
209	Which media do you regularly use? *(Multiple selections possible)*	① TV ② Radio ③ Newspaper ④ Internet ⑤ Social media ⑥ None
210	Which devices do you regularly use? *(Multiple selections possible)*	① Landline phone ② Cell-phone ③ Smartphone ④ Computer / laptop ⑤ Tablet ⑥ None

211	From whom and how often do you receive information on agricultural practices?	
	Extension worker from government	① Weekly or more ② Monthly ③ Yearly ④ Only once ⑤ Never
	Extension worker from non-government sector	① Weekly or more ② Monthly ③ Yearly ④ Only once ⑤ Never
	Input dealer	① Weekly or more ② Monthly ③ Yearly ④ Only once ⑤ Never
212	Do you participate in a civil society organization? If yes, in which? *(Multiple selections possible)*	① No ② Self-help group ③ NGO ④ Village council ⑤ Farmers' club ⑥ Farmers' cooperative ⑦ Religious institution ⑧ ……………………

No.	**Part-C: Use of agricultural practices**	
301	Have you observed any changes in climate? If yes, which changes did you observe? *(Multiple selections possible)*	
	① No ② Increase in temperature ③ Decrease in temperature ④ Rainfall more intense ⑤ Rainfall more erratic ⑥ Increase in rainfall quantity ⑦ Decrease in rainfall quantity ⑧ Shifts in monsoon season ⑨ Increased frequency of droughts ⑩ Increased frequency of floods ⑪ …………………...	
302	Have you observed any other environmental changes? If yes, which changes did you observe? *(Multiple selections possible)*	
	① No ② Increase in erosion ③ Increase in landslides ④ Increase in crop diseases ⑤ Increase in pest attacks ⑥ Decrease in yields / soil fertility ⑦ Increase in forest fires ⑧ Change in plant phenology ⑨ Change in animal phenology ⑩ …………………………………………….…	
303	Which of these practices have you already applied? *(Multiple selections possible)*	
	① Contour bunds ② Cover crops ③ Mulching ④ Intercropping with legumes ⑤ Manure ⑥ Mineral / chemical fertilizer ⑦ Vermicompost ⑧ New crop varieties ⑨ Change in crop mix ⑩ Rainwater harvesting ⑪ Irrigation ⑫ Non-jhum farming practices ⑬ None	
304	Why have you implemented the practice(s)? Indicate level of agreement to the reasons below. *① = strongly disagree ② = quite disagree ③ = slightly disagree ④ = undecided ⑤ = slightly agree ⑥ = quite agree ⑦ = strongly agree*	
	To increase yields of food crops	① ② ③ ④ ⑤ ⑥ ⑦
	To increase family income	① ② ③ ④ ⑤ ⑥ ⑦
	To diversify livelihood	① ② ③ ④ ⑤ ⑥ ⑦
	To increase social status	① ② ③ ④ ⑤ ⑥ ⑦
	To sustain natural resources	① ② ③ ④ ⑤ ⑥ ⑦
	To reduce working hours	① ② ③ ④ ⑤ ⑥ ⑦
	………………………………………..	① ② ③ ④ ⑤ ⑥ ⑦

305	Did you decide to implement the practice(s) in response to a specific event or experience? If yes, please specify. *(Multiple selections possible)*	
	① No ② Weather-related crop losses in previous year(s) ③ Crop losses in previous year(s) due to pests / diseases ④ Crop losses in previous year(s) due to landslides ⑤ Increase in cereal prices ⑥ Increase in fruit / vegetable prices ⑦ Increase in cash crop prices ⑧ Change in policies ⑨ Migration of family member(s) ⑩ Participation in training ⑪ Adoption of practice(s) by neighboring farmer ⑫ ……..…………………..….	
306	How did you learn about the practice(s)? *(Multiple selections possible)*	
	① Extension worker ② Input dealer ③ Family member ④ Village head ⑤ Neighboring farmer ⑥ Person from other villages ⑦ Newspaper ⑧ Radio ⑨ TV ⑩ Internet ⑪ Social media ⑫ NA ⑬ …………………………..…………	
307	On which agricultural practices did you receive training? *(Multiple selections possible)*	
	① Contour bunds ② Cover crops ③ Mulching ④ Intercropping with legumes ⑤ Manure ⑥ Mineral / chemical fertilizer ⑦ Vermicompost ⑧ New crop varieties ⑨ Change in crop mix ⑩ Rainwater harvesting ⑪ Irrigation ⑫ Terracing / Wet Terrace Rice Cultivation ⑬ Agroforestry ⑭ Horticulture plantation ⑮ Livestock rearing ⑯ Fishery ⑰ None	
308	For those measures that you have not applied yet, please explain why. *(Multiple selections possible)* *① = NA ② = financial constraints ③ = lack of information ④ = labor shortage* *⑤ = lack of capacity ⑥ = poor access to resources / inputs ⑦ = cultural barriers* *⑧ = social conflicts ⑨ = electricity shortages ⑩ = unwillingness ⑪ = ……….…..*	
	Contour bunds	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Cover crops	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...……….….
	Mulching	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Intercropping with legumes	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Manure	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Mineral / chemical fertilizer	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Vermicompost	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	New crop varieties	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Change in crop mix	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Rainwater harvesting	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ ……….…….…...
	Irrigation	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Terracing / Wet Terrace Rice Cultivation	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Agroforestry	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ ……….…….…...
	Horticulture plantation	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Livestock rearing	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
	Fishery	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ …...…….…......
309	Are there any practices that you quit again after having tried them for at least one season? *(Multiple selections possible)*	
	① No ② Contour bunds ③ Cover crops ④ Mulching ⑤ Intercropping with legumes ⑥ Manure ⑦ Mineral / chemical fertilizer ⑧ Vermicompost ⑨ New crop varieties ⑩ Change in crop mix ⑪ Rainwater harvesting ⑫ Irrigation ⑬ Terracing / Wet Terrace Rice Cult. ⑭ Agroforestry ⑮ Horticulture plantation ⑯ Livestock rearing ⑰ Fishery	
310	Why did you stop using the practice(s)? *(Multiple selections possible)*	
	① Support ended ② Inputs were not available ③ Not profitable ④ Too work-intensive ⑤ Social conflicts ⑥ Changes in policy ⑦ Environmental changes: ………..… ⑧ ……………………………..	

311	Do you agree with the following statements? *① = strongly disagree ② = quite disagree ③ = slightly disagree ④ = undecided* *⑤ = slightly agree ⑥ = quite agree ⑦ = strongly agree*	
	We should not give up jhum, because it is part of our culture.	① ② ③ ④ ⑤ ⑥ ⑦
	I would continue practicing jhum, even if it was abolished by law.	① ② ③ ④ ⑤ ⑥ ⑦
	If it increased our family income, I would give up jhum for another job or cultivation practice.	① ② ③ ④ ⑤ ⑥ ⑦
	As long as I can produce enough food to feed my family, I would not change my cultivation practices.	① ② ③ ④ ⑤ ⑥ ⑦
	I prefer cultivation practices that are less work-intensive.	① ② ③ ④ ⑤ ⑥ ⑦
	I prefer cultivation practices that conserve natural resources.	① ② ③ ④ ⑤ ⑥ ⑦
	I prefer to apply the same cultivation practices as the majority of the village community.	① ② ③ ④ ⑤ ⑥ ⑦
	I see migration as a possible option for me in the future.	① ② ③ ④ ⑤ ⑥ ⑦
312	Phone number for follow-up questions (only if ok for farmer):	

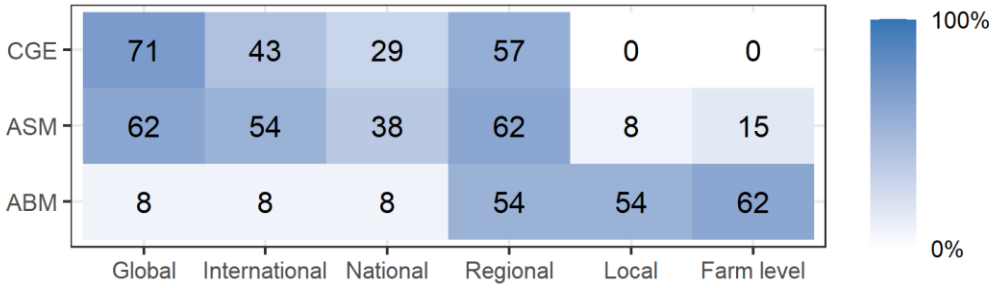
------------------------------------ **For interviewer only** -------------------------------------

401	Farmer was: ① Cooperative ② Interested ③ Uninterested ④ Off-hand in responding
402	Do you think you got realistic responses? ① Yes ② No
403	Please indicate GPS location of interview (in decimal degrees): ……..……E ; ………....N

***** Orange background color highlights the questions relevant for the analysis in article 2. In the original questionnaire, no background colors were shown. *****

C Supplementary material to article 3

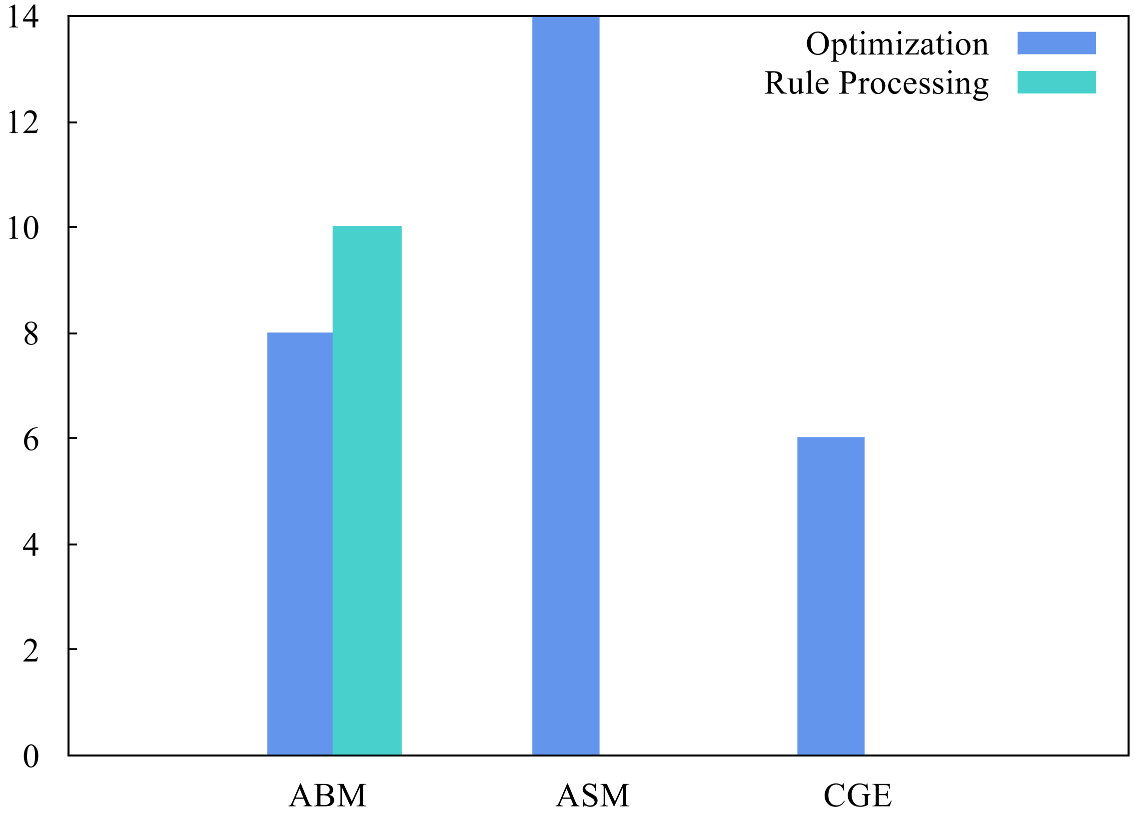
1 Extended results



	Global	International	National	Regional	Local	Farm level
CGE	71	43	29	57	0	0
ASM	62	54	38	62	8	15
ABM	8	8	8	54	54	62

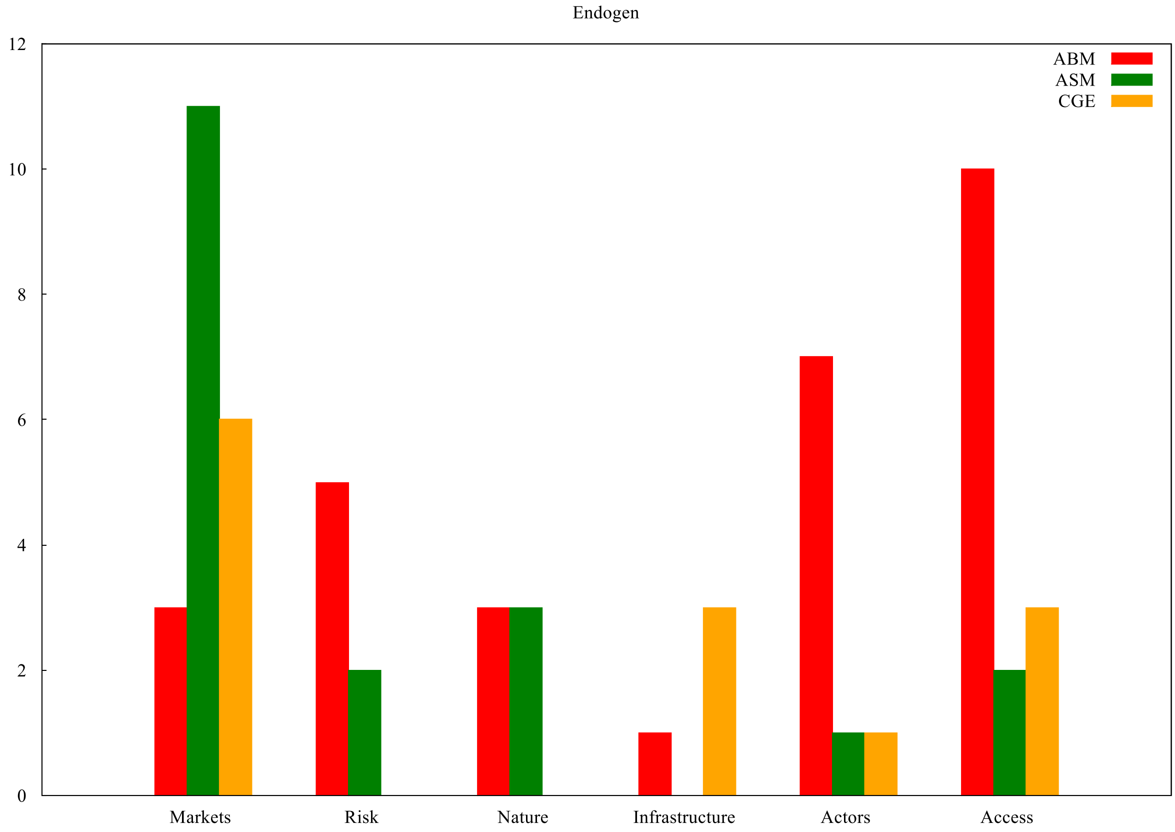
C. Figure 1: Spatial scope of land use models.

Values and color indicate the percentage of models which cover the scope displayed on the x-axis. Different model types are given on the y-axis.



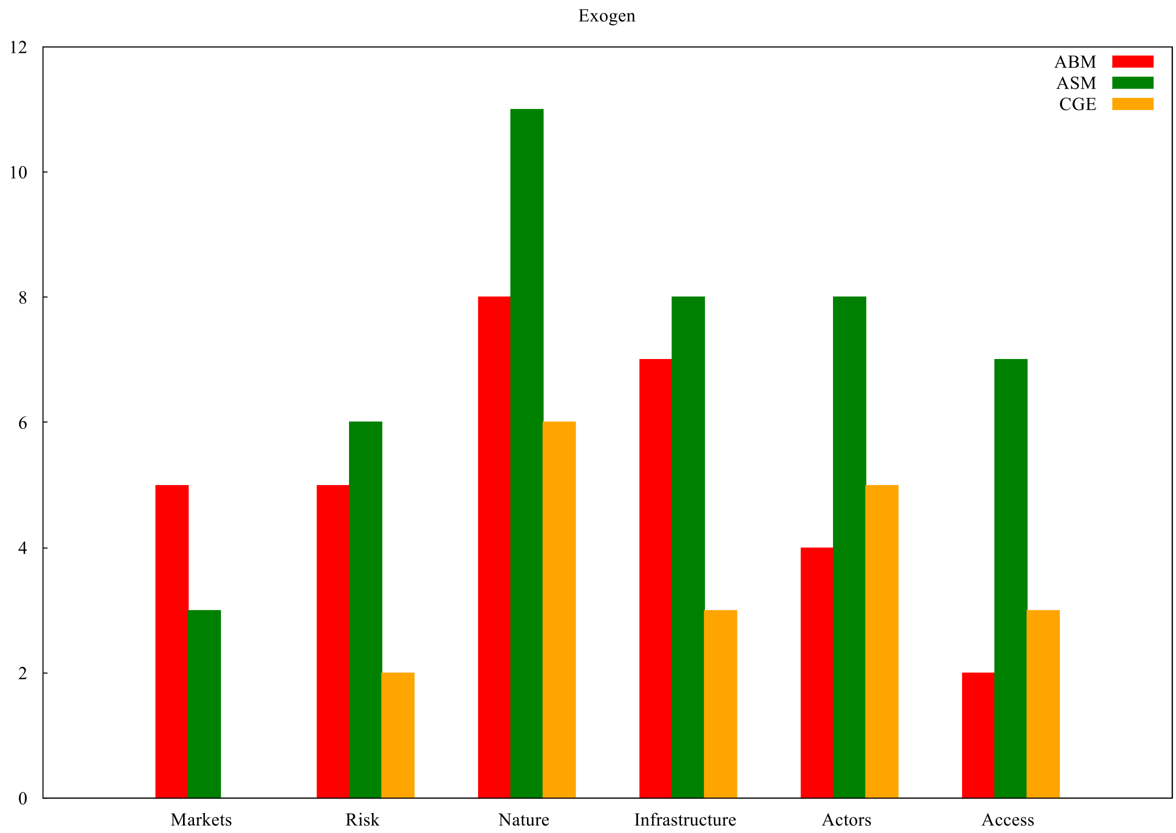
C. Figure 2: Driving mechanism of land use models.

Different model types are given on the x-axis. The y-axis shows number of models driven by optimization or rule processing.



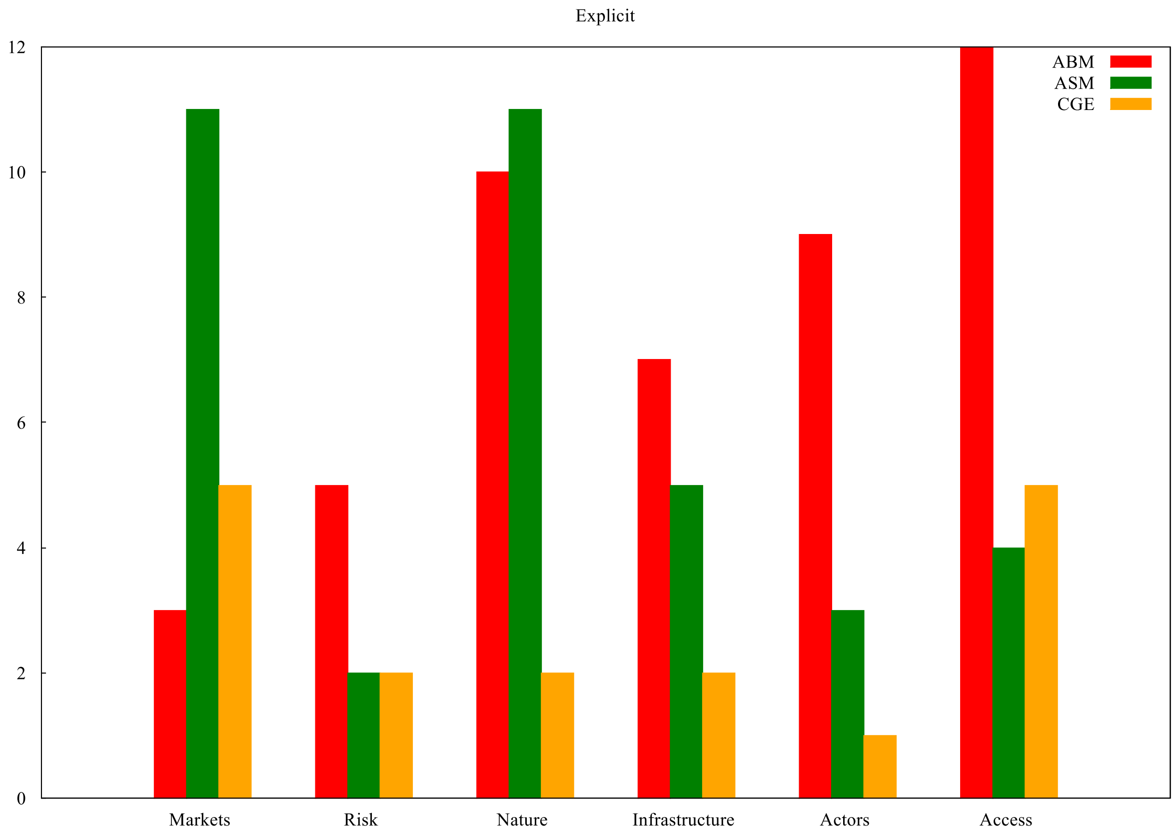
C. Figure 3: Endogenous representation of model factors.

Factors are displayed on the x-axis. The y-axis indicates the number of models per model type that represent the given factor endogenously. Colors indicate different model types.



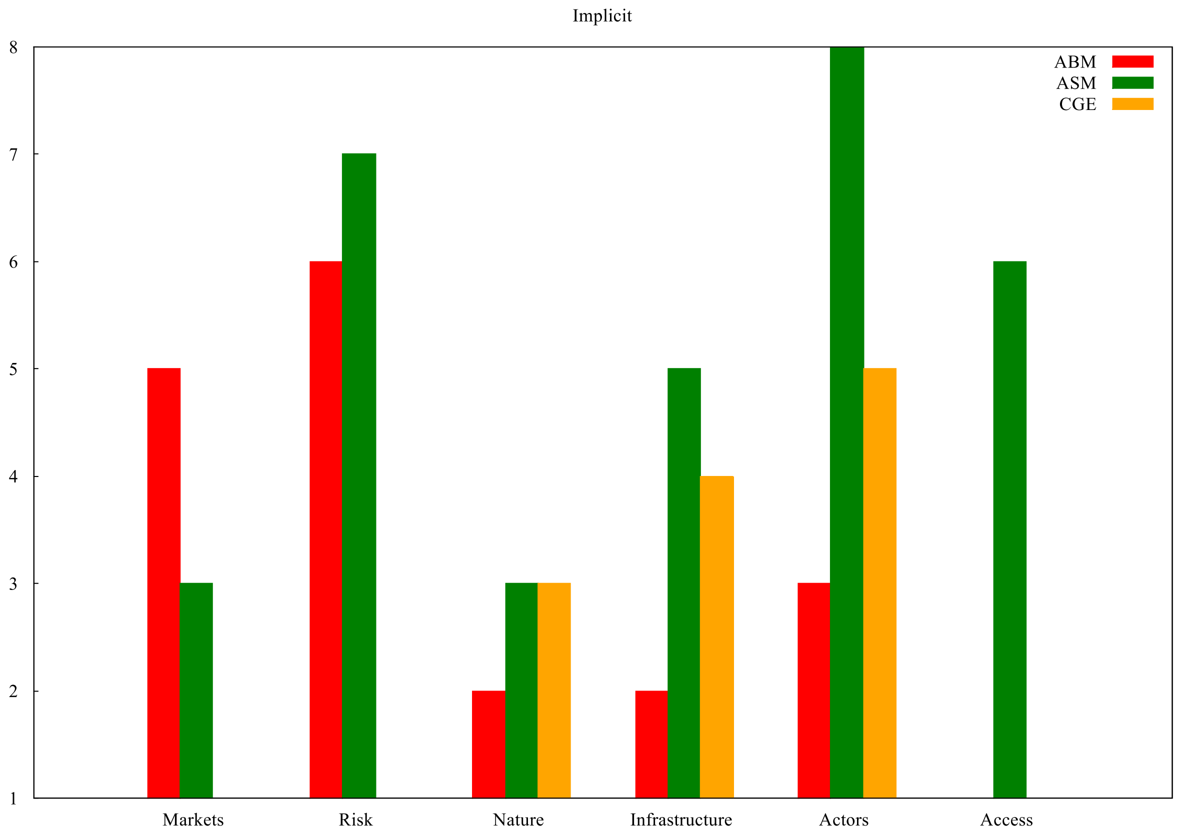
C. Figure 4: Exogenous representation of model factors.

Factors are displayed on the x-axis. The y-axis indicates the number of models per model type that represent the given factor exogenously. Colors indicate different model types.



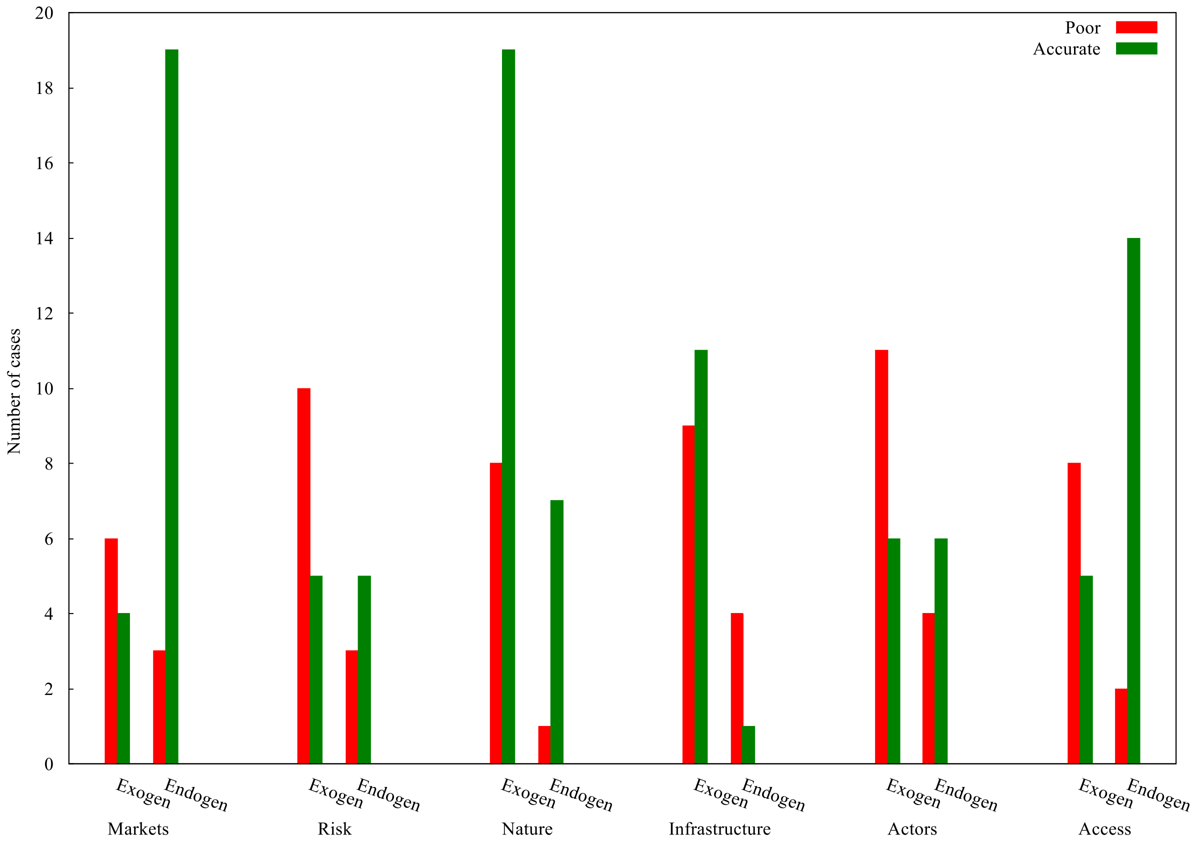
C. Figure 5: Explicit representation of model factors.

Factors are displayed on the x-axis. The y-axis indicates the number of models per model type that represent the given factor explicitly. Colors indicate different model types.



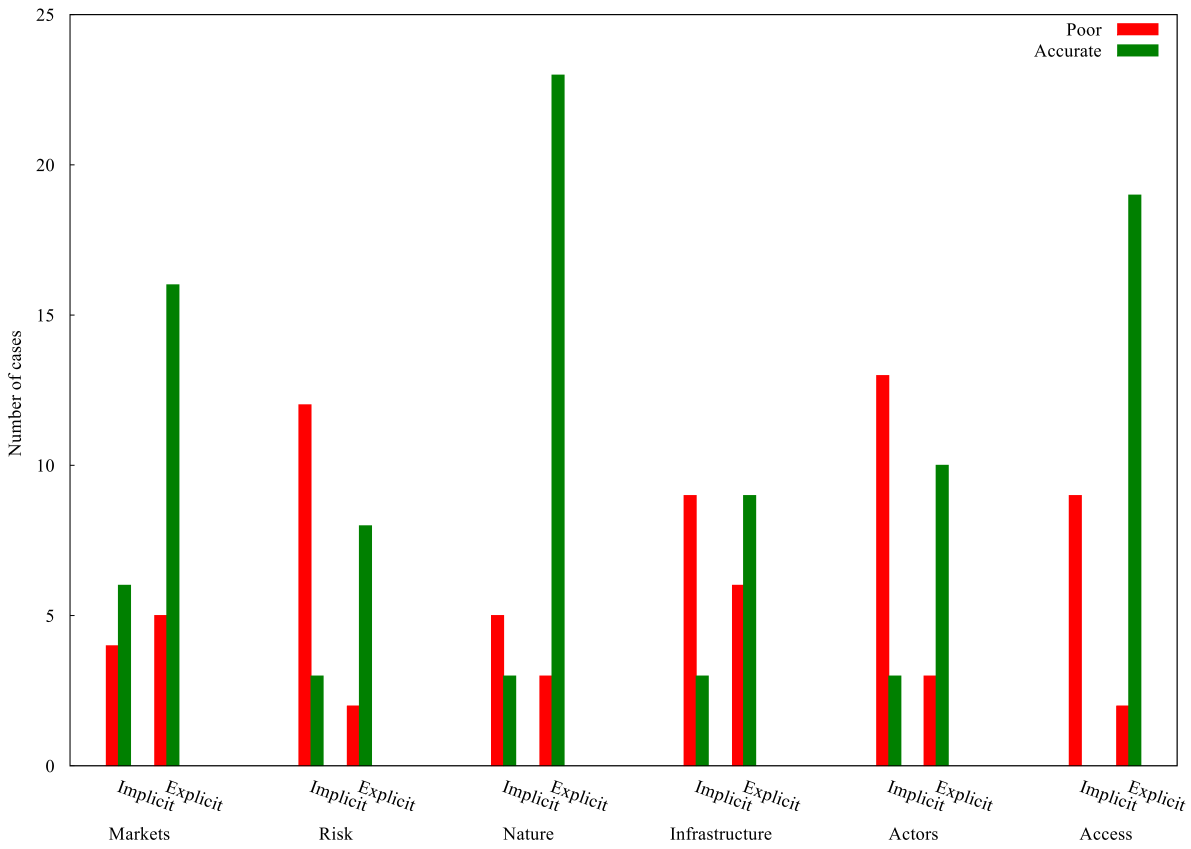
C. Figure 6: Implicit representation of model factors.

Factors are displayed on the x-axis. The y-axis indicates the number of models per model type that represent the given factor implicitly. Colors indicate different model types.



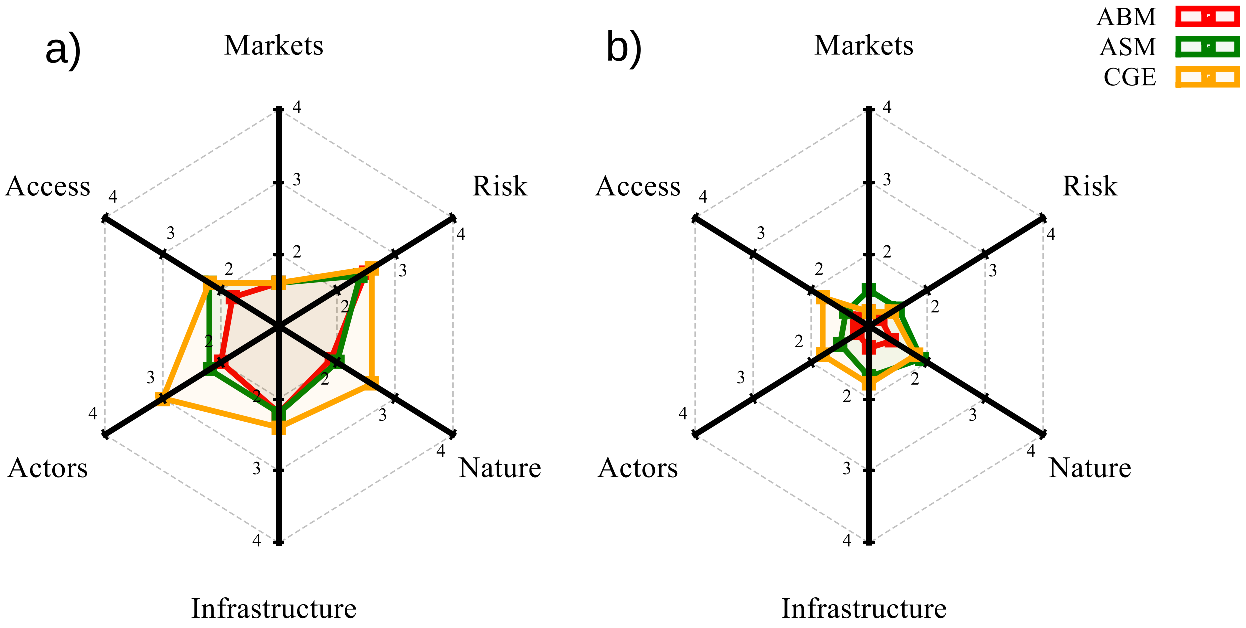
C. Figure 7: Perceived quality of representation of endogenous vs. exogeneous factors in land use models.

The y-axis indicates the number of models per factor, representation type (endogenous vs. exogeneous), and perceived quality of representation (poor vs. accurate). "Poor" includes "no representation" and "poor representation"; "accurate" includes "fairly accurate" and "very accurate" representation.



C. Figure 8: Perceived quality of representation of implicit vs. explicit factors in land use models.

The y-axis indicates the number of models per factor, representation type (implicit vs. explicit), and perceived quality of representation (poor vs. accurate). “Poor” includes “no representation” and “poor representation”; “accurate” includes “fairly accurate” and “very accurate” representation.



C. Figure 9: Relevance of data availability (a) and computing capacity (b) in limiting the implementation of factors in different land use models.

Factors include market equilibrium, risk aversion, natural environment, infrastructure, actor characteristics, and access to resources. Average values for CGE models (yellow), ASMs (green), and ABMs (red) are given. Results were generated from survey among land use modeling experts. Values refer to no limitation (1), a little limitation (2), a big limitation (3), and limitation makes implementation unfeasible (4).

2 Expert survey

Welcome!

How do scientific assessments of land use decisions integrate stakeholders, natural environment, and markets?

This survey is intended to answer this question. It should take about 15 minutes to complete.

We greatly appreciate your participation!

Part-A: Type of land use model		
1.1	Which model have you primarily worked with? **Please note: All following questions refer to this model!**	① Computable general equilibrium (CGE) model ② Partial equilibrium model (agricultural sector model) ③ Geographical model ④ Agent-based model ⑤ System dynamics ⑥ Cellular automata ⑦ Other: …………………....
1.2	<u>Optionally</u>: What is the name of the model?	……………………………..
1.3	How familiar are you with the model? 1 = not very familiar; 5 = very familiar	① ② ③ ④ ⑤
1.4	What is the typical spatial scope of this model? *(Multiple selections possible)*	① Global ② International ③ National ④ Regional ⑤ Local ⑥ Farm-level
1.5	Which mechanism or principle drives the model results? *(Multiple selections possible)*	① Economic surplus maximization ② Solving allocation problem ③ Rule-based simulation (may also include heuristics) ④ Causal feedbacks ⑤ Other: ………………
Part-B: Representation of different factors in model		
2.1	How well are the following factors represented in your model?	
	Market equilibrium (e.g., commodity prices)	① Not represented ② Poor ③ Fairly accurate ④ Very accurate ⑤ I don't know
	Risk aversion	① Not represented ② Poor ③ Fairly accurate ④ Very accurate ⑤ I don't know
	Natural environment (e.g., soil, terrain, climate)	① Not represented ② Poor ③ Fairly accurate ④ Very accurate ⑤ I don't know
	Infrastructure (e.g., roads, processing facilities)	① Not represented ② Poor ③ Fairly accurate ④ Very accurate ⑤ I don't know
	Actor characteristics (e.g., age, knowledge)	① Not represented ② Poor ③ Fairly accurate ④ Very accurate ⑤ I don't know
	Access to resources (e.g., labor, financial assets)	① Not represented ② Poor ③ Fairly accurate ④ Very accurate ⑤ I don't know

2.2	Are these factors represented endogenously or exogenously? Endogenous variables are those that are determined by the relationships within the model. Exogenous variables are data that influence the model simulation but are determined outside the model.	
	Market equilibrium (e.g., commodity prices)	① Endogeneous ② Exogeneous ③ NA
	Risk aversion	① Endogeneous ② Exogeneous ③ NA
	Natural environment (e.g., soil, terrain, climate)	① Endogeneous ② Exogeneous ③ NA
	Infrastructure (e.g., roads, processing facilities)	① Endogeneous ② Exogeneous ③ NA
	Actor characteristics (e.g., age, knowledge)	① Endogeneous ② Exogeneous ③ NA
	Access to resources (e.g., labor, financial assets)	① Endogeneous ② Exogeneous ③ NA
2.3	Are these factors represented explicitely or implicitely? Explicit factors are directly represented as model variables while implicit factors are only indirectly contained.	
	Market equilibrium (e.g., commodity prices)	① Explicit ② Implicit ③ NA
	Risk aversion	① Explicit ② Implicit ③ NA
	Natural environment (e.g., soil, terrain, climate)	① Explicit ② Implicit ③ NA
	Infrastructure (e.g., roads, processing facilities)	① Explicit ② Implicit ③ NA
	Actor characteristics (e.g., age, knowledge)	① Explicit ② Implicit ③ NA
	Access to resources (e.g., labor, financial assets)	① Explicit ② Implicit ③ NA
Part-C: Importance of factors and limitations		
3.1	How important do you consider the adequate representation of these factors in the model?	
	Market equilibrium (e.g., commodity prices)	① Not important ② Slightly important ③ Quite important ④ Very important
	Risk aversion	① Not important ② Slightly important ③ Quite important ④ Very important
	Natural environment (e.g., soil, terrain, climate)	① Not important ② Slightly important ③ Quite important ④ Very important
	Infrastructure (e.g., roads, processing facilities)	① Not important ② Slightly important ③ Quite important ④ Very important
	Actor characteristics (e.g., age, knowledge)	① Not important ② Slightly important ③ Quite important ④ Very important
	Access to resources (e.g., labor, financial assets)	① Not important ② Slightly important ③ Quite important ④ Very important

3.2	Is the availability of data a limiting factor for the integration of these factors in the model?	
	Market equilibrium (e.g., commodity prices)	① No ② Yes, a little ③ Yes, a lot ④ Yes, data limitations make the implementation infeasible
	Risk aversion	① No ② Yes, a little ③ Yes, a lot ④ Yes, data limitations make the implementation infeasible
	Natural environment (e.g., soil, terrain, climate)	① No ② Yes, a little ③ Yes, a lot ④ Yes, data limitations make the implementation infeasible
	Infrastructure (e.g., roads, processing facilities)	① No ② Yes, a little ③ Yes, a lot ④ Yes, data limitations make the implementation infeasible
	Actor characteristics (e.g., age, knowledge)	① No ② Yes, a little ③ Yes, a lot ④ Yes, data limitations make the implementation infeasible
	Access to resources (e.g., labor, financial assets)	① No ② Yes, a little ③ Yes, a lot ④ Yes, data limitations make the implementation infeasible
3.3	Is computing capacity a limiting factor for the integration of these factors in the model?	
	Market equilibrium (e.g., commodity prices)	① No ② Yes, a little ③ Yes, a lot ④ Yes, computing capacitiy make the implementation infeasible
	Risk aversion	① No ② Yes, a little ③ Yes, a lot ④ Yes, computing capacitiy make the implementation infeasible
	Natural environment (e.g., soil, terrain, climate)	① No ② Yes, a little ③ Yes, a lot ④ Yes, computing capacitiy make the implementation infeasible
	Infrastructure (e.g., roads, processing facilities)	① No ② Yes, a little ③ Yes, a lot ④ Yes, computing capacitiy make the implementation infeasible
	Actor characteristics (e.g., age, knowledge)	① No ② Yes, a little ③ Yes, a lot ④ Yes, computing capacitiy make the implementation infeasible
	Access to resources (e.g., labor, financial assets)	① No ② Yes, a little ③ Yes, a lot ④ Yes, computing capacitiy make the implementation infeasible
3.4	Optionally: What other aspects complicate or prevent the integration of these factors in the model?	
	Market equilibrium (e.g., commodity prices)	……………………………..
	Risk aversion	……………………………..
	Natural environment (e.g., soil, terrain, climate)	……………………………..
	Infrastructure (e.g., roads, processing facilities)	……………………………..
	Actor characteristics (e.g., age, knowledge)	……………………………..
	Access to resources (e.g., labor, financial assets)	……………………………..

Part-D: Options for future model development		
4.1	Optionally: If the following factors are not yet or only marginally represented in your model, do you have any idea how the representation could be improved? *Please briefly explain your idea.*	
	Market equilibrium (e.g., commodity prices)	……………………………..
	Risk aversion	……………………………..
	Natural environment (e.g., soil, terrain, climate)	……………………………..
	Infrastructure (e.g., roads, processing facilities)	……………………………..
	Actor characteristics (e.g., age, knowledge)	……………………………..
	Access to resources (e.g., labor, financial assets)	……………………………..

0.1	Would you like to recommend a publication of your model description, application or similar?	……………………………..
0.2	If you would like to receive the results of this survey, please leave your e-mail address below. *Your e-mail address will be treated confidentially and will only be used to inform you about the results of the study.*	……………………………..

***** This questionnaire shows the questions of the online survey which was distributed among land use modeling experts in December 2023 as part of study 3 of this thesis. As the original survey was set up in *LimeSurvey*, the presentation differs, but the questions and answer options are identical. *****

Eidesstattliche Versicherung

Declaration on Oath

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare upon oath that I have written the present dissertation independently and have not used further resources and aids than those stated.

Hamburg, den 30.01.2024 Lea Sophia Schröder