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Agroforestry adoption and adaptation: A farmer-centric case study in Son La, Vietnam

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Contents

Summary

Agroforestry is promoted in northwestern Vietnam for enhancing environmental sustainability and supporting livelihoods, particularly in resource-constrained settings. By integrating trees into agricultural landscapes, agroforestry fosters beneficial economic and ecological interactions, offering a broad array of ecosystem services and environmental benefits. Despite these advantages, the adoption of agroforestry has not reached the level necessary to fully realize the potential benefits. This stagnation can be attributed to inherent uncertainties in agroforestry planning and implementation, which may pose risks for farmers considering its adoption. While research and development programs have concentrated on identifying and mitigating barriers to initial uptake, the adoption of agroforestry is recognized as a non-linear and dynamic process where farmers adapt practices based on their perceptions and circumstances. Using northwestern Vietnam as a case study, this dissertation investigates the multifaceted processes of agroforestry adoption, focusing on the dynamics influencing decision-making among resource-poor farmers and the implications for policy and practice. The research comprises four main studies, organized in four main chapters:

- Chapter 2 integrates uncertainty into long-term benefit projections for agroforestry interventions by applying Decision Analysis and a probabilistic modeling approach. It reveals that while agroforestry offers promising long-term profitability, high upfront costs combined with uncertainties in discount rate, crop yields and prices significantly affect farmer preferences, often favoring annual monocultures over agroforestry. Addressing these knowledge gaps could enhance decision-making clarity for farmers and offer more targeted guidance for agencies promoting agroforestry adoption.

- Chapter 3 examines the factors influencing agroforestry adoption decisions using an expert-informed Bayesian Network approach. It reveals a complex network of interrelated drivers, with markets and incentives playing a particularly strong role in shaping adoption. Through adoption pathway analysis, the study also explores the diverse trajectories farmers follow, highlighting the adaptive and non-linear nature of the adoption process. The findings underscore the importance of coordinated, holistic strategies, along with sustained support mechanisms that are responsive to farmers' evolving needs and decision-making contexts.

- Chapter 4 employs Q methodology and systems thinking to explore farmers' perceptions and management decisions within the whole-farm context. The analysis reveals three dominant discourses among farmers regarding agroforestry and a shared mental model that reflects their systemic approaches to integrating agroforestry into farm operations. The study highlights the importance of understanding farmers' perspectives and reasoning processes deeply embedded in real-world contexts and offers insights that can inform innovation and policy development.

- Chapter 5 adopts a participatory approach to develop a farm typology that differentiates farmers based on farm structure and agroforestry adoption behaviors. The study identifies three distinct farm archetypes, each characterized by specific constraints, opportunities and support needs related to agroforestry adoption. By combining these archetype profiles with insights gathered from participatory workshops, the study facilitates a more targeted understanding of farmer diversity. The work supports the design of context-specific strategies to address the varying needs of different agroforestry archetypes.

This dissertation underscores the complexity of agroforestry adoption processes. Together, the four studies presented here offer strategic insights for designing support mechanisms that align with the dynamic and varied contexts of smallholder farmers in northwestern Vietnam.

Zusammenfassung

Agroforstwirtschaft wird im Nordwesten Vietnams gefördert, um die Landwirtschaft ökologisch nachhaltiger zu machen und die Lebensgrundlagen insbesondere in ressourcenarmen Gebieten zu verbessern. Durch die Integration von Bäumen in landwirtschaftlich genutzte Landschaften fördern die Agroforstsysteme vorteilhafte wirtschaftliche und ökologische Wechselwirkungen und bieten eine breite Palette von Ökosystemdienstleistungen und Nachhaltigkeitsvorteilen. Trotz dieser Vorteile hat die Akzeptanz von Agroforstsystemen noch nicht das Ausmaß erreicht, das notwendig wäre, um die potenziellen Vorteile voll auszuschöpfen. Diese Stagnation lässt sich auf inhärente Unsicherheiten bei der Planung und Umsetzung von Agroforstsystemen zurückführen, die für Landwirte, die ihre Einführung in Erwägung ziehen, ein Risiko darstellen können. Während sich Forschungs- und Entwicklungsprogramme auf die Identifizierung und Abschwächung von Hindernissen für die anfängliche Einführung konzentriert haben, wird die Umstellung auf Agroforstwirtschaft zunehmend als nichtlinearer, dynamischer Prozess anerkannt, bei dem die Landwirte ihre Praktiken basierend auf ihren Wahrnehmungen und Umständen anpassen. Anhand der Fallstudie Nordwestvietnams werden in dieser Dissertation die vielschichtigen Prozesse der Einführung von Agroforstwirtschaft untersucht. Der Schwerpunkt liegt dabei auf den Dynamiken, die die Entscheidungsfindung von ressourcenarmen Landwirten beeinflussen, sowie auf deren Implikationen für Politik und Praxis. Die Arbeit umfasst vier Studien, die in Form von vier Kapitel präsentiert werden:

- Kapitel 2 behandelt die Integration von Unsicherheiten in Prognosen des langfristigen Nutzens agroforstlicher Maßnahmen. Dafür kommen Entscheidungsanalyse und probabilistische Modellierung zum Einsatz. Die Ergebnisse zeigen, dass die Agroforstwirtschaft zwar eine vielversprechende langfristige Rentabilität bietet, jedoch führen hohe Vorlaufkosten sowie Unsicherheiten bei Diskontsatz, Ernteerträgen und Preisen dazu, dass viele Landwirte einjährige Monokulturen der Agroforstwirtschaft vorziehen. Das Schließen dieser Wissenslücken könnte die Entscheidungsfindung der Landwirte erleichtern und den Behörden, die die Einführung der Agroforstwirtschaft fördern, eine gezieltere Orientierung bieten.

- Kapitel 3 untersucht mithilfe eines von Experten informierten Bayes'schen Netzwerkes die Faktoren, die die Entscheidung für oder gegen Agroforstwirtschaft beeinflussen. Es zeigt sich ein komplexes Netzwerk von miteinander verbundenen Faktoren, wobei

Märkte und Anreize eine zentrale Rolle spielen. Anhand einer Analyse der Adoptionspfade untersucht die Studie auch die verschiedenen Wege, die die Landwirte einschlagen, und verdeutlicht die adaptive und nichtlineare Natur des Adoptionsprozesses. Die Ergebnisse unterstreichen die Bedeutung koordinierter, ganzheitlicher Strategien sowie nachhaltiger Unterstützungsmechanismen, die flexibel auf Bedürfnisse und Entscheidungskontexte der Landwirte eingehen.

- Kapitel 4 nutzt die Q-Methodik und Systems Thinking, um die Wahrnehmungen und Managemententscheidungen der Landwirte im Kontext des gesamten Betriebs zu untersuchen. Die Analyse zeigt drei dominante Diskurse der Landwirte über die Agroforstwirtschaft und ein gemeinsames mentales Modell, das ihre systemischen Ansätze zur Integration von Agroforstsystemen in den Betrieb widerspiegelt. Die Studie unterstreicht, wie wichtig es ist, die Perspektiven und Denkprozesse der Landwirte zu verstehen, die tief in reale Kontexte eingebettet sind, und bietet Erkenntnisse, die in die Entwicklung von Innovationen und rechtlichen Rahmenbedingungen einfließen können.
- Kapitel 5 verfolgt einen partizipativen Ansatz zur Entwicklung einer Betriebstypologie, die Landwirte nach Betriebsstruktur und Verhalten bei der Einführung der Agroforstwirtschaft unterscheidet. Die Studie identifiziert drei Archetypen von Landwirtschaftsbetrieben, die jeweils spezifische Einschränkungen, Potenziale und Unterstützungsbedarfe bei der Einführung von Agroforstwirtschaft aufweisen. Durch die Kombination dieser Archetyp-Profile mit Erkenntnissen aus partizipativen Workshops ermöglicht die Studie ein gezielteres Verständnis der Vielfalt der Landwirte. Die Arbeit unterstützt die Entwicklung kontextspezifischer Strategien, um auf die unterschiedlichen Bedürfnisse der verschiedenen Agroforst-Archetypen einzugehen.

Diese Dissertation unterstreicht die Komplexität von Agroforst-Transformationsprozessen. Zusammengenommen bieten die vier hier vorgestellten Studien strategische Erkenntnisse für die Gestaltung von Unterstützungsmechanismen, die auf die dynamischen und vielfältigen Kontexte von Kleinbauern im Nordwesten Vietnams abgestimmt sind.

Chapter 1. General introduction

1. Background

Agroforestry, which integrates trees into agricultural landscapes, offers a viable option to meet ecological and socio-economic goals (Atangana et al. 2014). While the definition of agroforestry varies, a common thread across its diverse forms is the intentional inclusion of trees alongside crops, animals or both within the same management unit, providing multiple products or benefits (Nair et al. 2021a). Agroforestry systems are typically classified based on their structural composition, such as agrisilvicultural (crops and trees), silvopastoral (pasture/animal and trees) and agrosilvopastoral (crops, pasture/animal and trees). They can also be grouped by system function (role or output), ecological context (factors like rainfall and elevation) or socio-economic settings (subsistence or commercial) (Nair et al. 2021b). Agroforestry is increasingly recognized for the beneficial interactions it fosters between its components. These synergistic interactions make it a multifunctional land use practice that delivers a wide array of ecosystem services and environmental benefits. Agroforestry enhances carbon sequestration and soil fertility (Kim et al. 2016; Octavia et al. 2023), reduces erosion (Jinger et al. 2022; Do et al. 2023), conserves biodiversity (Udawatta et al. 2019; Staton et al. 2022), boosts agronomic productivity (Jinger et al. 2022; Zeratsion et al. 2024) and improves water quality (Pavlidis 2017). These prospects have spurred the promotion of agroforestry as an alternative farming practice worldwide (Mbow et al. 2014; Luedeling et al. 2014; Hoang et al. 2017). However, despite its promise, agroforestry has not been widely adopted, often constrained by the complexity of planning, implementation and long-term management. Understanding both the potential and challenges of agroforestry requires greater attention to local development pathways, the uncertainty inherent in decision-making and the dynamic, context-specific nature of farmer adoption.

1.1. Agroforestry in Vietnam and its development in northwestern regions

In Vietnam, although the term ‘agroforestry’ (in Vietnamese: Nông Lâm Kết Hợp) may not be widely recognized among farmers, the practice has increasingly gained traction since the 1960s through two primary landscape agroforestry settings (Simelton et al. 2017). The first, a family-managed system, integrates crop production (**V**ườn - homegardens), aquaculture (**A**o - fishpond) and livestock production (**C**huồng - livestock pen), collectively known as VAC (**V**ườn – **A**o – **C**huồng) farming system. During the 1980s, the VAC system was considered the ideal model for subsistence farming across various agroecological conditions, including irrigated lowlands, rainfed uplands and peri-urban areas, due to its efficient allocation of resources among system components (Thanh Luu 2001). The garden is irrigated by pond water and produces by-products that feed both livestock and fish (Thanh Luu 2001). The fishpond, a source of fish, livestock feed and irrigation water, receives daily inputs of domestic and kitchen waste to nourish fish and fertilize pond flora. Livestock pens supply manure, which together with pond silt enriches the garden soil. The VAC setup forms a closed-loop cycle of resource recycling that optimizes agricultural production throughout the system. The VAC system was adapted to upland regions to include forestry component (**R**ừng-forest), known as VACR (**V**ườn – **A**o – **C**huồng – **R**ừng) (Simelton et al. 2017). In this setting, forest plots are incorporated to provide multiple ecological and economic benefits, including timber, fuelwood, non-timber forest products, and soil conservation services.

In addition to these landscape-level systems, field-level agroforestry practices have long contributed to rural livelihoods. Traditional homegardens, where subsistence households cultivated a mix of fruit trees, timber trees, medicinal plants and staple crops, are considered one of the earliest forms of field-level agroforestry in Vietnam (Nguyen and Catacutan 2012). These systems maximize species diversity for dietary, medicinal and cultural uses, and have remained a key component of household subsistence across Vietnam (Trinh et al. 2003). Introduced as part of government reforestation efforts in the 1990s, taungya systems represent another form of field-level agroforestry (Nguyen and Catacutan 2012). In these systems, annual crops such as upland rice (*Oryza sativa* L.), maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz) are often integrated with the plantation of trees such as timber trees or rubber (*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.). In these systems, annual crops are planted in the underutilized space between young tree seedlings until the canopy closes (Nair et al. 2021c). This system provides an interim source of income for farmers until the trees mature enough to generate yields and subsequent economic returns. More recently, agroforestry development has shifted toward market-oriented intercropping systems that combine staple crops with fruit trees or integrate perennial cash crops such as tea and coffee with shade trees. Mixed fruit tree systems are also gaining popularity, reflecting a broader trend toward commercial diversification and value-added production (Hoang et al. 2013).

Northwestern Vietnam, which borders Laos and China, is predominantly highland areas with elevations ranging from 300 m to over 1000 m above sea level (Hoang et al. 2017). The region is characterized by its remote locations, significant ethnic minority population and high poverty rate (Simelton et al. 2017). Traditionally, local ethnic minorities have practiced shifting cultivation of staple crops such as upland rice, maize and cassava on steep slopes, serving as the primary source of local livelihoods for decades (Catacutan et al. 2017). Increased population and arable land scarcity have led to expanding sedentary agriculture, with long cultivation and short fallow periods (Catacutan et al. 2017). Economic growth and urbanization during the 1990s led to an increased demand for meat, eggs and dairy products (Keil et al. 2008). This change triggered a maize production boom nationwide between 1990 and 2000, during which the production almost quadrupled in northwestern regions (Keil et al. 2008). The adoption of improved hybrid maize varieties and the application of chemical fertilizers presented attractive income opportunities for smallholder farmers (Keil et al. 2009; Dang and Nguyen 2020). However, these agricultural practices, characterized by high cropping frequency and low ground coverage, have led to soil erosion and degradation, resulting in the depletion of soil fertility, particularly soil organic matter, nitrogen and available phosphorus (Wezel et al. 2002). The loss of these crucial soil nutrients resulted in a significant reduction in maize and cassava yields (Wezel et al. 2002).

In response to these challenges, local authorities in several northwestern provinces, supported by international organizations such as World Agroforestry (CIFOR-ICRAF), have actively promoted field-level agroforestry (La 2019). CIFOR-ICRAF initiated a two-phase agroforestry project, funded by the Australian Centre for International Agricultural Research (ACIAR) and the CGIAR Research Program on Forests, Trees and Agroforestry (La 2019, 2022). The first phase, “Agroforestry for livelihoods of smallholder farmers in Northwest Vietnam” (AFLi) ran from 2011 to 2016. It was succeeded by “Developing and promoting market-based agroforestry and forest rehabilitation options for Northwest Vietnam” (AFLi2), which operated from 2017 to 2021. Within the project’s framework, plot-level experiments of various agroforestry settings were established and have been studied extensively. These trials specifically aimed to evaluate multiple agroforestry configurations combining timber, fruit, industrial trees, forage grass, and annual crops. These studies have generated solid scientific findings on agronomic and ecological performance of agroforestry, such as effects on crop yield, soil erosion and light use efficiency (Do et al. 2020b, 2023; Pham et al. 2024) However, assessments of the long-term economic viability of these systems, which are critical for supporting farmers' decision-making, are still lacking. In addition, during its second phase AFLi2, the project also established landscape agroforestry models over 50 hectares to demonstrate landscape-level agroforestry. Farmers participating in the project received tree seedlings, fertilizers and initial training to establish agroforestry systems on their land. There has been little follow-up since the project concluded in 2021, leading to limited understanding of farmers' adaptive decision-making process in planning and implementation of agroforestry.

These gaps, particularly the lack of long-term economic insights and the limited understanding of farmers' decision-making processes, highlight the need for deeper investigation into risks and uncertainties in the long-term projection of agroforestry benefits, the adoption dynamics and the viability of agroforestry systems.

1.2. Uncertainty in planning for agroforestry adoption

Agricultural production is inherently uncertain due to a wide range of uncontrollable biophysical and socio-economic factors. In open farming environments, climatic variability drives significant spatial and temporal variability in production outcomes (Hardaker et al. 2004; Selvaraju et al. 2011). Variability also stems from differences in farmers' management practices, shaped by their diverse levels of knowledge and experiences. Additionally, in many developing countries, additional sources of uncertainty arise from complex policy environments, such as land tenure regulation or policies on farming operations and volatile market conditions (Dillon and Heady 1960; Hardaker et al. 2004). In agroforestry, the complexity of system design and extended planning horizons amplify existing uncertainties, heightening the risks encountered by practitioners. As a result, the benefits of agroforestry systems are less predictable than those of monocultures (Do et al. 2020a). Moreover, agroforestry trials conducted under CIFOR-ICRAF's project framework may not fully capture risks that arise outside the typical 5- to 7-year experimental period. Uncertainty is often underrepresented in these partially controlled settings, limiting their relevance to real-world decision-making. This gap highlights the need for comprehensive approaches that explicitly incorporate critical sources of uncertainty, enabling decisions to be made without perfect information (Luedeling and Shepherd 2016).

Decision analysis is an interdisciplinary approach that includes a range of methods designed to support decision-making under uncertainty (Anderson and Hardaker 1972; Hardaker and Lien 2010). It has been adapted for use in agricultural development contexts, where decisions often need to be made quickly and with limited information (Luedeling and Shepherd 2016). The approach typically involves a participatory process in which stakeholders with diverse perspectives collaboratively identify and assess the key aspects of proposed interventions (Whitney et al. 2018). Unlike traditional assessments that may rely on assumptions of certainty, decision analysis enables a more realistic exploration of complex, real-world implications. It allows for the integration of diverse information sources, including expert judgment, empirical data, and documented knowledge, into a coherent analytical model to predict a range of plausible outcomes. This capacity supports more nuanced and informed decision-making in agroforestry planning (Do et al. 2020a) and makes advanced analysis tools accessible to both farmers and policy analysts. Such approaches are essential for managing agricultural risks and uncertainties in situations where complete information is rarely available (Luedeling and Shepherd 2016).

Building on this foundation, the first part of this dissertation applies a decision analysis procedure to evaluate the economic performance of the agroforestry systems promoted by CIFOR-ICRAF in northwestern Vietnam. The participatory process in decision analysis created space for both farmers and researchers to reflect on relevant risks and uncertainties associated with agroforestry implementation. By incorporating these uncertainties into the cost-benefit assessments, the analysis generated a range of plausible outcomes rather than a single deterministic result. This approach provides a more nuanced understanding of potential decision outcomes, addressing the limitation of traditional cost-benefit analyses, which often overlooks the variability and unpredictability inherent in farming systems.

1.3. Towards a context-specific and dynamic approach in studying agroforestry adoption

Agricultural innovations have traditionally been perceived as standardized technical packages disseminated linearly from researchers to farmers (Glover et al. 2016; Allan et al. 2022). In this view, adoption, often reduced to a binary variable of "adopted" and "not adopted", has served as the primary success metric in agricultural extension and development efforts (Glover et al. 2016; Allan et al. 2022). This framing has been increasingly criticized for its lack of sensitivity to the complexities and uncertainties of farming systems (Allan et al. 2022). An overly simplistic view of adoption can fail to capture the diversity in farmers' responses and overlook the dynamic, iterative and context-specific nature of how new practices are integrated.

Adoption is not a one-time event but a nonlinear, evolving process that unfolds in multiple stages (Pannell et al. 2006). These stages typically begin with becoming aware of new practices, trialing, making initial adoption decisions, reviewing and adjusting the practice and eventually considering long-term integration or dis-adoption (Pannell et al. 2006; Montes de Oca Munguia et al. 2021). Despite this dynamic, many existing studies on agroforestry adoption continue to rely on simplified models that treat adoption as a fixed outcome and often focus on understanding influencing factors of the binary decision (Dhakal and Rai 2020; Syano et al. 2022; Muthee et al. 2024). Sociodemographic factors such as age, gender, economic status, educational level, household size and land ownership, as well as, psychological and other contextual socio-economic factors are frequently investigated as influencing farmers' decisions (Mercer 2004; Jha et al. 2021). In most cases, these factors are analyzed separately using common variance-based methods, resulting in fragmented and sometimes contradictory insights (Mercer 2004; Rizzo et al. 2023). The inconsistency may suggest a context-dependent nature of the adoption process (Githinji et al. 2023) or may reveal the limitations of variance-based approaches to capture the complex interplay of variables or the underlying mechanisms shaping decision-making (Rizzo et al. 2023). To move forward, there is a need to adopt more configurational approaches that involve analyzing how different combinations of variables interact to influence outcomes (Rizzo et al. 2023). Such approaches offer more nuanced understanding by acknowledging that multiple pathways can lead to similar outcomes (Furnari et al. 2021). These approaches can also accommodate nonlinear relationships, where influential factors in one context may have little or even opposing effects in another (Fiss et al. 2013). In this way, they offer a holistic and flexible lens, capable of accounting for the complexity of real-life decision-making.

Moreover, the adoption of agroforestry is closely tied to dynamic on-farm adaptation that involves complex decision-making mechanisms (Do et al. 2024). Farmers typically experiment, modify and refine to align the new practices with their specific biophysical conditions, farming structures, market dynamics and changes in social contexts, rather than adopting the introduced practices as they are (Pannell et al. 2006; Montes de Oca Munguia et al. 2021). This ongoing process of learning and adjustments is essential for a sustainable transition, ensuring that new practices are highly compatible and yield favorable outcomes (Stevenson et al. 2019; Périnelle et al. 2024). However, such adaptation is frequently overlooked in research and development programs which tend to prioritize initial adoption rates. This oversight is particularly concerning given that farmers often possess deep knowledge of local resources and play a crucial role in sustaining socio-ecological systems in the face of change and disturbance (Šūmane et al. 2018). Their perspectives can offer valuable, context-specific insights into the factors that enable or hinder transitions and inform how systems can be better designed and managed to suit local conditions (Stuiver et al. 2004). However, such local knowledge remains underutilized in innovation processes, which are still largely shaped by dominant conventional scientific paradigms (Caron et al. 2014).

Recognizing that farmers are active experimenters and adaptors of new farming practices calls for research and development projects to engage more deeply with agendas that facilitate experimentation and learning, rather than merely promoting initial adoption (Périnelle et al. 2024). To effectively support farmers in transitioning to agroforestry, research and development projects should move beyond developing generic, widely applicable solutions (Coe et al. 2014). There should be greater emphasis on understanding farmers' perspectives, the heterogeneity among them and their implications for agricultural practices, resource management and livelihood strategies (Coe et al. 2014; Glover et al. 2019). Participatory and on-farm experimentation approaches have gained traction as promising ways to foster context-specific learning, encourage adaptation and better match innovations to farmers' realities (Glover et al. 2019; Lacoste et al. 2021; Périnelle et al. 2024). These considerations form the conceptual foundation for the second part of this dissertation, which seeks to investigate how farmers adopt and adapt agroforestry systems in their farm settings.

2. Research objectives

Farmers often face challenges due to the inherent risks and uncertainties associated with the complexity and long-term nature of agroforestry practices. To support decision-making at the initial stage of adoption, **the first objective** was to assess the economic performance of seven agroforestry designs that were tested and promoted by CIFOR-ICRAF across three northwestern provinces of Son La, Dien Bien and Yen Bai. These agroforestry systems include various combinations of timber trees, fruits trees, nut trees, coffee, annual crops and fodder crops.

As farmers move through the adoption process, they perceive, learn and adapt the practices to suit their specific circumstances. To gain deeper insight into this dynamic and iterative process, Son La was selected as a case study to address three additional objectives. In Son La, one of the seven agroforestry designs, featuring the integration of fruit trees and fodder grasses into traditional maize monoculture, was specifically recommended for farmers' implementation. Son La was selected based on the strong availability and engagement of farmers, as well as the continued collaboration with local stakeholders following the conclusion of a previous project in the region. These conditions were critical for facilitating the participatory research activities required for this study. While all three provinces are relevant to agroforestry development, Son La offered the most conducive environment for an in-depth investigation of adoption processes. Building on these advantages**, the second objective** of this study focused on identifying the factors that drive the adoption of agroforestry, and the pathways farmers take in adopting these practices. **The third objective** sought to explore the farm-level impacts of agroforestry from the farmers' perspectives, including the mental models that shape these perspectives. **The final objective** aimed to bridge the gap between understanding the heterogeneity among farmers and targeting interventions to support diverse pathways of agroforestry adoption.

Through a comprehensive exploration of agroforestry adoption and adaptation, this dissertation aims to fill the gaps in assessing risks and uncertainties in agroforestry planning, understanding important mechanisms in farmers' decision-making and accounting for diverse experiences. The work sets the stage for discussing farmer-centric strategies and potential interventions that policymakers and development organizations might consider in their future development agendas.

3. Overview of thematic chapters

This dissertation consists of four thematic chapters (chapter 2 – chapter 5) which correspond to the four research objectives.

Chapter 2. Decision Analysis of agroforestry reveals adoption risks for resource-poor farmers in Northwest Vietnam. In this study, we aimed to project long-term benefits of the agroforestry designs, experimented and promoted under the CIFOR-ICRAF project in three northwestern provinces, integrating risk and uncertainty. To develop such cost-benefit projections, my co-authors and I used the decision analysis procedure and a probabilistic modeling approach. Inputs for these models were derived from various sources including farmer interviews, focus group discussions, expert consultation and participatory modeling sessions with CIFOR-ICRAF's technical experts. The outcomes of the resulting model projections provide plausible ranges of Net Present Values for seven agroforestry settings, comparing them to that of maize monoculture. A post-hoc analysis identified important uncertain factors that influence the outcomes of choosing agroforestry over maize monoculture.

Chapter 3. Markets and incentives strongly drive agroforestry adoption: insights from ethnic minority smallholders in Son La, Vietnam. In this study, we examined factors and underlying mechanisms driving farmers' decisions and their pathways to adopt agroforestry. A Bayesian Network model was used to analyze joint effects of socio-economic, household and practice-specific factors that shape farmers' attitudes and intentions throughout the adoption process, from initial decision-making to sustained use. The Bayesian Network was developed using both qualitative and quantitative inputs from farmer interviews and workshops involving domain experts and farmers. Additionally, through an adoption pathway analysis of the interviewed farmers, this study explored the diverse trajectories farmers follow to integrate agroforestry into their systems. The development of Bayesian Network revealed a complex web of conditionally dependent factors that help enhance our understanding of farmer's decision making. The adoption pathway analysis categorized farmers based on diversity pathways they follow.

Chapter 4. Adapting agroforestry to upland farming systems: narratives from smallholder farmers in Northwest Vietnam. In this study, we investigated the perceptions and underlying mechanisms in decision-making processes of agroforestry farmers considering the whole-farm context, which aimed to uncover farmers' strategies for effectively managing adoption challenges. The Q methodology, a semi-quantitative approach used in studying human subjectivity, was used to examine prevalent perspectives within the farming community regarding the farm-level impacts of agroforestry. Systems thinking was applied to gain a comprehensive understanding of farmers' adaptive decision-making processes. By integrating these approaches, this study elucidated the dynamics shaping farmers' perceptions and their adaptive management of the adoption process.

Chapter 5. Agroforestry adaptation by farm households in northwestern Vietnam: who needs what and implications for practice and policy. In this study, we sought to address the farm-level and structural barriers that hinder the adoption of agroforestry. We looked for ways to tailor interventions to the diverse needs of farmers, understanding that farmers are a heterogenous group. We developed a farm typology to understand the diversity among agroforestry farmers using a participatory approach and archetypal analysis. This methodological combination facilitates the identification of agroforestry archetypes, characterized by unique resource constraints and farming strategies. These insights are crucial for tailoring interventions to meet the diverse needs of the farmers, thereby promoting more sustainable and effective agroforestry practices.

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Chapter 2. Decision Analysis of agroforestry options reveals adoption risks for resource-poor farmers

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Abstract

Agroforestry interventions have the potential to benefit the livelihoods of farmers and communities worldwide. However, given high system complexity, the long-term benefits of agroforestry are difficult to anticipate. This study aimed to integrate uncertainty into long-term performance projections for agroforestry interventions in the highlands of northwestern Vietnam. We applied Decision Analysis and probabilistic modeling approaches to produce economic ex-ante assessments for seven agroforestry options (intercropping of maize, forage grass or coffee with tea, nut, fruit and timber trees) promoted in the region. Our results indicate that farmers likely prefer annual monocultures due to the relatively early incomes and short time-lag on returns. However, results also show that annual profits from monocrops can be expected to decrease over time, due mainly to unsustainable soil use. Agroforestry systems, on the other hand, return substantial profits in the long term, but they also incur high establishment and maintenance costs and can generate net losses in the first few years. Initial financial incentives to compensate for these losses may help in promoting agroforestry adoption in the region. Uncertainties related to farmers' time preference, crop yields and crop prices appeared to have the greatest influence on whether monocropping or agroforestry emerged as the preferable option. Narrowing these key knowledge gaps may offer additional clarity on farmers' optimal course of action and provide guidance for agencies promoting agroforestry interventions in Vietnam and elsewhere. Our model produced a set of plausible ranges for net present values and highlighted critical variables, more clarity on which would support decision-making under uncertainty. Our innovative research approach proved effective in providing forecasts of uncertain outcomes and can be useful for informing similar development interventions in other contexts.

1. Introduction

Agroforestry has the potential to reduce poverty and improve food security while at the same time addressing land degradation and supporting delivery of other ecosystem services (Kuyah et al. 2019). These prospects have led to the promotion of agroforestry as a sustainable land use practice in various regions (Mbow et al. 2014; Luedeling et al. 2014; Hoang et al. 2017). However, adoption rates are still low in many regions, indicating that such systems do not always seem desirable from the farmer's perspective. Farmers often find it difficult to make predictions about long-term returns on investments in agroforestry systems, due to system complexity and long planning horizons. Models to forecast agroforestry performance may be helpful when exploring optimal management practices and the best ways to raise adoption rates. Building such models requires a realistic evaluation of the performance of new practices (Luedeling and Shepherd 2016).

Cost-benefit analysis has been widely used to assess the profitability of alternative agricultural practices in developing countries (Das and Bauer 2012; Pannell et al. 2014; Sain et al. 2017). Conventional cost-benefit models, however, are often deterministic and fail to account for uncertainty or variation in model variables (Davidson et al. 2006). Actual intervention outcomes can diverge considerably from decision-makers' expectations, especially in cases where wishful thinking shapes the model assumptions and choice of input values.

There are multiple ways to include uncertain values in calculations, including probability distributions (Rosenstock et al. 2014; Luedeling et al. 2015), conditional probability tables (Whitney et al. 2018), fuzzy numbers (Page et al. 2012), or arithmetic intervals (Davidson et al. 2006). Probability distributions are the dominant means for formally representing uncertainty, since they constitute an effective option to describe the likely values of a particular quantity (Uusitalo et al. 2015). By encoding uncertain factors as probability distributions, it is possible to derive distributions of model outputs and system performance indices. Frequently used techniques include Monte Carlo sampling (O'Hagan 2012; Luedeling et al. 2015; Sain et al. 2017) and Bayesian Networks (Whitney et al. 2018). Monte Carlo simulations have been employed to address field variability and parameter uncertainties to assess the cost-benefit profile of climate-smart agriculture options (Sain et al. 2017), to predict the range of yield benefits when adopting conservation agriculture practices (Rosenstock et al. 2014), and to project the impact of agricultural development policies on household nutrition (Whitney et al. 2017).

Decision Analysis is an interdisciplinary approach that provides methods and tools to support decision-making under uncertainty (Hardaker and Lien 2010; Luedeling and Shepherd 2016). The methods offer solutions for comprehensively evaluating decision options by incorporating all the available information that is relevant to a particular decision, including scientific data and expert knowledge. Decision analysis allows explicit quantification of all relevant uncertainties. In many complex environmental systems measured data and formal theories are limited, inconsistent or lacking. In such cases expert knowledge may be the best available information (Krueger et al. 2012) for supporting decision-making. Expert knowledge can come in many forms and be derived from different types of experts, including scientific specialists (Page et al. 2012), farmers and land managers (Oliver et al. 2012). Decision Analysis can harness this knowledge to obtain a qualitative understanding of a system and then translate this understanding into a set of mathematical equations (Krueger et al. 2012). The model can then be fed with data elicited from experts. Probability distributions derived from expert knowledge are widely recognized as an appropriate quantitative representation of uncertainty (Hubbard 2014). Assigning a range for a particular quantity helps to overcome the need for any assumptions of certainty, which are rarely justifiable in the analysis of real-world issues.

The complexity of development challenges calls for approaches that allow comprehensive analysis of the expected impacts of agricultural interventions. Such approaches could support social change and help enhance the sustainability of agricultural development (Nguyen et al. 2015). Decision Analysis appears highly suitable for such contexts, including for agroforestry interventions in Vietnam. Decision Analysis has been applied in a diversity of fields including computer science, public health, business, and natural resource management, but it is relatively new to agricultural development research (Luedeling and Shepherd 2016). Here we demonstrate the application of Decision Analysis approaches for conducting a probabilistic cost-benefit analysis. We showcase the approaches by applying them to seven agroforestry options, with the aim of comparing the proposed interventions to common monoculture systems. We also use Decision Analysis methods to highlight important uncertainties that influence resulting recommendations.

Fig. 1 Three agroforestry systems being promoted in northwestern Vietnam. a) Coffee-based agroforestry system (Macadamia in coffee-annual crop intercrop). b) Maize-based agroforestry system (*Dimocarpus longan* Lour. in maize system with grass strips). c) Simple agroforestry system (Shan tea with forage grass)

2. Materials and Methods

2.1. Study objects and locations

We applied Decision Analysis procedures to evaluate seven agroforestry intervention options in the northwestern uplands of Vietnam (Fig. 2a). The region faces low crop yields and has the highest poverty rate in the country. Much of the land features steep slopes that are difficult to cultivate (87% of the land has a slope >25 degrees; Hoang et al. 2017), with relatively infertile soils. Government reforms in the mid-1980s, aimed at de-collectivizing cultivated land and transitioning from subsistence agriculture to commodity production, dramatically changed the landscapes of the region. Growing population pressure and unclear ownership of forest land led to the expansion of cultivated land and widespread deforestation. Cash crops such as maize, cassava, paddy rice, coffee and tea have since become the main sources of income (Hoang et al. 2017). During this transformation, agriculture intensified, leading to rising farm incomes. However, these short-term benefits have come at the expense of long-term sustainability. With the introduction of high-yielding maize varieties and the use of chemical fertilizers, fallow periods have shortened. This has led to severe soil erosion on the heavily sloping land and accelerated land degradation, leading to declines in crop yields. In order to address deforestation, eradicate hunger and alleviate poverty, several rural development programs have been implemented in the region (Simelton et al. 2017). Among them the project "Agroforestry for livelihoods of smallholder farmers in Northwest Vietnam" (AFLi), run by World Agroforestry (CIFOR-ICRAF), applies on-farm agroforestry trials to create sustainable options for upland farming systems (Fig. 1). AFLi has tested several agroforestry interventions with diverse combinations of timber trees, fruit trees and commodity trees together with forage grass and annual crops, in order to identify the most suitable options for local conditions. Follow-up research has focused on agricultural productivity and development of tree and crop components. However, the project currently lacks any assessments of economic profitability or consideration of uncertainty. These gaps provided the motivation for the present study.

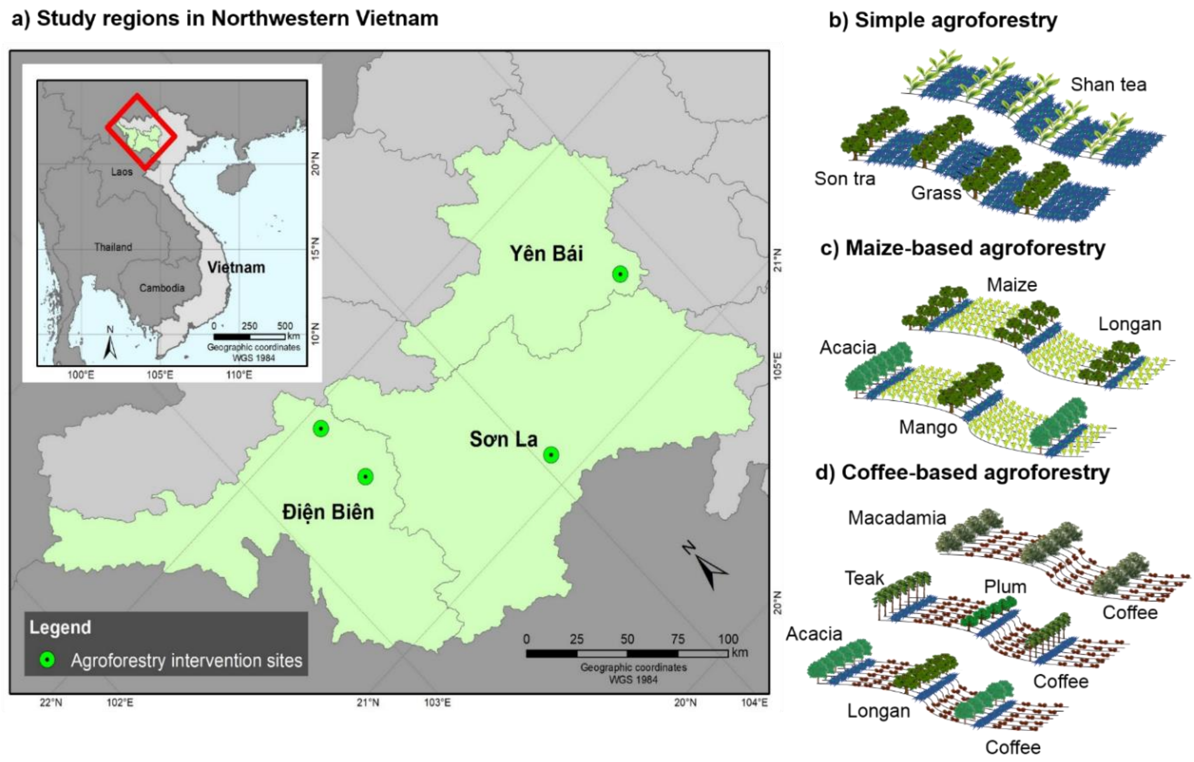

Fig. 2 Study regions (a) and agroforestry interventions in northwestern Vietnam. Simple agroforestry systems (b) are located at high altitudes (>800 m above sea level) of Dien Bien province; maize-based agroforestry systems (c) are located at low altitudes (300-400 m above sea level) of Yen Bai province; coffee-based agroforestry systems (d) are located in the middle altitudes (600-800 m above sea level) of Son La and Dien Bien provinces

Three groups of agroforestry systems were categorized mainly based on the tree species involved. Two simple agroforestry systems (Fig. 2b) are traditional plantations of son tra (*Docynia indica* (Wall.) Decne.) and Shan tea (*Camellia sinensis* L. Kuntze) intercropped with forage grass. In maize-based agroforestry systems (Fig. 2c), fruit trees including longan (*Dimocarpus longan* Lour.) and mango (*Mangifera indica* L.), timber acacia (*Acacia mangium* Willd. and *Acacia auriculiformis* Benth.) and grass strips are integrated with traditional maize cultivation. Coffee-based agroforestry (Fig. 2d) consists of one intercropping system, where coffee (*Coffea arabica* L.) and macadamia (*Macadamia integrifolia* Maiden & Betche) are cultivated together with annual crops, and two complex agroforestry systems (CAFS), where coffee is combined with timber trees including acacia and teak (*Tectona grandis* L.f.), fruit trees including longan and plum (*Prunus salicina* Lindl.), grass strips and annual crops. Cash tree crops are grown with densities of 500 trees ha^{-1} for Son tra, 2240 trees ha^{-1} for Shan tea in simple agroforestry systems, whereas maize-based agroforestry systems featured 240 longan trees ha^{-1} and 125 mango trees ha^{-1}. The two coffee-based systems included 154 macadamia trees ha^{-1} intercropped with 2160 coffee trees ha^{-1}, and 125 longan/plum trees ha^{-1} intercropped with 1680 coffee trees ha^{-1}, respectively.

2.2. Model specification

We built a decision model following a Decision Analysis approach (Fig. 3) designed for research for agricultural development (Luedeling and Shepherd 2016). Twenty-one farmers who had been either engaged in agroforestry trials or had experience in the cultivation of the various tree crops were involved in the model development process as essential sources of information regarding local contexts and practices. We chose staff of the AFLi project and CIFOR-ICRAF's technical experts, responsible for agroforestry trials throughout the project, to be core experts for model development. We also consulted three experts from other local research institutes for their expertise and extensive research experience in related fields, e.g. fruit and coffee production.

We derived expert knowledge from one-on-one interviews with all participants, providing each of them with the opportunity to express their ideas about the structure of the decision model. We also organized discussions with groups of farmers, groups of experts and mixed groups consisting of both farmers and experts. These discussions culminated in a consensus model structure that captured opinions and information of all stakeholders about the costs, benefits and risks of the interventions. We also made use of our own extensive observations in the field, as well as information from relevant literature when formalizing inputs and refining the decision model.

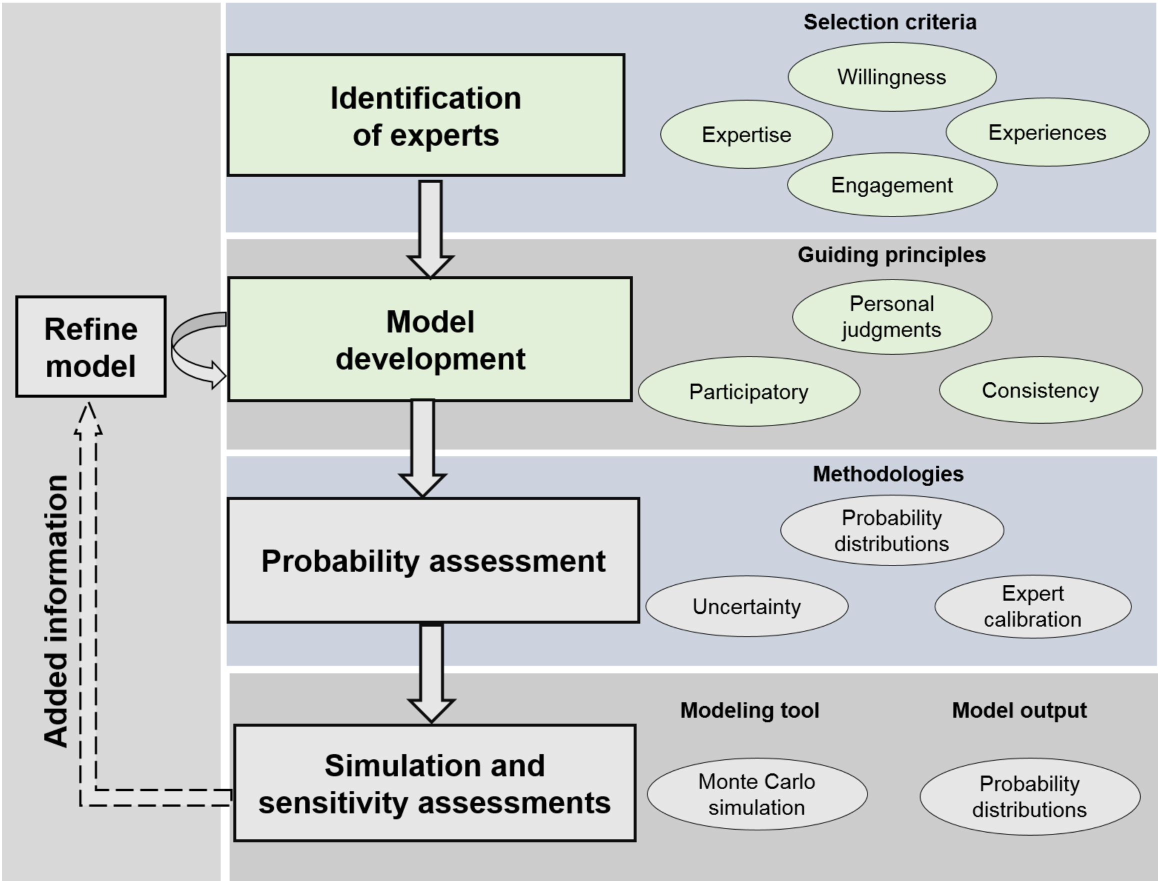

Fig. 3 Principal stages of the Decision Analysis approach used to study the impacts of adopting agroforestry in northwestern Vietnam

We considered two decision alternatives, for which experts specified all costs, benefits and risks:

Decision alternative 1: Implementation of agroforestry systems. This decision option had two main types of costs:

- *Establishment costs* incurred when agroforestry is adopted, including expenses for land preparation (manual or mechanical depending on local geographic and socio-economic conditions), seedlings and other inputs such as fertilizers, compost, herbicides, and farming equipment.
- *Maintenance costs* incurred annually to ensure established systems continue to operate, including costs of labor and other inputs such as fertilizer and pesticides.

The benefits of the decision options were derived mainly from revenues gained from the harvest of crop components such as fruits, nuts, coffee, timber, maize, and grass biomass.

Decision alternative 2: Maintaining conventional monocultures of maize. Under this decision option, farmers incur annual costs for fertilizer, seeds, and labor, but no installation costs are required. Benefits were calculated as the estimated income from maize production.

2.3. Conceptualization of the decision model

We worked together with experts to derive a conceptual model that explicitly identified all the important factors and relationships in CIFOR-ICRAF's agroforestry interventions (Fig. 4). Since crop yield and input demand depend on the age of the plantation, all benefits and costs were modeled in relation to the age of the systems. The establishment cost was only incurred in the first year. Since annual input costs varied throughout the production cycle, maintenance costs were estimated corresponding to time intervals specified by experts. Risks were quantified in the model by simulating the likelihood and consequences of events perceived as consequential for farm-scale outcomes. The main consequences of these events were calculated as the decline of tree and crop yields compared to the yield in normal years (Table 1). Experts divided yield variables into component parameters, e.g. tree yields per hectare were calculated on the basis of representative individual trees multiplied by tree density in the stand. In coffee-based agroforestry systems, the revenues from annual crops were assigned for only the first three years, at which point annual crops would likely no longer be productive. The monetary value from soil loss prevention was estimated as the savings in fertilizer costs which would otherwise have been incurred to compensate for nutrients lost with eroded soils under monoculture maize production.

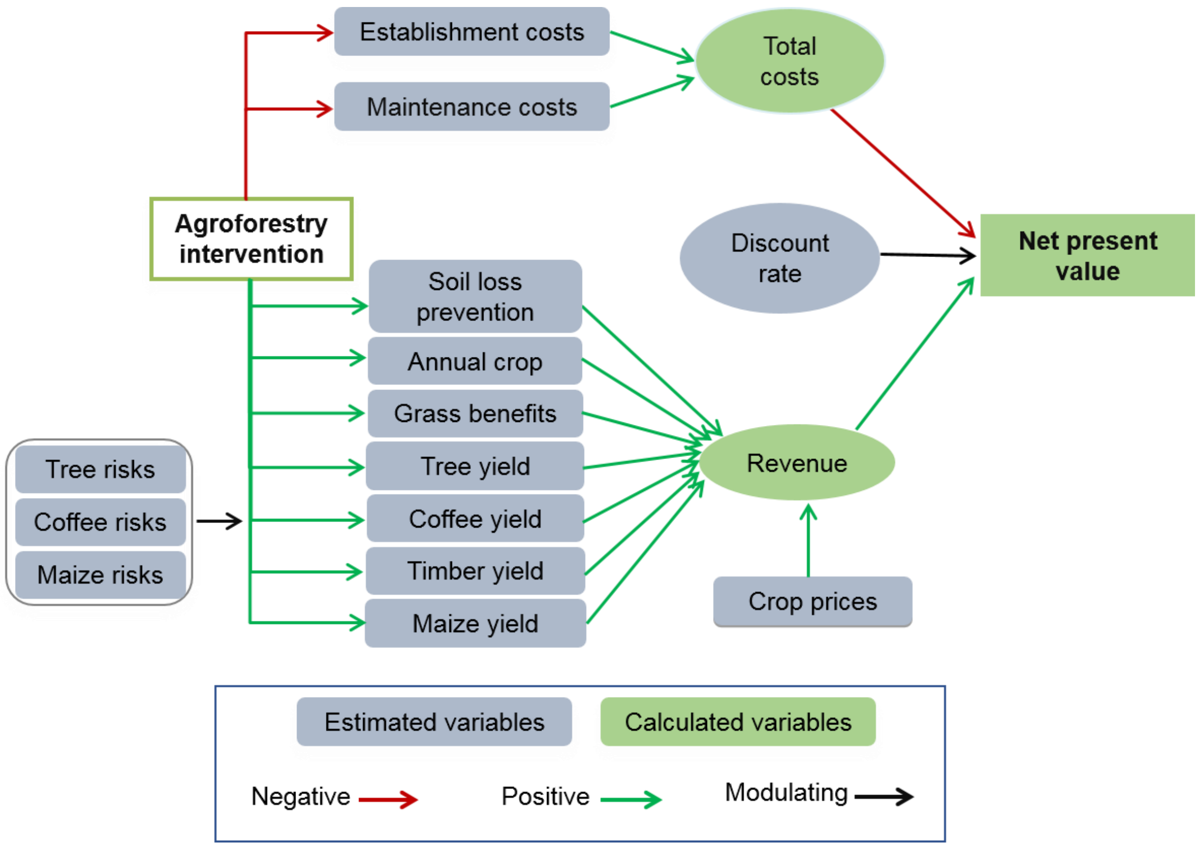

Fig. 4 Conceptual model of cost-benefit analysis incorporating risk factors for agroforestry planning in northwestern Vietnam. "Tree yield" indicates Shan tea harvest, son tra fruits, longan fruits, mango fruits, plum fruits and macadamia nuts

Impacts of extreme weather were considered as the most important risks and modeled explicitly. Problematic extreme weather events in northwestern regions include frosts, droughts, and hot and dry winds, which negatively affect crop production. Winter frosts are the greatest threat to coffee production in the region. Hot and dry winds blowing from Laos in summer threaten fruit trees and maize production. The winds cause a quick reduction in humidity and speed up evapotranspiration. Together with frequent drought in the region, the winds can induce premature flower and fruit drop in fruit trees and cause yield loss in maize.

Table 1. Expected yield losses (90% confidence interval) due to risk events. Losses were assumed to be normally distributed, truncated at 0 (precluding negative values, which would indicate yield gains). For coffee, where the main risk considered was the occurrence of frost events, the normal distribution was not truncated (allowing for a small chance of yield gains)

Crop	Yield loss (90% confidence interval)	
	Lower bound (%)	Upper bound (%)
Shan tea	20	40
Son tra	20	50
Longan (maize system)	50	70
Mango	30	50
Plum	20	40
Longan (coffee system)	30	50
Macadamia	20	50
Coffee	0	70
Maize	20	80

External factors such as crop prices and discount rates were also included in the evaluation for both decision alternatives. The causal impact model generated through these processes was then converted into a mathematical model to enable simulation of agroforestry outcomes. The resulting simulation model considered all the factors included in the conceptual model and expressed their relationships using mathematical equations.

Crop yield patterns

One important aspect of the model included estimating yields of tree crops over time. We modeled these to follow the pattern of the Gompertz curve (Luedeling et al. 2019). According to this model, tree yields increase over time until reaching a plateau that represents their full productive capacity. This production level is then maintained for the remainder of the tree's productive life. Three critical points were specified to define these yield curves (Fig. 5).

The plateau Y_{max} of the Gompertz curve is the maximum yield that a tree can attain throughout its life cycle. The curve was parameterized based on yields Y_{T1} and Y_{T2} at time T_1 and T_2, respectively, considering the ages of trees for which participants were best able to provide estimates. The yield of Arabica coffee was simulated with two productive periods following the same Gompertz patterns. The first fifteen-year productive cycle was followed by a second ten-year productive cycle.

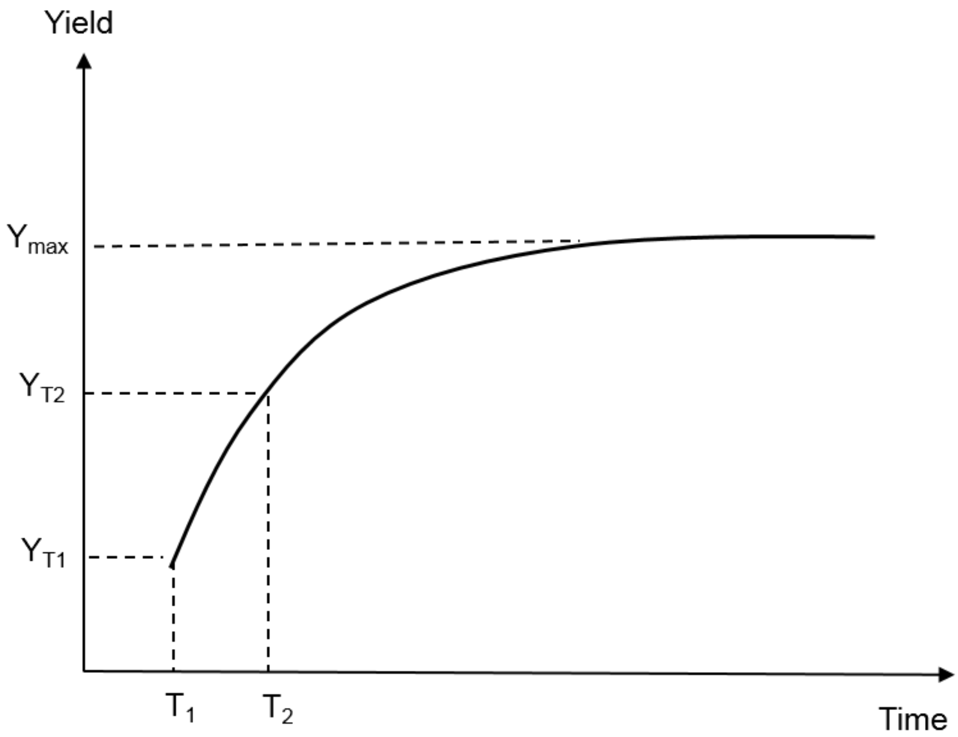

Fig. 5 Gompertz curve describing the yield of tree crops (i.e. Shan tea, son tra, longan, mango, plum, and macadamia)

The yield of maize in agroforestry systems was assumed to decline corresponding to an exponential decay function:

$$Y = Y_f + (Y_o - Y_f)e^{-kt}$$

in which Y_0 is the initial maize yield in the year a system is established. Y_f is the minimum yield that maize can maintain. The minimum yield reflects the ability of agroforestry to stabilize maize yield during the simulation period. Coefficient k represents how fast maize yield will approach the Y_f value, t indicates the production cycles. This decline was included because space occupation and shading of forage grass and tree components in agroforestry systems are expected to reduce yields over time.

The yield of maize in monoculture stands decreased in response to the decrease in soil organic matter and soil nutrient status in the course of cultivation:

$$Y = Y_o e^{-kt}$$

Quantification of uncertainties in the model

We formally represented uncertainties in the model by expressing all variables as probability distributions derived from expert assessments. However, relying on expert judgment requires awareness of the many cognitive biases (Tversky and Kahneman 1974) that can affect experts' ability to provide accurate uncertainty estimates (Uusitalo et al. 2015). Experts often overestimate the precision of their knowledge (Hubbard 2014), are easily influenced by initial estimates or even unrelated numbers (Page et al. 2012), or consider recently experienced or remarkable events to be more common than they actually are (Hubbard 2014). A number of methodologies have been proposed for reducing the influence of such cognitive biases (Page et al. 2012; Hubbard 2014; Luedeling et al. 2015; Whitney et al. 2018). We followed the de-biasing techniques described by Hubbard (2014), known as calibration training, to elicit expert knowledge for both qualitative and quantitative information. During the training we presented experts with trivia questions and asked them to provide probability distributions of uncertain quantities or quantitatively express their confidence that their answers to true/false questions were correct. We gave them feedback and tools for providing more accurate estimates, which have been shown to lead to a reduction of overconfidence (Hubbard 2014). In this way we were able to increase the accuracy of expert estimates (Hardaker and Lien 2010) and reduce the potential biases associated with the experts' estimations (Page et al. 2012). After experts had participated in the calibration training they were asked to provide upper and lower bounds of 90% confidence intervals, as well as distribution shapes for all the input variables of the decision model.

Calculation of Net Present Value

The decision model was used to quantify the overall economic outcome for each decision option by calculating the Net Present Value (NPV) over a twenty-five-year period. The comparative financial performance was assessed on the basis of the net benefit per hectare by subtracting costs from revenues for each option. To account for the time preference of money, we used a discounting procedure to convert the net values into financial NPVs:

$$NPV = -C_0 + \sum_{i=1}^{t} \frac{C_i}{(1+r)^i}$$

C_0 = establishment cost

C_i = cash flow in year i

r = discount rate

t = time of simulation

2.4. Probabilistic analysis

We applied Monte Carlo simulations to generate the ranges of possible values for NPVs of all agroforestry options, as well as for maize monocultures as the baseline system. We ran simulations with 10,000 model runs to generate the distributions of expected NPVs by randomly selecting values from distributions of input variables and feeding them into our mathematical formulation of the decision model.

We applied Projection to Latent Structures (PLS) regression as a sensitivity analysis to identify critical uncertain input variables that best explained variation in NPVs (Luedeling and Gassner 2012). The parameters of interest from this procedure included the variable importance in the projection (VIP) and the regression coefficient. The VIP is a weighted sum of squares with weights calculated from the amount of explained variance for response variable in each PLS dimension. It represents the contribution of each predictor in fitting the PLS model. The regression coefficient shows the direction and magnitude of the impact of each variable on the PLS model output (Luedeling and Gassner 2012). We used a threshold of VIP = 1 to distinguish between important and unimportant variables (Chong and Jun 2005).

We then applied Value of Information analysis to determine whether collecting additional information on a certain input variable would be warranted for providing more certainty about the most beneficial decision option. We quantified the value of information by computing the expected value of perfect information (EVPI). The EVPI represents the monetary value that would hypothetically be worth investing in order to completely eliminate uncertainty on specified variables in the decision-making process (Hubbard 2014). The EVPI can guide and underpin research priorities, especially in a research environment with limited funding (Luedeling et al. 2015; Whitney et al. 2018).

All model coding and probabilistic analyses were implemented in the R programming language (R Core Team 2018) with functions of the *decisionSupport* package (Luedeling et al. 2019). The model script and input tables with full list of variables are provided in supplements (http://doi.org/10.5281/zenodo.3727576).

3. Results and discussion

3.1. Profitability of agroforestry

Model simulations revealed wide ranges of possible values for NPVs of all agroforestry options and maize monocultures. Simulations showed an estimated NPV of maize monocultures between -348 USD ha^{-1} and 8,360 USD ha^{-1} (90% confidence interval) after twenty-five years of continuous cultivation. Agroforestry systems were expected to achieve higher NPVs with a greater chance of high positive outcomes (Simulated net benefits; Fig. 6). Models of the two simple agroforestry systems generated 90% confidence intervals between -1,515 USD ha^{-1} and 15,995 USD ha^{-1} for Shan tea and between 2,600 USD ha^{-1} and 62,889 USD ha^{-1} for son tra. The two maize-based agroforestry systems were expected to generate NPVs between 4,068 USD ha^{-1} and 33,531 USD ha^{-1} for the system with longan and between 3,525 USD ha^{-1} and 22,779 USD ha^{-1} for the system with acacia and mango. In coffee-based agroforestry, a 90% confidence interval of -561 USD ha^{-1} to 23,556 USD ha^{-1} was predicted for the system with macadamia, -467 USD ha^{-1} to 19,888 USD ha^{-1} for the system with teak and plum (CAFS-Teak) and 1,208 USD ha^{-1} to 28,661 USD ha^{-1} for the system with acacia and longan (CAFS-Acacia). A small number of model runs resulted in net losses for both agroforestry and monoculture systems. Specifically, 10,000 model runs of the simple system with Shan tea produced negative outcomes 13.9% of the time. Coffee-based systems with teak and plum and with macadamia resulted in negative NPVs 7.1% and 7.5% of the time, respectively. Models indicated a 7.0% probability of negative outcomes for the baseline system.

These results support CIFOR-ICRAF's intervention to promote agroforestry practices among farmers in mountainous regions of northwestern Vietnam. Nevertheless, despite the relatively low economic return, monocultures of maize still dominate the region (Hoang et al. 2017). The simulations reveal a long-time lag before the initial agroforestry investments pay off. This leads to lower short-term profits in agroforestry compared to monocultures, which already begin to generate profits in the first year of production. Due to the early income from maize harvests, the two maize-based agroforestry systems needed only 2 to 3 years before reaching a 50% chance of positive cumulative cash flow. The simple agroforestry system with son tra took 4 years and Shan tea took 7 years to reach a 50% chance of positive cumulative cash flow. A similar time lag of 7 to 8 years was also forecast for coffee-based agroforestry systems to compensate for initial investments, despite the early income from annual crops. These lags may be a prohibitively long wait for many resource-constrained small-scale farmers, who have high discount rates (i.e. they strongly prefer benefits now to benefits that occur later) (Pannell et al. 2014). Large investments with time lags for returns, such as agroforestry interventions, can be effective if they are supported, for example by enabling environments that provide secure land tenure, the support of long-term land use practices and diversified short-term livelihood options (Sain et al. 2017). The Vietnamese government's new Land Law (45/2013/QH13) seeks to extend farmers' land leases from 20 to 50 years and could encourage long-term investments in permanent land use (Simelton et al. 2017). However, many farmers may not have sufficient savings or access to enough credit to make such investments. Lack of support for and promotion of sustainable land use practices is a major factor limiting the adoption of agroforestry, including in Vietnam. The currently small estimated compensation (savings in fertilizer to compensate for nutrients lost through soil erosion) may not be enough to incentivize farmers to practice soil conservation. If reasonable monetary incentives were provided to farmers, the adoption of soil conservation practices could increase substantially (Quang et al. 2014). The government's policy on Payments for Ecosystem Services (Decree 99/2010/NĐ-CP) aims to maintain and support forestry but not agroforestry (Simelton et al. 2017). A study on the effect of hypothetical monetary incentives for households in northwestern Vietnam to adopt soil-conserving land use practices found that a payment of 12-16 USD per ton of soil saved would be needed to effect a reduction of 40% of estimated soil loss (Quang et al. 2014). However, financial incentives for sustainable land-use practices are still lacking.

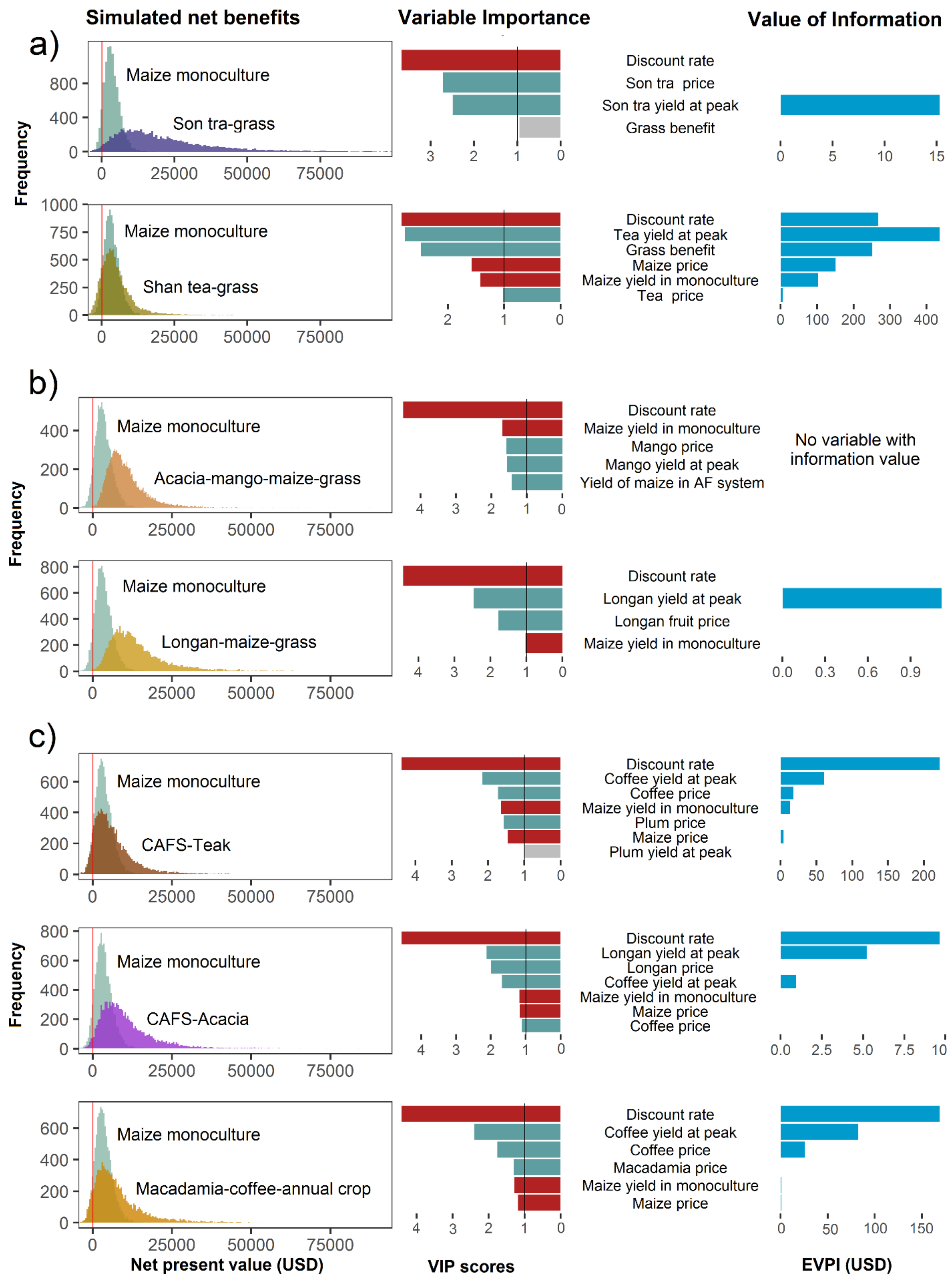

Fig. 6 Probabilistic analysis of agroforestry intervention decisions in Northwestern Vietnam: a) implement simple agroforestry systems vs. maize monoculture. b) implement maize-based agroforestry systems vs. maize monoculture. c) implement coffee-based agroforestry systems vs. maize monoculture. Histograms (left) present the Net Present Values of 10,000 Monte Carlo simulation runs

of agroforestry and maize monocultures. Bar graphs (right) indicate Variable Importance (expressed by VIP scores) for variables to which the model was most sensitive (green bars indicate positive relationships with the outcome variables; red bars indicate negative relationships; grey bars indicate variables with VIP scores less than 1) and Value of Information calculated as Expected Value of Perfect Information (EVPI) in USD

3.2. Decision-relevant uncertainties and their value of information

Across all agroforestry options, VIP scores were considerably higher for discount rates than for other variables, with discount rate being negatively correlated with NPVs (Variable Importance; Fig. 6). This indicates that decision outcomes are highly sensitive to the discount rate, with a high discount rate having a negative effect on the decision outcome. Other factors related to fruit tree yield, coffee yield, and the prices of crop and tree products were also marked as key uncertain variables (VIP ≥1).

The discount rate of the farmers was a consistently important factor across simulations (VIP scores ranged from 3 to 5). This is consistent with the long-time frame of agroforestry practices, which can take several years to begin producing substantive benefits. Farmers have a strong preference for present-day net benefits over future benefits, and they value present pay-offs much more highly than long-term profits in their decision making. Therefore farmers' discount rates can be decisive for adoption decisions, which often differ substantially among farmers, even for the same technology in the same project area (Hoekstra 1985). Discount rates may vary according to multiple factors, such as farmers' savings, alternative income sources, risk preferences and degrees of tenure security. Choosing an appropriate discount rate, especially when dealing with subsistence-oriented and resource-constrained smallholders, is essential for the analysis of agroforestry systems (Hoekstra 1985; Pannell et al. 2014). We based our 90% confidence interval estimate for the discount rate on a rate used to identify the economic merits of afforestation for rural farm households in northern uplands of Vietnam (Nguyen et al. 2010) and a rate used for resource-poor farmers when analyzing farm-level economics of conservation agriculture (Pannell et al. 2014). The range likely captures the discount rates of the majority of farmers in the region.

Yield variability was a factor of high importance in the model simulations (VIP scores ranged from 1 to 3). Yield variability results from heterogeneous biophysical conditions (e.g. soil properties, precipitation, field slope direction), interactions among tree components in agroforestry systems and, possibly more importantly, from local socio-economic factors such as farming habits and levels of investment. Northwestern Vietnam features large field-to-field variability in terms of cropping practices, fertilizer use and soil fertility status, which results in high variability in crop productivity. In this mountainous region, many farmers manage steep terrain in a range of topographic positions, which give rise to substantial spatial variability in soil fertility and crop yields (Wezel et al. 2002).

Crop prices were another set of important uncertainties affecting model outcomes (VIP scores ranged from 1 to 3). Experts agreed that crop prices would be influenced by factors such as annual crop productivity, product quality and farmers' ability to negotiate on prices. This is important, since weak post-harvest technologies and the lack of market information can lead to markets being temporarily flooded with particular agricultural commodities. This often results in price drops during peak harvest seasons. Prices of many crops can also be highly uncertain, since they are often set by private middle-men and traders. Additionally, with the exception of a few cooperatives and state-owned enterprises involved in tea and wood processing, policies for markets and product distribution are largely missing in the agroforestry value chain (Simelton et al. 2017), especially markets for new agroforestry products that work effectively even when agroforestry practices are widely adopted and scaled up to larger areas.

Resource-poor farmers often need to prioritize their families' immediate needs and do not have the luxury of being able to make income sacrifices in the short term. Even if practices can result in higher long-term benefits, farmers may still choose lower short-term benefits (Pannell et al. 2014). Likewise, small farmers are risk-averse and often tend to choose practices with low investment requirements and highly certain economic returns. They are less likely to adopt new agricultural practices with uncertain costs, crop yields and output prices relative to those of conventional practices. However, critically, due mainly to their unsustainable mining of soil nutrients and high levels of erosion, projected annual profits of maize monoculture systems decrease over time. This option, although regionally dominant at the moment, cannot reasonably be expected to remain the dominant system in the future. Experiences from farmer-driven cooperatives of small-scale organic producers in Vietnam propose potential solutions to address some of the challenges to agroforestry adoption. Cooperatives, with clear leadership structures and predictable commitments by a number of farmers, offer opportunities for producing agricultural commodities in a more standardized way. They can thus facilitate a regular supply of products with homogenous quality, allowing farmers to access markets that may otherwise be beyond their reach and opening prospects for stable and high sale prices (Islam et al. 2018). Production cooperatives can also empower smallholder farmers by facilitating the exchange of skills and knowledge on crop production and marketing.

Supporting policies for establishing effective farmer cooperatives in agroforestry could be instrumental in promoting this farming practice.

All variables in models for simple agroforestry with son tra and grass (Value of Information; Fig. 6a), two maize-based systems (Value of Information; Fig. 6b) and the coffee-based system CAFS-Acacia (Value of Information; Fig. 6c) had either no information value or very low values of the EVPI. The remaining systems had non-zero EVPI for discount rates, coffee yield and coffee prices (Value of Information; Fig. 6c), tea yield, the yield of maize in monoculture and maize price (Value of Information; Fig. 6a). Collecting additional information on the variables that have non-zero EVPI could be helpful for better determining whether farmers should be incentivized to choose maize monoculture or the respective agroforestry options. Nevertheless, decision-makers should not be willing to spend more than the estimated amounts (EVPI) for further investigating selected variables. The lack of information value for many variables (i.e. EVPI = 0) suggests that no further evidence would be helpful for making a better decision when choosing agroforestry systems over monoculture. The differences in the forecasted decision outcomes (Simulated net benefits; Fig. 6) already offer high confidence in agroforestry being the more sustainable long-term solution. No further evidence should be necessary for appropriate supporting policies to be put into place to facilitate the implementation of agroforestry interventions.

3.3. Probabilistic analysis of agroforestry systems

The modeling approaches we applied allowed for the incorporation of expert knowledge and elicitation of uncertainties. In this way, the model reflects the high variability in local farming systems in aspects such as cropping practices, fertilizer use, soil fertility and resulting crop yields in northwestern Vietnam. The uncertainties, elicited from experts for feeding the model, reflect the current state of the participants' knowledge of each agroforestry system. The model in this study presents the costs and benefits of agroforestry systems at the farm level only. Other factors may also be important to the wider social and ecological systems surrounding these farms. However, off-farm benefits of agroforestry, such as those provided to local communities, may be important from a social perspective but may not influence the decision-making of resource-poor smallholder farmers (Das and Bauer, 2012). This study provided an analysis of the economic returns, which is the priority for local farmers (Simelton et al. 2017) and is considered critical by CIFOR-ICRAF and governmental stakeholders (La 2018, personal communication). The results constitute a solid background for further analyses on farmers' adoption of agroforestry by taking a broad view of the diverse factors that influence regional land use systems. During adoption, farmers may modify or adapt agroforestry innovations to their circumstances. Instead of an abrupt change from a monoculture system to an entirely new agroforestry system, which may require a large investment and reduce the short-term returns from the land, gradual transition in the implementation of agroforestry is a potential decision alternative, especially for resource-poor farmers. Such gradual transition could be an alternative approach for CIFOR-ICRAF Vietnam to improve the feasibility of agroforestry implementation in the local context. To more fully capture the current situation of smallholder farmers in the target region, assessment of the relative profitability of agroforestry practices compared to other major land use types, such as the production of cassava or upland rice, may also be needed. The holistic modeling approach demonstrated in this analysis can easily be tailored to compare a greater number of land use options, allowing customized assessments that serve the needs of different decision-makers.

4. Conclusion

We present an innovative approach for supporting complex decisions. We apply expert knowledge in the design and parameterization of models of costs, benefits, risks, and uncertainties associated with adopting various agroforestry options. All modeled agroforestry systems offer positive returns in the long term. However, high establishment and maintenance costs reduce economic returns in the short term, generating time lags of more than three years, which may be too long for most smallholder farmers. The currently dominant practice of maize monoculture may be preferred for the relatively early lag-free returns, yet in this system, annual profits decrease over time. Agroforestry systems outperform maize monocultures in the long term, yet the required investments may not be economically viable for farmers in the short term. Economic incentives that compensate for these short-term losses can aid in agroforestry promotion. A better understanding of uncertain factors such as the discount rate, crop yields and crop prices may be useful for supporting agroforestry decisions. The results and methods of this study promise to be useful in the design of future policies for sustainable development and for further analyses of agroforestry interventions.

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Data availability All data generated during this study are available in the repository http://doi.org/10.5281/zenodo.3727576.

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Chapter 3. Markets and incentives strongly drive agroforestry adoption: insights from ethnic minority smallholders in Son La, Vietnam

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Abstract

Agroforestry has been promoted in northwestern Vietnam as a sustainable land management practice that offers multiple benefits, including livelihood enhancement, income diversification, adaptation to climate variability and reduced soil erosion on steep slopes. However, research on the multi-stage adoption process of agroforestry and the complex web of factors influencing farmers' decisions remains scarce. Our study addresses this gap by investigating the adoption process of fruit tree-based agroforestry practices in the upland farming systems of Son La, a northwestern province of Vietnam. Using a Bayesian Network model, we analyzed the combined effects of socio-economic, household and practice-specific factors that shape farmers' attitudes and intentions throughout the adoption process, from initial decision-making to sustained use. The Bayesian Network was developed using both qualitative and quantitative inputs from 124 farmer interviews and workshops involving domain experts and farmers. Additionally, through an adoption pathway analysis of 124 interviewed farmers, we explored the diverse trajectories farmers follow to integrate agroforestry into their systems, highlighting the adaptive and non-linear nature of the adoption process. Our findings suggest that effective agroforestry promotion requires coordinated, holistic strategies and sustained support rather than single-point interventions or binary adoption models. This study contributes to the understanding of agroforestry adoption as a dynamic, context-sensitive process and provides insights for designing support mechanisms that align with farmers' evolving needs and decision-making pathways.

1. Introduction

Agroforestry strategically integrates woody perennials with agricultural crops and/or animals in the same land management unit, spatially or temporally (Nair 1993). Agroforestry can improve food security, alleviate poverty and address land degradation and climate change while enhancing ecosystem services (Kuyah et al. 2019). These multifaceted benefits have driven the promotion of agroforestry in both temperate (Dmuchowski et al. 2024) and tropical regions (Mercer 2004). Agroforestry practices have been promoted in northwestern Vietnam to sustain livelihoods and address soil erosion problems linked with intensive tillage practices in conventional annual monocultures (La 2019). Facilitated by various development initiatives led by both local government and international research organizations, agroforestry has been adopted and practiced by local farming communities (La 2019, 2022). Understanding farmers' decision-making processes in adopting agroforestry remains a key priority for many development initiatives aiming to scale out these practices (Nguyen et al. 2021).

1.1. Gaps in studying agroforestry adoption and implications for its practicality in Vietnam

The predominant approach to understanding farmers' decision-making involves analyzing the effects of sociodemographic factors including age, gender, economic status, education level, household size, land ownership, and land size (Githinji et al. 2023). In addition to these factors, psychological and other contextual socio-economic factors have also been examined as determinants of farmers' decision-making (Mercer 2004; Jha et al. 2021). In most cases, these factors are analyzed separately using common variance-based methods (i.e. analyzing correlation and regression coefficients), which yield variable and sometimes conflicting results (Mercer 2004; Rizzo et al. 2023). For instance, while Dhakal and Rai (2020) found that male farmers are more likely to adopt agroforestry than female farmers, Muthee et al. (2024) reported a lower agroforestry adoption rate for male-headed households than for female-headed ones. Similarly, Syano et al. (2022) observed that more educated farmers and older household heads are more likely to adopt agroforestry, whereas Muthee et al. (2024) found no significant impact of education or age on agroforestry adoption. Household size also shows conflicting patterns, with Syano et al. (2022) finding that larger households are more likely to adopt agroforestry while Dhakal and Rai (2020) suggested the opposite. In addition, network memberships have been shown to positively impact the adoption of agroforestry practices in Sweden while factors like farmer identity, perceived economic benefits and labor constraints showed little statistical significance (Leduc and Hansson 2024). In Tanzania, farmers' adoption of agroforestry practices was influenced by their participation in agroforestry projects, access to reliable seedling sources and perception of climate or land fertility (Jha et al. 2021). The inconsistency in study results suggests that the adoption process is highly context-specific (Githinji et al. 2023). The variation may also stem from the limitations of the commonly used variance-based approach, which may fall short of capturing the complex interactions between factors and underlying mechanisms in the decision-making environment. Rizzo et al. (2023) advocated for more configurational approaches that examine combinations of variables, offering a nuanced understanding by acknowledging that multiple pathways can lead to similar outcomes (Furnari et al. 2021). These approaches acknowledge nonlinearity, where variables determining a phenomenon in one context might yield different results in another situation (Fiss et al. 2013).

An exclusive focus on the adoption rate disregards the granularity of processes and decision-making mechanisms through which innovation occurs on farms (e.g. Hermans et al. 2021; Do et al. 2024). This approach often fails to accommodate diverse adoption pathways where farmers do not simply adopt but continually experiment with the introduced practices and adapt them to specific biophysical conditions, farming structures, market dynamics and changes in social contexts (Pannell et al. 2006). The process of continual on-farm adaptation is essential to ensuring a sustainable transition where the new practices achieve high compatibility and yield favorable outcomes. Research efforts in agricultural innovation have focused largely on promoting initial adoption, with limited attention to post-adoption follow-up. Follow-up is, however, important given the high heterogeneity in farm outcomes and the drivers of decision-making across diverse smallholder farmer communities (Ishtiaque et al. 2024). Such follow-up facilitates understanding and measuring the impact of research and extension activities, which are vital for the adaptive management of innovations (Montes de Oca Munguia et al. 2021b).

1.2. The importance of transitioning to tree-based farming systems in northwestern Vietnam

Shifting cultivation is a land use practice in which plots of land are cultivated periodically with the same or different crop species and abandoned after harvest to allow natural succession to replenish soil fertility (van Vliet et al. 2012). In northwestern Vietnam, agriculture has traditionally revolved around shifting cultivation of staple crops such as upland rice (*Oryza sativa* L.), maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz), which served as the primary livelihoods for a diversity of minority groups inhabiting the area (Do 1994; Catacutan et al. 2017). The widespread shifting cultivation has been considered a primary contributor to deforestation, forest fires and environmental degradation (Catacutan et al. 2017). Since the 1960s, the government has implemented various policy measures to promote sedentary agriculture and reforestation (Catacutan et al. 2017) (Table S1, Supplementary Materials). Government policies that took effect in the northern region in 1961 aimed to relocate lowland people to mountainous areas. These reallocation policies have resulted in a growing population in the mountainous areas, reducing the area available for shifting cultivation and shortening fallow periods (Catacutan et al. 2017). Consequently, agriculture has transitioned toward settled cultivation, characterized by more intensive use of labor and external inputs such as agrochemicals.

Son La, a province in northwestern Vietnam, faces a high risk of soil erosion stemming from the prevalence of steep land, high seasonal rainfall and prolonged monoculture of staple crops (Nguyen and Pham 2018). Maize cultivation experienced a significant expansion in the region between 1995 and 2012 (Dang and Nguyen 2020), primarily due to the adoption of hybrid varieties (Keil et al. 2008). While these technological advancements contributed to substantial improvements in farmers' living standards, the associated poor land management resulted in severe soil erosion, ultimately jeopardizing the sustainability of local livelihoods (Keil et al. 2008). Since 2013, local authorities of Son La and several other northwestern provinces have introduced and promoted agroforestry, supported by international organizations such as World Agroforestry (CIFOR-ICRAF) (La 2019, 2022). CIFOR-ICRAF initiated a two-phase agroforestry project: "Agroforestry for livelihoods of smallholder farmers in Northwest Vietnam" (AFLi) from 2011 to 2016 and "Developing and promoting market-based agroforestry and forest rehabilitation options for Northwest Vietnam" (AFLi2) from 2017 to 2021. The project was funded by the Australian Centre for International Agricultural Research (ACIAR) and the CGIAR Research Program on Forests, Trees and Agroforestry. The aim was to mitigate soil erosion while sustaining local livelihoods by integrating fruit trees into cropping systems, leveraging the province's existing emphasis on fruit tree cultivation (Dang and Nguyen 2020). Within the project, plot-level experiments of various agroforestry settings were set up for scientific assessments (Do et al. 2020b, 2023). These experiments have been studied extensively, generating solid scientific findings that were published in peer-reviewed papers (Do et al. 2020a, b, 2023; Pham et al. 2024) and technical reports (La 2019, 2022). Since 2015, six model agroforestry landscapes have been established across three northwestern provinces to showcase agroforestry in larger areas. In these landscape models, farmers were involved based on their willingness to participate and on the proximity of their fields to the demonstration sites. Participants were supported by the project with tree seedlings and fertilizer for the first three years. Nguyen et al. (2021) explored the role of social and cultural norms and showed that farmers from different ethnic groups perceive the benefits of agroforestry practices differently, which may shape their aspirations and adoption decisions. However, studies investigating joint effects of multiple factors influencing farmers' decisions remain unavailable. There has also been little follow-up on the adoption progress since the project concluded in 2021, which motivated this study.

1.3. Study objective

Our study addresses two key gaps in understanding farmers' adoption of agroforestry in the context of northwestern Vietnam. First, we articulated the complex web of factors involved in adoption decisions, focusing on identifying key variables and their joint effects. Second, we investigated post-adoption dynamics, exploring farmers' unique pathways as they integrate agroforestry into their farming systems.

Our study contributes to the existing literature in several ways. First, we provide insights into the pathways perceived by farmers that lead to adoption outcomes, offering a nuanced understanding of their decision-making processes. This perspective can inform the design of more inclusive and effective interventions. Second, we investigate the post-adoption phase of agroforestry, with a particular focus on marginalized communities. Such follow-up is essential for sustaining engagement with new practices (Montes de Oca Munguia et al. 2021b), yet it is overlooked in most research-for-development projects in Vietnam.

This paper is organized into four sections. The Introduction section provides background information on the significance of agroforestry in Vietnam, examines existing research on agroforestry adoption, highlighting the gaps that this study aims to fill and outlines the study's objectives and its relevance. In Materials and Methods, we detail the study area and the target population, the analytical techniques employed and the data collection process. The Results and Discussion section presents the findings and implications for stakeholders and acknowledges the limitations of the study. The Conclusion section summarizes the key findings and offers specific and actionable recommendations.

2. Materials and methods

2.1. Study sites

We chose three villages in Hat Lot commune, Mai Son district, Son La province (Fig. 1), one of the key focus areas of the AFLi project, as our study sites. These villages are dominated by the Thai ethnic group, the target population in this study. The primary food and income-generating agricultural activities consist of the cultivation of staple crops, sugarcane (*Saccharum officinarum* L.) and fruit trees, supplemented by livestock husbandry and occasional paddy rice. Conventional annual monocultures have caused severe soil erosion (Nguyen and Pham 2018). This problem has been exacerbated by extreme weather conditions (Keil et al. 2008), which regularly lead to reductions in crop yields (La 2019; Do et al. 2024). In response to the challenges caused by climatic events and market dynamics, farmers have diversified their land use, including sugarcane and fruit trees to sustain household income and mitigate soil erosion (Do et al. 2024). Fruit tree-based agroforestry typically involves intercropping of fruit trees (e.g. longan (*Dimocarpus longan* L.), mango (*Mangifera indica* L.), and plum (*Prunus salicina* Lindl.)) as the main cash crops, along with annual crops like maize, cassava, achira (*Canna edulis* Ker.) and fodder grass (*Pennisetum purpureum* Schumach. and *Panicum maximum* Jacq.). Fruit trees are integrated at 300 to 400 trees ha^{-1} depending on species and management preferences of farmers. On most farms, trees occupy 60 - 70 % of plot areas. The ongoing adoption process of agroforestry practices provides a solid foundation for our study by offering an established context and the opportunity to elicit direct feedback from adopting farmers.

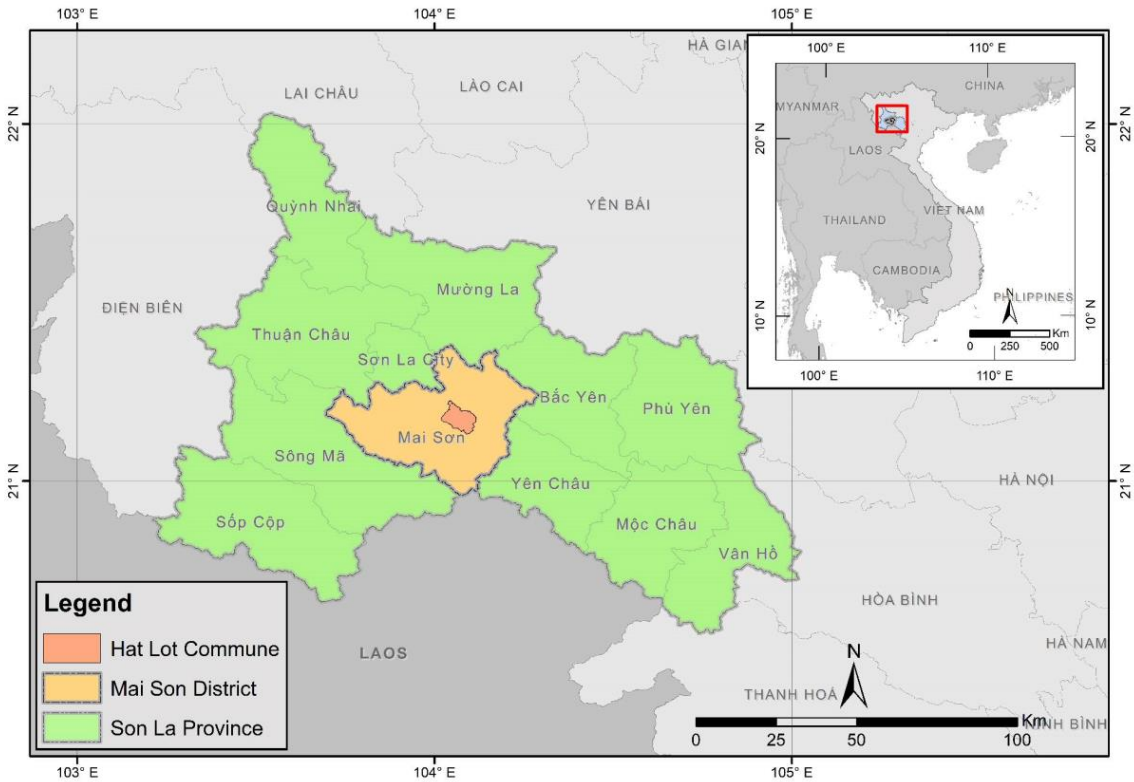

Fig. 1 Map of the study area in Son La province, adapted from Do et al. (2024)

2.2. Methodological approach

We combined Bayesian Network modeling and adoption pathway analysis (Montes de Oca Munguia et al. 2021b) to analyze farmers' adoption processes. We used a Bayesian Network to model factors and underlying mechanisms that drive adoption decisions. Adoption pathway analysis was adapted to explore individual journeys in adopting agroforestry practices.

A Bayesian Network is a probabilistic model using a directed acyclic graph to represent the relationship between different factors and target outcomes. The graph shows how these factors are interconnected and how they influence the outcomes in a cause-and-effect manner, with each connection assigned a probability that describes the strength of the relationship. This representation allows models to capture and represent uncertainty in predicting the outcome based on the influence of multiple factors. Each node contains a finite set of states that the variable may take. For example, a variable for an adoption decision can have 'yes' and 'no' as its states. If the state of one variable (parent node) influences the state of another (child node), a directional arc is drawn between the two nodes. Nodes are quantified according to the likelihood associated with each state the node can adopt. These probabilities are considered unconditional for nodes without parents (root nodes). For child nodes, conditional probabilities presenting the influence of parents are defined in the conditional probability tables (CPTs) associated with the nodes. The inference from Bayesian Network models provides probabilistic explanations or predictions for a set of target variables given probability distributions of other variables based on Bayes' theorem (Heckerman et al. 1995). The intuitive graphical structure of Bayesian Networks avoids the black-box character of other statistical models, facilitating effective communication and enabling a shared understanding of the interconnectedness of variables and potential intervention points.

Adoption pathway analysis (Montes de Oca Munguia et al. 2021b) categorizes the farming population based on their adoption journeys. The method traces individual progress throughout adoption stages and graphically represents the diverse array of pathways. The approach adds nuance to the analysis of adoption progress (Montes de Oca Munguia et al. 2021b). The application of adoption pathway analysis has been demonstrated for different technological practices for pastoral farming in New Zealand (Montes de Oca Munguia et al. 2021b)

Our study includes five steps (Fig. 2), starting from reviewing existing frameworks and theories on adoption, to developing the core analytical framework.

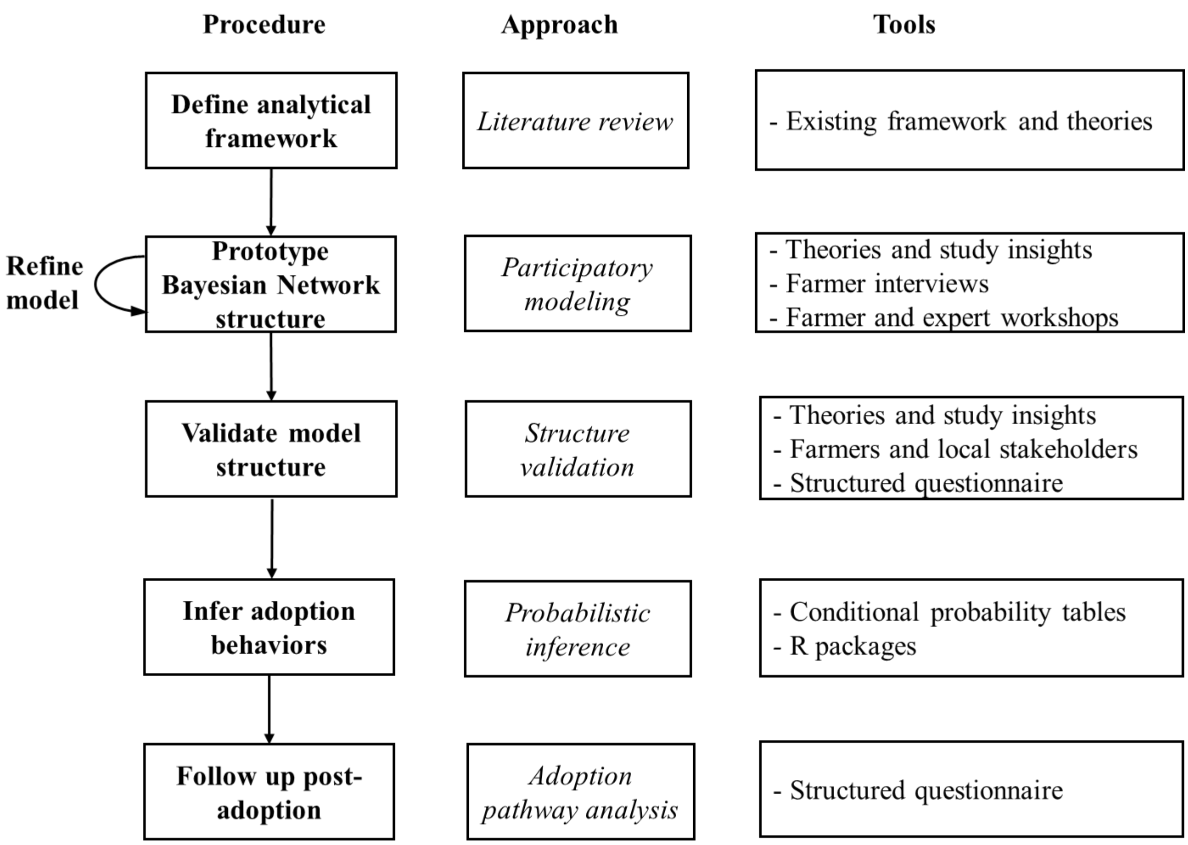

Fig. 2 Research procedure with corresponding approaches and tools used in this study

2.2.1. Define analytical framework

Pannell et al. (2006) outlined potential stages in the adoption process of agricultural technology and innovation. The adoption process often starts with awareness of the existence of an innovation and its potential practical relevance to the farmers. The awareness of the problem or opportunity triggers farmers to begin paying attention and collecting information on the new practice to inform their decisions. Information can be obtained by consulting external sources (non-trial evaluation) or through own experience (trial evaluation). Depending on the collected information or trial results, farmers may fully adopt the practice (adoption) or reject adopting the practice (non-adoption). Farmers often change or modify practices to adapt them to their specific circumstances (review and adjust). The use of adopted practices can be discontinued due to changes in circumstances (dis-adoption). We adapted the staged model of farm-level adoption proposed by Pannell et al. (2006) (Fig. 3). We found that about 81% of farmers (101 out of 124 respondents in exploratory interviews) were unsure or unclear about whether they considered themselves trialing or adopting agroforestry when initially integrating the practice into their farms. We treated trial and adoption as equivalent stages to address this uncertainty. If farmers introduced agroforestry on at least one of their plots, we counted this as adoption.

Farmers then evaluate agroforestry performance through on-farm implementation (Review and Adjust) to inform and update their decisions on whether to drop (Dis-adoption) or continue using (Future use) the practices. Non-adopters (Non-adoption) may turn into adopters (Adoption) if the circumstances change in a way that facilitates agroforestry adoption.

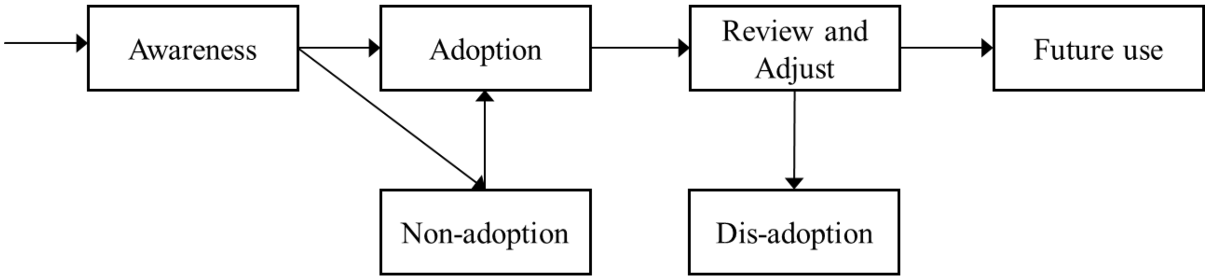

Fig. 3 Analytical framework used for identifying adoption stages in the Bayesian Network and for investigating the adoption pathway

2.2.2. Prototype the Bayesian Network structure

We analyzed factors that drive farmer decisions at two key stages in the adoption framework (Fig. 3), including 1) the decision to adopt and 2) the decision to sustain use. Sustained use was defined as farmers expressing their intention to maintain the adopted agroforestry practices for 20 – 25 years, the typical timeframe for productive cycles of fruit trees in the location.

We employed an expert-informed approach in developing the Bayesian Network to derive factors that represented the views of agroforestry practitioners regarding their decisions (Whitney et al. 2018). This approach leverages the experiential knowledge of farmers and relevant stakeholders, incorporating insights that go beyond quantitative data to capture real-world decision-making dynamics (Mayfield et al. 2023). Experts and farmers contribute nuanced, context-specific insights that allow the model to prioritize influential factors and relationships, focusing on the most critical variables. By including the perspectives of farmers and local stakeholders, the model benefits from collective reviews which enhance its credibility and reliability as a tool for decision-making and policy guidance. Moreover, this approach supports iterative refinement, ensuring that the model remains adaptable and practically applicable as new insights emerge (Robertson and Wang 2004; Stewart-Koster et al. 2017).

The network structure was populated with inputs from farmers, local extension workers and researchers involved in previous collaborative projects run by CIFOR-ICRAF through an iterative process of clarification and revision. The development of the Bayesian Network involved the following steps:

- Elicit network structure: Factors were identified and connected using participatory modeling workshops.
- Assign states for network nodes: Each variable in the developed network was assigned possible states that it may take.
- Develop conditional probability tables: The probability table associated with each variable in the network was constructed based on inputs from workshop participants and farmer interviews.

Elicit network structure. We started by identifying variables to be included in the network by reviewing different concepts and theories used in decision-making models from the extensive body of research on sustainable farming practices summarized by Montes de Oca Munguia et al. (2021a) and Githinji et al. (2023). We then selected and connected variables using contextual insights from extensive field observations and interviews. We conducted face-to-face interviews with 124 farmers from June to August 2022. Village heads and extension workers helped us compile lists of adopting and non-adopting farmers within each of the villages. Adopters were farmers who had implemented fruit tree-based agroforestry on at least one of their plots, whereas non-adopters manage only sugarcane and/or annual crop plots without having any tree-based plots in their systems. Invitations were extended through phone calls and direct communication, with participation in interviews being voluntary. Whenever possible, snowballing was employed to recruit additional participants not on the initial lists, through recommendations from previously interviewed farmers. Fourteen farmers, including two adopters and twelve non-adopters, declined our invitations, mainly due to time constraints caused by their farm work. A summary of the characteristics of interviewed farmers is provided in Table S2 in the Supplementary Materials.

We then conducted workshops with two different stakeholder groups:

- The researcher group consisted of 2 researchers from the Northern Mountainous Agriculture and Forestry Science Institute (NOMAFSI), 3 researchers from the Soils and Fertilizers Research Institute (SFRI) and 1 researcher from CIFOR-ICRAF. These experts were selected for their active involvement in the previous projects' work packages on farm-level implementation of agroforestry in the study area. Contacts of the AFLi project leader facilitated communication with experts from NOMAFSI and SFRI. The main purpose of setting up this group was to gather expert opinion on the modeling approach and collect suggestions to prepare for the participatory modeling exercises.

- The local stakeholder group consisted of 12 farmers including both adopters and non-adopters (10 males and 2 females), 2 village heads and 1 extension worker. This group was the main source of information for the model-building. All farmers who participated in the workshop had also participated in the farmer interviews.

We conducted these workshops separately due to the physical distance and difficulties in synchronizing attendee availability. Given the motivation and scope of the model (i.e. analyzing farm-level decisions), we also found it unnecessary to have everyone in the same workshop.

In the workshop with the researcher group in September 2022, we presented our analytical framework and the initial conceptual models to the domain experts. The experts conducted a thorough review, critically examining all variables and their relationships. They emphasized the importance of markets and affordability in farmers' decision-making process and confirmed that the model structure was adequate for capturing farm-level decision factors. We also received valuable suggestions for the upcoming modeling workshop with farmers. The experts recommended categorizing potential factors into groups to facilitate systematic consideration during network development with local stakeholders.

The workshop with local stakeholders took place shortly after the workshop with the researcher group. In this workshop, we first presented the analytical framework to the participants and clarified the purpose of the modeling exercise. We used a simple Bayesian Network example to explain the concept of conditional probability, avoiding technical jargon. The network was co-constructed with the participants. We deliberately withheld the pre-existing models derived from literature and expert consultations to enable us to capture fresh perspectives from farmers who were actively engaged in adopting the practice. Following the experts' recommendations, we considered factors by categories such as characteristics of farmers (e.g. sociodemographic traits, experience and knowledge, personal preferences and attitudes) and household-level factors (e.g. land endowment, income, farming strategy). We also considered attributes of the agroforestry practices (e.g. investment and technical requirement, advantage perceived by farmers), as well as external factors (e.g. supporting incentives). We started populating the network backwards from the outcome variables. Participants were asked to identify variables belonging to each factor category that they believed to have driven their decisions on adoption and sustained use. To avoid cluttering the network with many arcs pointing to the same node, which could overwhelm the later stages of populating conditional probability tables (CPTs), we limited the number of parent nodes to three for each child node to maintain focus and clarity.

For instance, when participants linked a list of factors (e.g. market condition, household economic status, incentive, peer experiences, confidence, household need and soil erosion) directly to the adoption node, we encouraged them to conduct a detailed analysis of the direct and strict influences. We requested further elaboration on the underlying interactions between these factors by adding intermediary nodes where necessary. Based on the farmer-derived network and our preliminary network, we generated a final network (Fig. 4) and used it for the next steps of the model development. A full description of the variables is provided in Table S3 of the Supplementary Materials.

Assign states for network nodes. After the network structure was completely defined, we assigned a set of states representing possible values the node may take for each node in the network (Table S3, Supplementary Materials). This discretization process was straightforward since most network nodes were categorical variables. We built on the results from Do et al. (2024), which identified three discourses on fruit tree-based agroforestry practices, to assign states for variables on farmers' attitudes and perceived benefits. The three discourses include one in which farmers believe that agroforestry benefits their households, one where farmers perceive some benefits but also recognize challenges and one where farmers focus on the challenges of the practices. These three discourses fit to three state levels of attitudes ("Positive", "Neutral", "Negative") and perceived benefits ("High", "Moderate", "Low").

The node on sustained use, which can assume the states "Continue", "Dis-adoption" and "Unknown", aims to describe the post-adoption behavior of farmers in the long run (i.e. maintaining agroforestry practices for 20 to 25 years). This node is conditioned on the adoption node, which has "Yes" and "No" states. To consider use "sustained", the adoption must first have happened ("Yes"). The "No" state of the adoption node was not explicitly considered, since this would require an update of the adoption node in the next time step, which is beyond our model's scope. Therefore, we extended the state space of the future-use node to include an "Unknown" state. This extension accommodates scenarios where the adoption node takes "No", as well as situations where the adoption node takes "Yes" but uncertainty remains regarding future use of agroforestry.

Develop conditional probability tables. We constructed conditional probability tables of the entire network mainly based on knowledge elicited from workshop participants, combined with information derived from 124 farmer interviews. We used the data from the interviews to derive probabilities for some root nodes such as nodes on extension, farmer network, household income, incentives, farming strategy, and experience with soil erosion. For nodes with parents, we used a direct elicitation method (Stewart-Koster et al. 2017) to construct conditional probability tables (CPTs), which provided probabilities of node states given all the configurations of its parents. We elicited values in the CPTs of all the nodes during our second workshop in July 2023 with the same groups of participants. An example of a conditional probability table for the node describing farmers' access to information is provided in Table 1. The node has two states, "Yes" and "No", representing two possibilities of whether farmers have access to information. The probabilities for these possibilities sum up to 1 and are conditioned on all combinations of the node's parent states, in this case, *Extension* ("Strong "and "Weak") and *Network* ("Good" and "Poor"). The values in the table were derived from consensus estimates provided by farmers during the modeling workshop. The model code explicitly formulates CPTs for all model nodes (available in a data repository at https://doi.org/10.5281/zenodo.12682675).

Table 1. Conditional probability table for the node describing farmers' access to information

Extension	Network	Access to information	
		Yes	No
Strong	Good	0.9	0.1
Weak	Good	0.7	0.3
Strong	Poor	0.6	0.4
Weak	Poor	0.1	0.9

2.2.3. Validate Bayesian Network model structure

The development of a Bayesian Network exposes the model to four areas that contribute to uncertainty in model validity: structure, factor discretization, population of CPTs and model behavior. The model behavior arises from the joint likelihood of the entire network, including sub-networks and relationships. The confidence in model behavior is, hence, founded upon the validity of the other three dimensions of the model. We employed a broad construct of validity proposed by Pitchforth and Mengersen (2013) to provide local validity assessments of network components by comparing the developed network with existing literature and acquiring confirmation from participants who contributed to network development. We presented the model structure and outcomes to farmers and extension workers during our field visits between May and July 2023 and asked for their comments on model behavior.

2.2.4. Bayesian Network model programming and inference

We used the Bayesian Network to make inferences on adoption behavior given the combined effects of factors. We also examined the model responses by introducing evidence on some key variables suggested by workshop participants. We systematically changed one variable at a time and assessed the effects on adoption and sustained-use decisions. Additionally, we conducted an analysis where these variables were changed simultaneously to examine their collective influence. We estimated the uncertainty in the model outcomes of *Adoption* and *Usage* nodes by performing 10,000 Monte Carlo simulation runs. In each run, the model randomly sampled values for each node based on its predefined conditional probability table (CPTs). This stochastic process allows us to explore and quantify the variability in the outcomes caused by the probabilistic nature of the inputs. The distribution of results from these simulations provides an empirical basis to assess the range and likelihood of different adoption rates for different scenarios.

Programming and inference of the Bayesian Network were implemented in the R statistical software (R Development Core Team 2022) using the bnlearn (Scutari 2010) and gRain (Højsgaard 2012) packages. The code and analyses are available in a data repository at https://doi.org/10.5281/zenodo.12682675.

2.2.5. Follow-up after adoption

We elaborated our analyses on post-adoption behavior to investigate the progress of individual farmers, which cannot be considered explicitly with the Bayesian Network model (e.g. Review and Adjust). We adapted the adoption pathway analysis procedures proposed by Montes de Oca Munguia et al. (2021) to analyze farmers' adoption processes (Fig. 3). The adoption pathway analysis was based on a structured questionnaire focusing on farmers' land allocation given the context of agroforestry adoption. The questions captured the dynamics of cropping patterns, covering the historical and current situations and future land use plans for each land plot. This knowledge allowed us to identify non-adopters, current adopters, and former adopters and the level of adoption. For adopters, we included questions on changes in the structure farmers had already made, as well as on their intentions to modify system design and change the area allocated to agroforestry over the next 5 years. The 5-year timeframe was chosen to ensure that farmers could provide reliable responses. The interviewed adopters had been practicing agroforestry for an average of 7 years (ranging from 5 to 11 years), making a 5-year time period a reasonable basis for considering their future intentions. The structured questions were included as part of the same farmer interview conducted during the exploratory phase of the development of the Bayesian Network. We used a Sankey diagram (Sjoberg 2021) to visualize individual adoption processes as a flow of farmer proportions along the pathways.

3. Results and discussion

3.1. Farmers' reasoning behind adoption decisions

The network structure consists of 20 variables which are connected to provide a comprehensive understanding of the mechanisms that drive farmers' decisions regarding agroforestry practices (Fig. 4). There are two main structuring elements: the adoption decision (*Adoption*) and the sustained-use intention (*Usage*). The below sections explain farmers' reasoning on the two structuring elements, starting from the outcomes (i.e. *Adoption* and *Usage*).

Structure of adoption decisions. The direct enabling conditions for the adoption of agroforestry (*Adoption*) involve a farmer's desire to practice agroforestry (*Intention*) and the financial viability of agroforestry practices. While the farmer's intention is important, it alone is insufficient for adoption. Some farmers "*wanted to incorporate fruit tree-based systems but did not have enough financial capital until [they] got tree seedlings and input support from projects* (*Incentives*)" (workshop participant). Conversely, some farmers "*could afford the investment (Affordability) but [did not] feel the need to adopt*" (interviewed farmer). Therefore, intention to adopt, affordability and incentive were identified as the three variables that strictly influenced the adoption decision. Affordability is defined by the overall household income situation (*Household income*) and the investment required for implementing agroforestry practices (*Investment*).

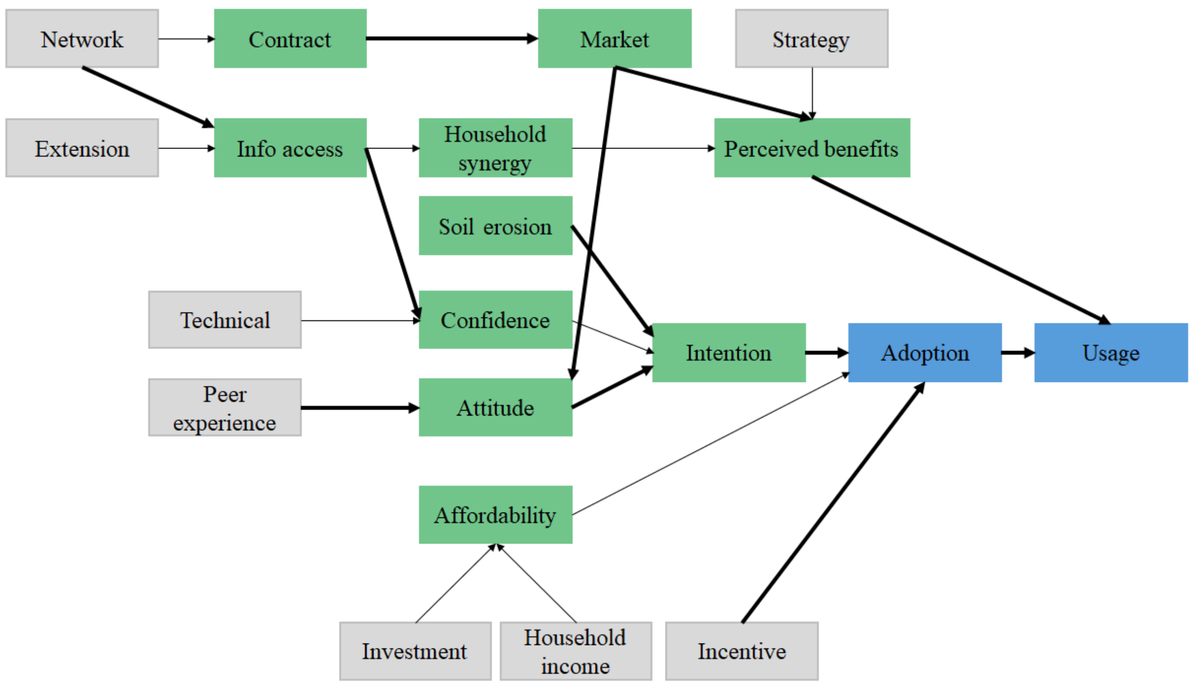

Fig. 4 The web of factors affecting agroforestry adoption, as conceptualized by farmers. Bold arrows indicate a particularly strong influence of parent nodes on child nodes, while thin arrows indicate a weaker influence. The probabilities of root nodes (grey boxes) were derived from 124 farmer interviews. Conditional probabilities of intermediate child nodes (green boxes) and outcome nodes (blue boxes) were derived from results of the farmer workshop

Farmers are motivated to adopt agroforestry (*Intention*) when they are confronted with severe soil erosion (*Soil erosion*), which aligns with the findings by Nguyen et al. (2021) and Do et al. (2024) that soil erosion is among the key drivers of the shift towards tree-based farming systems among the studied population. Furthermore, the perception of agroforestry as an effective method for controlling erosion has been found to positively correlate with adoption likelihood (Ahmad et al. 2023) and serves as a primary motivation for adopting agroforestry practices (Ullah et al. 2023). The intention to adopt agroforestry is strengthened when farmers hold positive views of agroforestry (*Attitude*) and are confident in their knowledge and skills (*Confidence*) related to the practice. Some farmers hesitated to adopt because "*agroforestry could be difficult, and [farmers] do not know the techniques*" (*Technical*) (workshop participant). Access to information (*Info access*) might boost farmers' confidence. Farmers mainly "*ask others in the villages about cultivation techniques or pest and disease control*" (workshop participants). Occasionally, farmers "*come to training sessions organized by the government*" (workshop participants). This indicates that the robustness of extension activities (*Extension*) and farmer networks (*Network*) contributes to the farmers' access to information.

Attitude toward agroforestry is influenced by "*good market prices of fruits*" (*Market*) (workshop participants) and by farmers seeing "*others in the village get fruits to eat and to sell* (*Peer experiences*)" (workshop participant). One workshop participant stated that "*market prices would be more stable if [farmers] got fixed contracts for fruits"* (*Contract*), which, however, may be unavailable in the context of the fragmented production patterns of smallholder farming. The feasibility of such a contract can be enhanced by the presence of organized farmer networks (*Network*), which can serve as a "*venue to collect fruits for large supply to meet the company requirements*" (workshop participants). Literature similarly emphasizes the importance of market incentives, peer influence, and organized networks in promoting agroforestry adoption. For instance, Rois-Díaz et al. (2018) found that learning from others and witnessing the benefits firsthand serves as a key motivation for farmers to adopt agroforestry practices. Farmers often need visible examples of profitability and other benefits to feel confident about investing in such practices. Additionally, Andersson (2020) indicates underdeveloped markets as a critical challenge in agroforestry value chains and suggests that smallholders could benefit significantly from organizing themselves into cooperatives. Such structures can strengthen market positions, potentially transforming the system to reach a broader group of smallholders. Once cooperatives or organized producer groups can guarantee a steady product volume to outlets like supermarkets or farmers' markets, price stability can improve.

The structuring elements of the adoption node align with the theory of planned behavior (Ajzen 1985), which distinguishes between intention and behavior. In our adoption model, the decision on initial uptake (*Adoption*) can be considered as the behavior, which is influenced by the farmer's desire to adopt (*Intention*) and other enabling factors, in this case, the affordability of the practice (*Affordability*) and external support (*Incentive*). The two factors *Attitude* and *Confidence*, which influence the farmers' intention to adopt, draw parallels to the constructs of attitude and perceived behavioral control, which influence the intention to display a certain behavior (Ajzen 1985).

Structure of sustained use. The decision of using agroforestry practices (*Usage*) is first conditioned on previous adoption (*Adoption*). Farmers who have adopted these practices develop perceptions from their own experiences with the new practices (*Perceived benefits*). The perceived benefits, including market opportunities (*Market*) and synergistic effects of agroforestry practices on household needs (*Household synergy*), play a crucial role in sustaining the use of these practices. These advantages are perceived differently by farmers depending on their individual farming strategies (*Strategy*), such that "*even though prices for fruits are unstable, [agroforestry] still supports family needs for food and livestock and reduces labor intensity*" (workshop participant). The structure regarding the sustained use of agroforestry practices is comparable to the satisfaction model describing behaviors of sustained use or intensity of using a new practice (Johnson et al. 2001). The satisfaction model suggests that the quality of the experience using the innovation results in satisfaction, which leads to the user's loyalty toward the innovation (Johnson et al. 2001). The satisfaction model has been suggested as a potential framework to explain the ongoing use and the intensity of use of agricultural innovations (Montes de Oca Munguia et al. 2021a). Referring to our network structure, a positive experience resulting in high satisfaction (*Perceived benefits*) could lead to continued use of agroforestry practices. In contrast, negative experiences cause a reduction in the level of satisfaction, which may trigger the need to explore alternative options.

3.2. Farmers' adoption behavior under different scenarios

We calculated the model outcomes on adoption behavior (i.e. *Adoption* and *Usage* nodes) for the current situation and for scenarios that assumed changes in some variables suggested by participants during the workshops, including *Network, Extension, Market,* and *Incentive*. We investigated how changes in these variables would influence farmers' decisions. We systematically changed one variable at a time and changed all the variables simultaneously to assess the impacts of single changes and combined modifications.

In the current situation, the likelihood of farmers adopting a fruit tree-based agroforestry practice is 0.54. The joint probability of farmers adopting agroforestry (*Adoption* = "Yes") and continuing it (*Usage* = "Const") is 0.34. This means that once adopted, agroforestry is likely to be retained with a likelihood of 0.64. The probability of dis-adoption is low, at 0.09 given the joint probability of *Adoption* = "Yes" and *Usage* = "Dis" is 0.05.

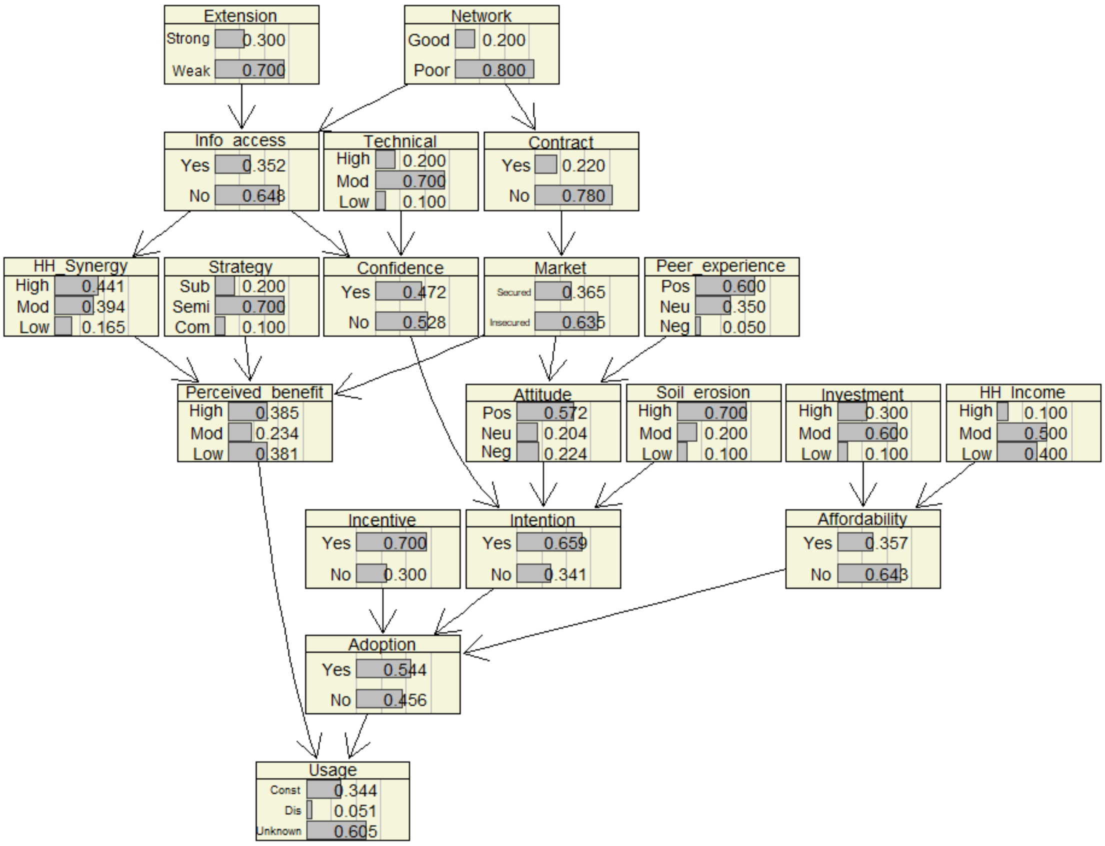

Fig. 5 Bayesian Network model of the adoption of fruit tree-based agroforestry practices. Boxes are variables with their states and associated (conditional) probability tables. Arrows indicate dependencies between variables

Table 2 presents model outcomes for different scenarios of factors, including *Network, Extension, Incentive* and *Market*. The probability of adoption changes to 0.55 with robust extension activities (*Extension* = "Strong"). The adoption probability increases to 0.57 in the presence of a well-organized farmer network (*Network* = "Good"). The presence of a secured market (*Market* = "Secured") and incentives (*Incentive* = "Yes") raise the probability to 0.62 and 0.63, respectively. When combined (*Incentive* = "Yes", *Extension* = "Strong", *Market* = "Secured"), these factors synergistically increase the likelihood of adoption to 0.72. The rate is comparable with the observed rate of 86.3% in the adoption pathway analysis (Fig. 6). The observed rates might stem from the influence of the previous project, where incentives, extension activities, networks, and market conditions were set up to favor the adoption of agroforestry. Within project frameworks, farmers often receive tree seedlings and subsidized production inputs (La 2022). Such projects enhance extension activities through well-organized training sessions and regular interactions between farmers and extension agents. Additionally, farmers can participate in project networks to learn from peers and establish market connections (La 2022). However, these favorable conditions often deteriorate once the projects end. The difference between the simulated adoption rate of 0.72 and the observed 86.3% may have several causes. Additional contextual influences during project implementation, such as enhanced community engagement or favorable external economic conditions, may have boosted the observed rate. Additionally, this difference could reflect an initial surge in adoption, a common phenomenon in development projects, or it could be due to sampling bias, where farmers who did not participate in our interviews are predominantly non-adopters.

The findings highlight the impact of support mechanisms such as extension services, farmer networks, secure markets and incentives in promoting the adoption and continuity of agroforestry practices. The analysis indicates that each factor raises the likelihood of adoption, especially with incentives and secure markets. The combined effect amplifies the adoption probability even further. Once adopted, agroforestry practices are generally sustained, as evidenced by the low likelihood of dis-adoption observed in the adoption pathway analysis (Fig. 6). This persistence underscores a strong commitment among adopters to tree-based systems, largely because farmers perceive trees as a long-term investment. The low likelihood of dis-adoption may also result from farming strategies inherently being tailored to local farm structures. Farmers typically manage multiple land plots, and they allocate these plots to diverse crop settings. This diversification helps secure income from other plots when market risks for agroforestry products arise (Do et al. 2024). Meanwhile, agroforestry contributes to households' livelihoods in various ways, e.g. by providing livestock feed and diversified food sources for household consumption (Nguyen et al. 2021; Do et al. 2024) and by reducing labor needs relative to other farming options (Do et al. 2024). The increased likelihood of adoption under combined support scenarios and the high adoption rates observed during project periods highlight the need for durable support systems to promote widespread adoption of agroforestry practices.

Table 2. Mean values and 90% confidence intervals (CI) (in parenthesis) of the model outcomes (*Adoption* and *Usage* nodes) under various evidence scenarios

Evidence	*Adoption* = "Yes"	*Usage*		
		Continuous	Dis-adoption	Unknown
Baseline	0.54 (0.25 – 0.73)	0.34 (0.16 – 0.49)	0.05 (0.02 – 0.08)	0.60 (0.46 – 0.81)
Incentive = "Yes"	0.63 (0.5 – 0.74)	0.40 (0.31 – 0.51)	0.06 (0.04 – 0.08)	0.54 (0.44 – 0.64)
Extension = "Strong"	0.55 (0.25 – 0.74)	0.35 (0.16 – 0.48)	0.05 (0.02 – 0.07)	0.59 (0.46 – 0.82)
Market = "Secured"	0.62 (0.32 – 0.75)	0.49 (0.25 – 0.61)	0.01 (0.007 – 0.02)	0.5 (0.37 – 0.74)
Network = "Good"	0.57 (0.28 – 0.74)	0.40 (0.20 – 0.52)	0.04 (0.02 – 0.05)	0.56 (0.43 – 0.78)
Incentive = "Yes"; *Extension* = "Strong"; *Market* = "Secured"	0.72 (0.64 – 0.77)	0.57 (0.51 – 0.62)	0.02 (0.01 – 0.02)	0.41 (0.37 – 0.48)

3.2.1. Model implications for potential supporting schemes

The strong responses of the *Adoption* node to changes in the *Market* and *Incentive* nodes suggest these two nodes for potential interventions. A lack of secure markets remains a structural challenge hindering the wider use of agroforestry in the area. The establishment of fruit processing facilities by the private sector was expected to boost markets for fruits. However, these facilities have disappointed farmers' expectations due to the low and unclear commitment of the private sector to the local fruit value chains. Fragmented production in smallholder contexts, however, cannot easily meet the requirements of large fruit processing companies. This limitation makes it difficult for farmers to secure reliable contracts with such companies. Addressing these issues requires a dialogue among relevant stakeholders to understand each other's expectations and capacities to find optimal solutions. The role of the government is crucial in coordinating and implementing such dialogues to avoid undesirable consequences of improved market access facilitated through production contracts. Government involvement is important because investments that are driven exclusively by profit expectations may carry significant ecological costs (e.g. biodiversity loss) (Abman and Lundberg 2024). Appropriate support and coordination from the government are also essential for encouraging the commitment of private-sector actors and for strengthening cooperation among farmers and between farmers and the private sector. Such cooperation could enhance the sustainability of value chains for local agroforestry products.

During model development and farmer interviews, we recognized that farmers focused on soil erosion as a key driver of adoption while neglecting other environmental aspects. This oversight may not be caused by disinterest but rather reflect their lack of awareness of a direct connection of such aspects to local livelihoods, which may not have been the focus of supporting schemes aiming to promote new farming practices. Lessons can be drawn from past experiences, such as the introduction of hybrid maize varieties and synthetic fertilizers to increase maize yield (Keil et al. 2008; Dang and Nguyen 2020). The government's strong support for this technology package promoted the expansion of intensive monocultures, often leading to soil erosion and subsequent degradation of agricultural landscapes, especially in the uplands (Keil et al. 2008; Quang et al. 2014). Interviewed farmers stated that the focus on yield increase induced them to "*plough the soil thoroughly and completely remove weeds using both herbicide and hand hoeing*" thinking that they are "*diligent farmers for the efforts*". In many places, this practice led to topsoil erosion, exposing infertile soil layers. This degradation has had environmental implications and has been perceived by farmers as harming crop yield. This environmental feedback was overlooked when promoting and adopting the new technologies, as evidenced by farmers being *"[unaware] of potential consequences of soil erosion, which has now jeopardized the soil fertility and its ability to secure [their] crop yields*.".

The government can justify supporting schemes based on the climatic impacts of agroforestry, citing, for instance, its policy on Payments for Ecosystem Services, which aims to maintain and support forestry (Simelton et al. 2017). Agroforestry is recognized in Vietnam's Nationally Determined Contributions (NDCs) among climate measures in the Land Use, Land Use Change, and Forestry (LULUCF) sector (Decision 891/QĐ-BNN-KHCN) (Mulia et al. 2020). There is a mismatch between national climate ambitions related to agroforestry and the level of support provided for the practice. In Decision 156/QĐ-BNN-KHCN, the government highlighted its commitment to supporting fruit tree-based agroforestry to enhance livelihoods and strengthen climate change adaptation in the northwestern region. This initiative is among missions for implementing the national plan for climate change adaptation for 2021–2030, with a vision extending to 2050 (Decision 1055/QĐ-TTg). While short-term incentives for farmers, such as subsidies for tree seedlings and inputs, have been embedded in pilot projects aiming to increase adoption rates, sustained support remains limited. According to a provincial extension officer, government policies supporting specific cropping systems "*require standardized* *technical specifications which are currently lacking for agroforestry due to the diversity of farmer-adapted implementations*". This diversity makes it challenging to monitor and measure agroforestry progress and its potential for climate change mitigation. Addressing this gap requires research focusing on developing frameworks for engaging land users and other stakeholders in gathering and providing site-specific data and sharing local knowledge on agroforestry management. Such frameworks may provide a transparent procedure to support policymakers in setting clear climate targets and formulating supporting mechanisms. Thereby, the environmental benefits of agroforestry can be linked to national and individual-farmer benefits. Such climate-focused support mechanisms could be win-win options for both the government and farmers. The bottom-up engagement of farmers in developing an agroforestry carbon measuring framework can also enhance farmers' awareness about the importance of environmental impacts to their farming activities and the direct influence of these impacts on their livelihoods.

3.2.2. Model implications for outreach and extension measures

Strong extension activities (*Extension* = "Strong") did not result in a higher adoption likelihood, implying that the public extension services currently do not play a role in farmers' adoption decisions. The weak influence indicates a disconnect between farmers and the current public extension system. Farmers revealed that they have few contacts with public extension systems (at best "*once or twice a year during annual governmental extension programs or in the presence of funded projects*"). Some farmers *"[did not] know or [were not] interested in knowing who is currently responsible for agricultural extension work*". This lack of trust can be attributed to low effectiveness due to the weak organizational capacity of public agricultural extension departments. On the other hand, the interviewed farmers valued information exchange through informal networks such as farmer-to-farmer communication or conversations with local input providers. This preference may stem from relational values held in these networks, including relevance, trust, and place attachment (Martini et al. 2023). The relevance of agricultural extension is reflected in its orientation to farmers' needs, local resources, and social and cultural systems, i.e. its ability to extend beyond a narrow focus on increased production. The extension system should support two-way interactions for trusted learning and communication between farmers and extension agents and place greater emphasis on farmers' adaptation of innovations rather than simply on adoption. The integration of relational values is needed to gain people's support and involvement (Uehara et al. 2022) to achieve the goals of an agricultural innovation. The changing socio-ecological contexts require a paradigm shift in agricultural extension from a top-down to a co-constructionist approach (Allan et al. 2022). To achieve this goal, the existing public extension should be improved by introducing more robust, holistically oriented, and participatory extension approaches, such as on-farm experimentation (Lacoste et al. 2021) or by encouraging farmer-to-farmer extension through, for example, well-organized agricultural cooperatives (Do et al. 2024). The shift towards more inclusive extension systems can foster locally adaptive use of sustainable agricultural practices (Martini et al. 2023; Ishtiaque et al. 2024).

3.3. Farmers follow different adoption trajectories

All respondents were aware of fruit tree-based agroforestry (Fig. 6). The outcomes reveal that varying proportions of the farming population follow different adoption pathways, highlighting the diversity of farmers' adaptation of agroforestry to the local farming context. Most farmers (86.3%) had adopted the practice on at least one of their farm plots. Among the adopters, since first adopting the practices, 41.1% retained the initial level of adoption, 55.1% have expanded the area of agroforestry and 3.7% had reduced their agroforestry area, with one farmer reporting dis-adoption. Most adopters continued practicing agroforestry with some adjustments to the initial designs of the systems, for example, increasing the fruit tree density with species diversification, rotating annual crops, or integrating fodder crops for animal feed. These adjustments helped farmers to adapt to changes in market and climate conditions. Some farmers discontinued intercropping of annual crops in agroforestry plots after a few years due to increased tree canopy cover. Although the resulting trees-only practices may not fit the conventional definition of agroforestry, they can still be regarded as 'agroforestry as natural climate solution' (AF-NCS), given their potential contributions to carbon storage within the agricultural landscape (Terasaki Hart et al. 2023). About 15% of farmers maintained the initial system design since adoption. Most current adopters (66.4%) had allocated more than half of their land to agroforestry, with 16.9% devoting all land to fruit tree-based practices. Another 13.7% of interviewed farmers were aware of the practice but had never adopted it and remained non-adopters by the time of the interview, together with one farmer who dis-adopted, making up 14.5% of farmers with no agroforestry area in their current farm settings. The delayed adoption and dis-adoption can be attributed to the systemic nature of the shift to fruit tree-based agroforestry practices where fruit trees become the main cash crop, replacing annual crops that generate most of the farms' income in the existing annual monocultures. The investment level is moderate to high, forcing most farmers to modify the adoption process to afford the related expenses. Such adaptations include gradual transitions and allocation of agricultural land to various available farming options to secure short-term income and alleviate the investment (Do et al. 2024). Rapid transitions by small portions of surveyed farmers led to their farming systems being locked into a loop of unwavering investment with little gains, given the relatively weak markets for fruits. Consequently, farmers had to decrease or discontinue agroforestry and convert land back to annual crops to ease financial constraints arising from debt. High market risks in recent years also discouraged non-adopter farmers from taking up fruit tree-based farming practices.

About 87% of the adopters intended to maintain their current level or expand agroforestry areas, with very few aiming for full-scale adoption. Two farmers were considering reducing their agroforestry area or dis-adopting the practice because of weak markets for fruit products. Half of the non-adopters were interested in adopting agroforestry in the future. About 15% of interviewed farmers, including both adopters and non-adopters, were uncertain about their future decisions regarding agroforestry practices due to their perception of high market risk for fruits.

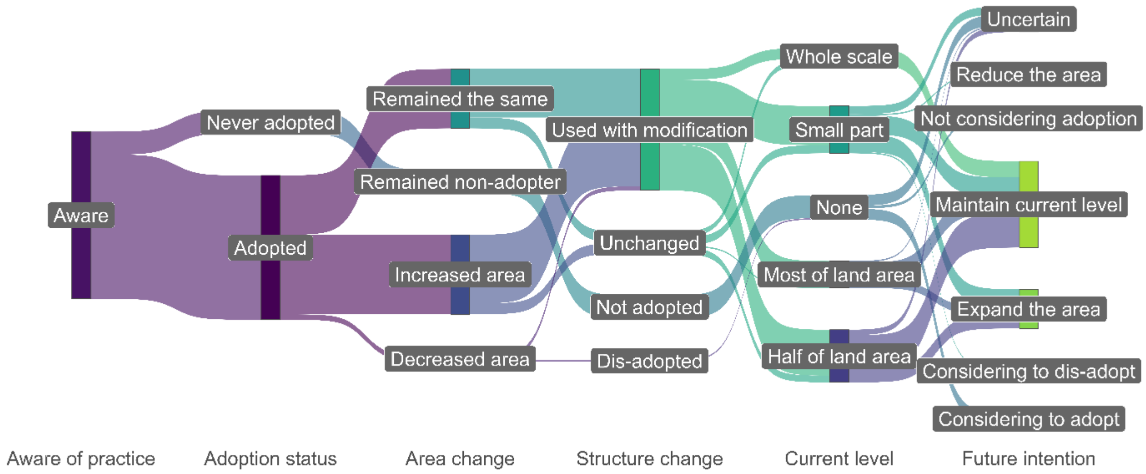

Fig. 6 Adoption trajectories taken by farmers since becoming aware of agroforestry practices and their future intention on the practices (Future intention). The interviewed farmers are categorized into groups that follow different trajectories, allowing researchers and development agents to pinpoint specific groups for targeting support

The adoption pathway analysis identified farmers who decreased or intended to decrease the use of agroforestry, as well as those who have successfully engaged in and expanded the practice in their existing routines. Engaging with these target groups becomes crucial for comprehending the circumstances that farmers encounter and their adaptation strategies. This engagement may allow planning effective extension strategies, co-learning to support behavioral change, and sustaining adoption. Hence, agroforestry research and development programs should consider adoption as a dynamic process, moving away from the conventional, categorical concept of adoption. This approach would incentivize shifting investment away from perfecting the full-scale adoption of technology packages towards focusing on the processes and farming systems in which the innovations occur (Montes de Oca Munguia et al. 2021b). Such a framework requires considering and exploring the relationships between farmers' decision-making and the system context (Do et al. 2024), which becomes increasingly important when scaling agricultural innovations.

3.4. Limitations of the study approach

Although farmer-derived Bayesian Networks provide valuable insights into decision-making from the farmers' point of view, the approach may introduce cognitive biases, potentially overlooking other important factors and interactions. For instance, farmers may anchor on soil erosion as the only environmental driver, as we highlighted earlier in the discussion. Given the flexibility of Bayesian Networks to incorporate a broad array of relevant issues and factors, including those that may emerge later (Moglia et al. 2018), ongoing updates are essential to ensuring that the model remains comprehensive and reflective of the full decision-making context.

To facilitate farmers' reflections during the workshop, the model was simplified to consider the sustained use of agroforestry over a single period (e.g. 20 - 25 years of maintenance). However, adoption is a dynamic process that requires ongoing review and adjustment (Pannell et al. 2006). Therefore, the probability of sustained use should be used to understand patterns rather than as a strong predictor of future behavior. To increase the accuracy of policy planning, e.g. the development of land use strategies, dynamic approaches such as dynamic Bayesian Networks could be used to capture changes over time with increasing precision as more data become available.

In addition, it is important to note that the model is built upon the perceptions of a specific community with distinct farming structures and preferences. As such, the factors integrated into the model are heavily influenced by their inputs, which may not necessarily be representative of other ethnic communities in northwestern Vietnam. The region is characterized by high heterogeneity in cultural practices and agricultural strategies, which may limit the generalizability of our findings. For instance, the model is tailored to the geographical and ecological specifics of an area that has historically engaged in monoculture on steep lands, leading to significant soil erosion. This historical context has made soil erosion a critical factor in the farmers' decision-making process regarding the adoption of agroforestry. However, this factor might not hold the same level of relevance in regions where soil erosion is less of a concern or managed differently. Given these conditions, the outcomes of our model are best understood as highly contextual to the studied community and its immediate environment. While this provides deep insights into the dynamics of agroforestry adoption in this particular setting, caution must be exercised when attempting to extend these findings to broader contexts. This limitation is acknowledged as a constraint to the external validity of our results. Future research should explore the adaptability of the approach to different contexts, potentially broadening the applicability of the methodology.

4. Conclusion

Our study seeks to delineate the complex web of factors involved in adoption decisions, focusing on identifying key variables and their joint effects. We also aim to investigate post-adoption dynamics, exploring farmers' unique pathways as they integrate agroforestry into their farming systems. The combination of a Bayesian Network and adoption pathway analysis demonstrated a comprehensive analytical framework for studying the dynamic adoption process of agroforestry. Informed by a participatory modeling approach, the Bayesian Network model analyzes the factors influencing adoption in a way that reflects farmers' mental models around their decision at a particular point in time. A secure market and the availability of incentives are two key measures that can enhance adoption outcomes by increasing adoption probability from 0.54 for the baseline to 0.62 and 0.63, respectively. When coordinated with robust extension services and strong cooperation among farmers, these measures can create a supportive environment that encourages adoption (probability of 0.72). Developing a Bayesian Network based on qualitative and quantitative information facilitated understanding of the multifaceted factors influencing farmers' decision-making in adopting agroforestry practices. The Bayesian Network model provides a boundary object for all relevant stakeholders to engage with and to provide assessments of the agroforestry adoption process in a manner of shared understanding. The adoption pathway analysis provided an easy-to-use tool that can support policymakers, researchers, and extension workers in following up on adoption, thereby facilitating the development of tailored and effective strategies to foster locally adapted farming practices. Sustained incentives via a climate-focused support scheme, enhanced market access for agroforestry products, and the development of inclusive, community-based extension services are essential for policies aimed at promoting widespread adoption of agroforestry. Future research should continue refining the understanding of adoption dynamics, including, for instance, analyses of farmers' perceptions on the impacts of agroforestry adoption and their satisfaction with these impacts. Such aspects are essential for comprehending the sustainability of adoption decisions. These insights can facilitate the design of support structures that are not only effective but also perceived as beneficial by the farming community. This will support the transition toward more resilient and sustainable farming systems.

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Data availability Model codes and Supplementary materials are included in a data repository https://doi.org/10.5281/zenodo.12682675.

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Chapter 4. Adapting agroforestry to upland farming systems: narratives from smallholder farmers in Northwest Vietnam

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Abstract

Fruit-tree based agroforestry has been promoted as an alternative farming practice in upland Northwest Vietnam to replace monocultures of staple crops. Although many studies have focused on evaluating the performance of agroforestry systems at the plot level, research on how farmers perceive and evaluate agroforestry considering whole-farm contexts is limited. We explored the perceptions and reasoned management decisions of agroforestry farmers to uncover challenges that hinder the wider use of agroforestry, and we assessed farmers' strategies for effective management of adoption challenges. We combined the Q methodology and the systems thinking approach. With the Q methodology, we explored prevalent discourses among the members of the farming community on the impact of agroforestry. Systems thinking elucidated a system-wide understanding of farmers' adaptive decision-making processes. By combining the two approaches, we uncovered the dynamics that shape farmers' perceptions and the rationale behind their management of the adoption process. Through the Q method, we identified three distinct discourses among participants. Two of these discourses are in favor of agroforestry, highlighting its beneficial impacts on livelihoods and the environment, e.g. through diversification of household income and through soil erosion control. We also generated a collective development pathway outlining how farmers navigated and adapted agroforestry practices to overcome adoption challenges through a whole-system approach to farm resource management. We identified structural barriers, such as unstable farm-gate prices, that may need high-level interventions. Our study adds a new dimension to the assessment of

agroforestry through farmers' perspectives and contributes to the existing body of research on knowledge systems in agroforestry. Considering farmers' views and their ways of reasoning during innovation processes may allow tailoring appropriate innovations by accounting for unique farm situations and local farming systems. Such locally generated knowledge will have relevance for real-world contexts and therefore be useful for guiding actions.

1. Introduction

Agroforestry is often promoted as a multi-benefit land use practice that increases the resilience of agricultural landscapes across tropical and temperate zones (Kuyah et al. 2019; Do et al. 2020b; Nair et al. 2021). However, farmers who adopt the practices still face many challenges in the transition towards viable agroforestry-based livelihoods. Agroforestry adoption requires drastic changes in cropping patterns, including the integration of new components. The change may carry with it economic trade-offs and risks for adopting farmers, especially those with limited resources. Reasons for this are complex interactions that agroforestry adds to the farming system, as well as the long-term planning horizon involved in the cultivation of trees (Do et al. 2020a). Meanwhile, scientific experiments might be insufficient to evaluate agricultural innovations such as agroforestry, especially within the context of small-scale farms in the tropics and sub-tropics, where farm management is diverse and heterogeneous. The heterogeneity is the result of diverse strategies, modes of thinking and aspirations that farmers may have with regard to their social and natural environments, in addition to a diversity of ways in which farmers organize their livelihoods (Stuiver et al. 2004). During the adoption process of new farming practices, farmers often make significant adaptations to the methods introduced to them by researchers (Stuiver et al. 2004). This can cause research-oriented designs to lose their predictive power when put into the real context of farm operations. Fig. 1 demonstrates the diversity of farmer-managed landscapes including agroforestry (intercrop of fruit trees, maize and fodder crops), paddy rice, sugarcane and community forest. Given the adaptive nature of farm management, understanding the underlying logic and rationale behind farmers' management decisions is important when aiming at a sustainability-oriented transition.

Farmer perception often involves various psychological constructs such as the farmer's knowledge, attitudes and beliefs regarding certain aspects of the farming system. A range of factors can influence and shape perception, including an individual's characteristics, personal experience, knowledge, and cultural beliefs, as well as local environment conditions (van der Linden 2015). These factors often vary greatly among farmers. Farmers' perceptions are therefore expected to vary accordingly, which may result in very diverse behaviors among farmers. In addition, farmers draw from a rich understanding of local resources and often engage strongly in maintaining socio-ecological systems in the face of changes and disturbance. Their views and perceptions, therefore, can provide contextual insights on what facilitates or hinders the transition, and on how systems can be designed and managed to better engage in a diversity of contexts. However, such local knowledge has remained under-exploited during the innovation process within the context of the prevailing dominant scientific knowledge system (Stuiver et al. 2004; Caron et al. 2014). Therefore, in this study, we aimed: 1. to identify different narratives that explain barriers for the wider use of agroforestry, and 2. to explore the reasoning behind management decisions for effective management of adoption challenges among agroforestry-practicing farmers in Northwest Vietnam. The findings may aid social learning and provide pointers on which outreach interventions may be effective in promoting wider adoption.

Fig. 1 Agroforestry managed by farmers in a mixed cropping landscape. Photo credit: Hoa Do

2. Materials and methods

2.1. Agroforestry projects in northwestern Vietnam

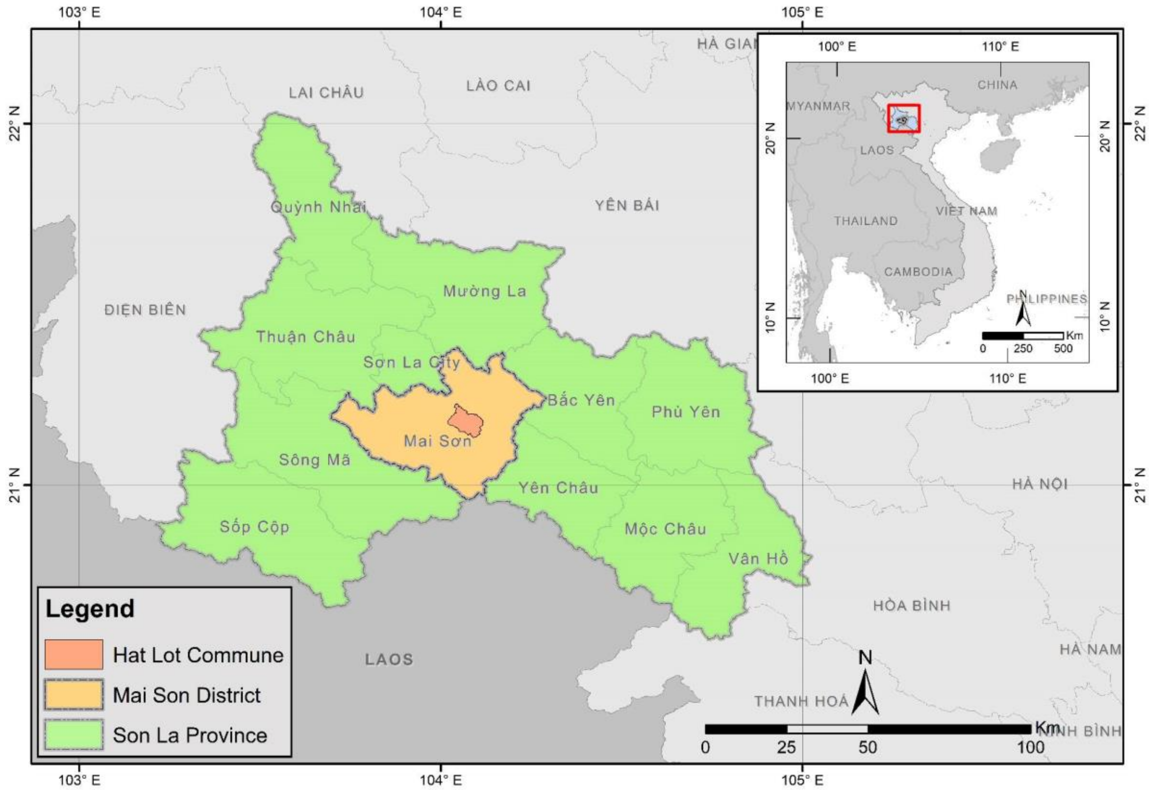

Fig. 2 Study location in northwestern Vietnam

We targeted agroforestry-practicing farmers in Son La, a province in northwestern Vietnam. In the region, agricultural activities mostly happen on slopes and have been dominated by monocropping systems of staple crops (mainly maize, upland rice and cassava) and sugarcane. Son La province has experienced a rapid expansion of intensive maize monocropping on slopes with the introduction of hybrid varieties and intensive use of synthetic fertilizers. The expansion of the maize area has impacted upon the environment through deforestation, intensive ploughing, and shortened fallow periods contributing to widespread soil erosion and land degradation. The depletion of soil fertility has reduced maize yields dramatically. The yield reduction has been exacerbated by climate change, which has been linked to increasingly frequent and unpredictable drought periods, especially at the critical stage of maize growth and development. Local livelihoods have been highly vulnerable. The province was one of the foci of recent efforts by World Agroforestry (CIFOR-ICRAF), who undertook a two-phase agroforestry project "Developing and promoting market-based agroforestry and forest rehabilitation options for Northwest Vietnam" (AFLI) from 2011 to 2021, which was funded by the Australian Centre for International Agricultural Research (ACIAR) and the CGIAR Research Program on Forests, Trees and Agroforestry. The aim was to enhance the livelihoods of smallholder families by introducing and promoting more sustainable land management practices. Through the project, agroforestry was first introduced via replicated on-farm trials of several agroforestry settings for scientific assessments. Research efforts have been invested to examine the agronomic, economic and environmental performance of replicated on-farm trials (Do et al. 2020a, b, 2023). Since 2015, exemplary landscape models of agroforestry have been established, alongside a government resolution promoting the cultivation of fruit trees on slopes (2015 – 2020), to encourage local participation within a larger area. Adoption of tree-based practices has transformed the structure of local land use from intensive monoculture of cash crops to more diverse and mosaic land use patterns. In this study, we directed our focus towards farmers who participated in the exemplary landscape models in two villages in Hat Lot Commune in Mai Son District of Son La (Fig. 2). Fruit tree-based agroforestry was introduced to participating farmers as an alternative to conventional monocropping systems. The participation of farmers in the exemplary landscape models was based on their willingness to participate and on the farmers' field plots being close to each other, to allow investigation of a landscape of agroforestry practices.

2.2. Research approach

We combined the Q methodology (Stephenson 1935) with systems thinking (Fig. 3). We used the Q method to uncover perceptions of farmers who have adopted agroforestry practices. Systems thinking was applied to elicit farmers' mental models, through which linkages between knowledge and action in managing the adoption can be captured.

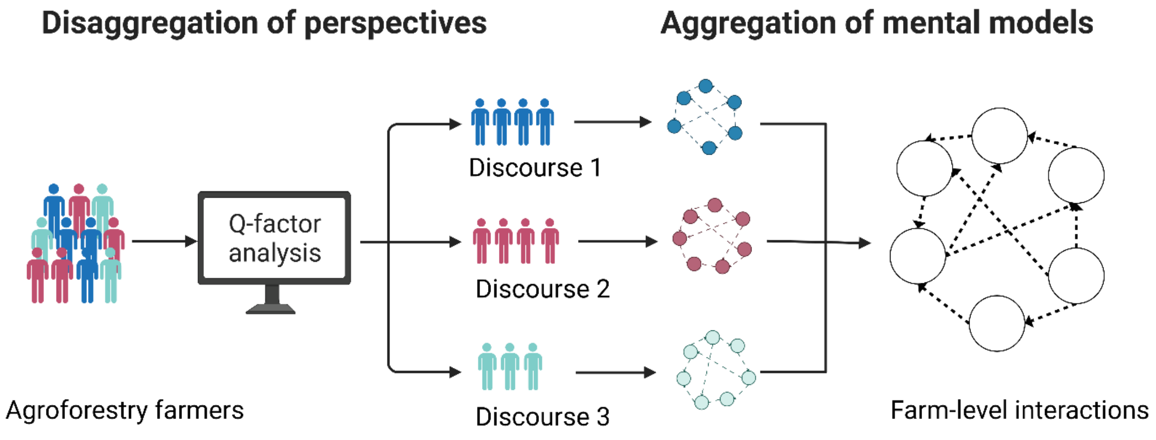

Fig. 3 Protocol combining the Q method and systems thinking to study farm-level impacts of agroforestry from a farmer perspective. Created with BioRender.com

2.2.1. The Q method for studying human subjectivity

The Q method is a semi-quantitative approach to facilitate the understanding of highly complex and socially contested concepts and subject matters in which human subjectivity is involved (Watts and Stenner 2005). The method seeks to uncover patterns of perspectives (discourses) within a group of actors on the topic of interest (Mukherjee et al. 2018). It provides a robust and systematic method to reveal consensus and disagreement among respondents. Q has been increasingly used across disciplines for multiple purposes such as policy evaluation (Zabala et al. 2017), understanding decision-making (Alexander et al. 2018) and guiding participatory processes (Sumberg et al. 2017; Truong et al. 2017; McHugh et al. 2019; Buckwell et al. 2020). The three main steps involved in the Q method are sorting, analytical process, and interpretation (Rost 2021). In its most frequent form, the Q method consists of selecting a set of statements from a universe of statements (concourse) on a certain concept (Watts and Stenner 2005) and asking respondents to sort them over a grid distribution (e.g. Fig. 4) based on their psychological significance, e.g. from "most agree" to "most disagree" (Mukherjee et al. 2018). The distribution shape can be predefined or freely defined throughout the interviews (Rost 2021), which is usually decided by researchers (Zabala 2014) based on the research context. The set of statements is ideally a representative sample of possible expressions on the issue of interest, gathered from all possible points of view. The analytical process synthesizes the data into a typology of perspectives using multivariate data reduction techniques such as principal component analysis (PCA) and factor analysis (FA). In contrast to regular PCA and

FA, the Q method correlates respondents (Stephenson 1935; Zabala 2014) rather than variables. These data reductions are then followed by a set of analytical steps specific to the Q method to obtain a clear interpretation of the statements (Zabala 2014; Zabala and Pascual 2016).

The Q method employs a few key terms to describe the analysis process and interpret the results: Q-sorts, factors, factor loadings, z-scores and factor scores (Zabala and Pascual 2016):

- A Q-sort is an array of integer values that a single respondent assigns to statements when arranging the statements over the given frequency distribution.
- A factor or discourse is a hypothetical best-representative respondent of those with similar views, which is extracted from the sample of Q-sorts.
- A factor loading is the correlation of each Q-sort with each factor. A respondent who is most similar to the factor has the highest loading.
- The z-score is calculated for each statement in each factor. The score is a continuous value presenting a weighted average of the values given to the statements by Q-sorts that are most closely related to the factor. It is used to determine statements that distinguish a factor from the other extracted factors (Zabala et al. 2017)
- Factor scores are integer values that a factor would assign to statements. They are used to reconstruct the Q-sort of a factor.

Statements are ranked relative to each other to reflect the salience of the statement within each factor and the distance of the statement compared to that of other factors (Zabala et al. 2017). The ranking of statements is based on z-scores and factor scores, which are also used in the final interpretations.

2.2.2. Systems thinking for system-wide understanding

Systems thinking emphasizes the recognition of dynamic interdependence between components of a system and is commonly used to understand and manage complex systems (Levy et al. 2018). By considering interdependencies, systems thinking can help to avoid unintended consequences of decisions that focus on only one part of a system and may help address complex problems with uncertainty and diverse causal pathways (Head and Alford 2015). The four successive levels of systems thinking are 1. observing events, 2. identifying patterns of behavior over time, 3. exploring the underlying structures that drive those events and patterns and ultimately 4. unveiling the mental model describing the values and perceptions of decision-makers (Aivazidou and Tsolakis 2022). The resulting mental models allow decision-makers to better understand their perceptions of problems, courses of action and likely impacts and outcomes. Systems thinking, therefore, allows for informed decisions. Systems thinking has been applied in various domains including healthcare (Peters 2014; Stalter and Mota 2018), agriculture and sustainability (Levy et al. 2018; Jagustović et al. 2019; Bustamante et al. 2021; Desbois et al. 2021; Groundstroem and Juhola 2021), project management (Charbonnier et al. 2017) and education (Shaked and Schechter 2019; York et al. 2019).

In technical terms, systems thinking often uses Causal Loop Diagrams to facilitate the process of thinking and the analysis of the system of interest (Jagustović et al. 2019; Groundstroem and Juhola 2021). Causal Loop Diagrams capture the structure of a system by mapping out cause-and-effect interactions and feedbacks within the system (Aivazidou and Tsolakis 2022). They consist of three basic components: 1. Causality (causal relationship between variables), 2. Polarity (direction of the causal links) and 3. Feedback loops (closed links of variables) (Cavana and Mares 2004). Variables are connected by arrows to indicate causal links between them. An arrow with a positive sign (+) represents a positive link, indicating the same direction of change for the two connected variables. In contrast, an arrow with a negative sign (-) represents a negative link, indicating the opposite direction of change in the two variables. After all the variables and links are mapped, feedback loops, which are closed loops of variables (Cavana and Mares 2004), might appear. By connecting variables and links of important loops, one can create a coherent and holistic story of a system. A feedback loop can be either reinforcing (R), if events or behaviors created by the variables in the loop amplify each other, or balancing (B), if some variables create counteracting changes, resulting in equilibrium (Cavana and Mares 2004; Lin et al. 2020). The most common way of assessing feedback loop effects is to count the number of negative links in the loop. An even number of negative links results in a reinforcing loop, and an odd number of negative links results in a balancing loop (Lin et al. 2020). The causality, in some cases, can be characterized by time delays between taking a decision and its effects. The feedback loops with delay, whether for long-run or short-run responses, enable the system to cope with and adapt to change in order to sustain its function. Long delays and indirect consequences can make it difficult to recognize the feedback structure and its impacts (Jagustović et al. 2019).

2.3. Data collection and analysis

2.3.1. Q methodology

Design and administration of the Q study. We generated a comprehensive sample of statements (concourse) based on expert consultation and in-depth interviews conducted with 70 farmers, as well as through extensive field observations. Local extension officers and village heads supported us in selecting 70 farmers in two villages, who are currently practicing agroforestry, based on a range of farm characteristics (Table S1, Supplementary) and the farmers' willingness to engage in the research. The generated concourse covered topics on farm-level impacts of agroforestry adoption with a main regard to perceived benefits and challenges of the practices. There was a high level of redundancy among the statements. We selected the most frequently mentioned statements by both experts and farmers. Those statements focused on investment level, profitability, relative advantage of labor demand, pests and diseases, management complexity, complementary impacts (soil erosion, climate impacts, income diversification and livestock production support). Less frequently mentioned statements related to herbicide use, manure application and farmers' knowledge on agroforestry were also considered because they appeared highly relevant to the study area context. We included additional statements on farmer cooperation, adoption level and the possibility of dis-adoption due to their relevance to the context of our study. We discarded statements mentioned only by experts on topics such as landscape aesthetics, benefits from tourism, or agroforestry certification schemes (VietGAP or GlobalGAP), which were not closely related to farm-level interactions and did not seem relevant to the interviewed farmers. The final Q set contained 23 statements (Fig. 5). The number of statements is low in comparison with other Q studies, however the set sufficiently covered the topics that we aimed to explore in this study. We attempted to create a low number of statements for more stable and reliable Q-sorts given the limited literacy of our participants. During the sorting process, we found that participants could understand and manage the given number of statements well. The selected statements were randomly numbered and each was printed on one card. The stack of cards was then provided to respondents, to be ranked over a given grid distribution. We predetermined the distribution with a quasi-normal shape (Fig. 4), as this was convenient for our participants. The forced distribution helped encourage thinking and reflecting efforts of participants to ensure that each statement was compared and ranked relative to each other statement, in order to capture their interdependence and complexity (Rost 2021). On the other hand, the distribution, whether predetermined or free, has been statistically shown to not make a noticeable contribution to the emergence of factors (Brown 1980).

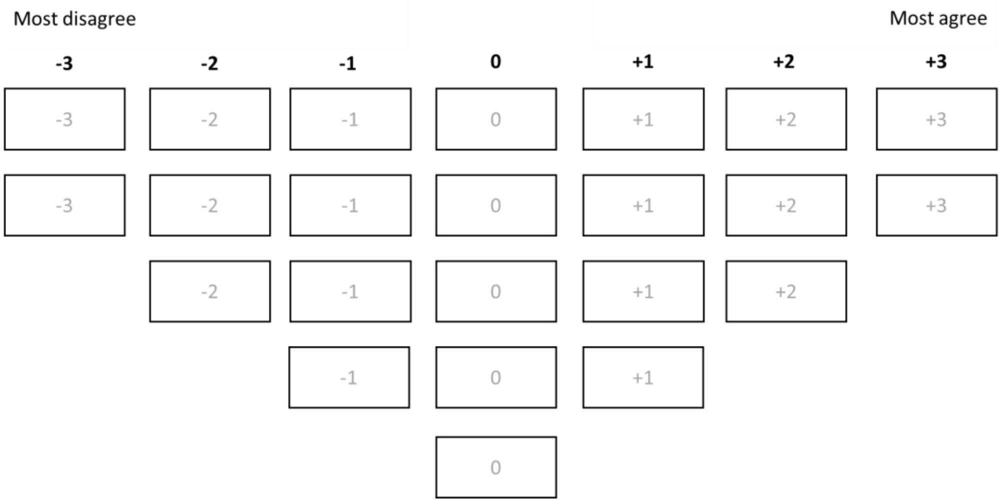

Fig. 4 Grid distribution used for statement ranking in the Q method

We piloted Q sorting with seven farmers and one extension officer to make sure statements were clearly worded and transparent. The piloting also helped us anticipate situations that might arise during the actual implementation. We followed maximum variability sampling (Zabala et al. 2017) to include a broad range of smallholder farmers. Of the 70 farmers who participated in our face-to-face interviews, we selected 40 with wide ranges of land area, level of agroforestry adoption, level of livestock production, diversity of livelihoods and diversity in attitudes toward agroforestry, based on results from the exploratory interviews.

The Q-sorting was conducted face-to-face with the 40 selected farmers. For each participant, we explained the sorting procedure and associated materials (i.e. the stack of cards and the printed frequency distribution grid), with the instruction "Please rank the statements regarding your opinions on agroforestry adoption in the context of your farm operation". To facilitate the sorting, participants were advised to initially divide statements into three piles of *agree, disagree* and *neutral* to reduce the number of cards for each level of assessment and then distribute each set of cards to the corresponding grid cells. Participants found it easy to manage the number of statements in this way. Farmers had a chance to revisit and change the position of cards if they found this necessary. The complete response was recorded on a printed sheet with the respondent's basic information. The ranking exercise was followed by a post-sorting interview where respondents provided in-depth rationale behind their ranking of statements, especially for the statements in extreme positions. This information was used to support the interpretation of the results.

Reducing Q-sorts to factors. The set of 40 Q-sorts collected from all participants was structured in a two-dimensional matrix with statements in rows and Q-sorts in columns. Q-sorts were then correlated to generate a correlation matrix. Fewer factors that explained most of the variance were extracted from the correlation matrix using PCA. The number of factors to extract was decided based on the elbow rule and on the eigenvalues of components. The elbow rule suggested two factors while the eigenvalues demonstrated five factors could be retained. We explored the results that emerged when using different numbers of factors (from two to five factors) and decided to retain three factors based on the number of respondents loaded in each factor, percentage of explained variance (Table S2, Supplementary) and the ease of result interpretation. The extracted factors were then rotated using the *varimax* technique (Zabala 2014). This resulted in a matrix of factor loadings that correlated Q-sorts with the rotated factors. Based on the raw data and the factor loading, the most representative Q-sorts for each factor were identified. Z-scores and factor scores within each factor were then estimated and identified for each statement.

Accounting for uncertainty in the outcomes. To obtain more precise levels of confidence in the results and to enhance the accuracy of the interpretation, we applied bootstrap re-sampling (Zabala and Pascual 2016) to our original sample of Q-sorts. The bootstrap with replacement was implemented as a first step before Q-sorts were correlated. For each bootstrap repetition, a resample of 40 Q-sorts was generated from the original set of Q-sorts. A full Q analysis was performed for each resample of Q-sorts. We ran 3000 bootstrap steps and repeated the Q analysis on the 3000 generated resamples. This resulted in, for a given statistic (i.e., factor loadings and z-score), a distribution which provided the estimates of the outcomes with uncertainty (mean and standard deviation). Bootstrapping Q was implemented using the *qmethod* (Zabala 2014) package in the R statistical language (R Development Core Team 2022).

2.3.2. Systems thinking with agroforestry farmers

We applied the systems thinking approach to complement the Q method through a process of collectively reflecting on the dynamic understandings of farmer perceptions from adaptive decision-making viewpoints. We conducted systems thinking sessions through series of workshops with three groups of farmers, representing three discourses in the Q study.

For each group, farmers were invited to reflect on the dominant changes they observed or made on their farms since adopting agroforestry. We asked farmers to list elements within their farms, reflecting on what has affected and been affected by agroforestry adoption. Each element listed by farmers was written on an empty card by our facilitator and placed on a large paper board. For each element, farmers identified the direct influence by reflecting on the question "*what does this influence and what influences this*?" The researcher drew arrows indicating direct links stated by farmers. Farmers then described the direction of the influence guided by IF-THEN dynamics (Jagustović et al. 2019). For all changes in the causal variables involved in these IF-THEN statements, farmers determined whether they expected other elements impacted by the variable to increase or to decrease. If farmers stated that the change of one variable caused a change in another variable in the same direction, the researcher added a positive sign (+) to the arrow connecting the two variables. The negative sign (-) was placed if the change in one variable caused a change in the opposite direction in another variable. At this point, new elements were introduced as intermediate cause-and-effect relationships. The IF-THEN dynamics were also applied to detect the direction of links between the added elements.

Participants identified important feedback loops and discussed how these loops would interact with each other to create the system dynamics. We defined the concept of feedback loop as the case *when a change in one element leads to a change in the same element after some tim*e (Jagustović et al. 2019). The researcher illustrated an example of a feedback loop in the working diagram and then invited farmers to identify and describe other feedback loops. Loops were highlighted as dominant when farmers pointed them out as the most dominant dynamics that they observed in their farm environment since adopting agroforestry.

In addition to paper-based documentation, we digitally recorded and transcribed the results of the group work and discussions during the workshops to support the process of model construction and interpretation. We unified the conceptual diagrams from the three groups by including both common and distinguishing elements and links to ensure diverse presence of elements and their causal structure from different points of view. We conceptualized the outcomes from the systems thinking exercise into a Causal Loop Diagram using the Vensim PLE 9.2.4 software (Ventana System, Inc.)

3. Results

Forty farmers participated in the Q study, including 21 males and 19 females, and ranging between 20 and 64 years of age (median age of 46 years). All farmers had experience with agroforestry and kept livestock, with 87.5% owning cattle. Farm sizes ranged from 0.65 to 4 hectares (median of 1.2 hectares), scattered over 1 to 7 plots of land (median of 4 plots). Cropping systems were diverse but featured three major systems including maize, sugarcane and fruit tree-based agroforestry systems. Small parts of the land were devoted to the production of fodder and other annual crops such as cassava and achira (*Canna edulis*). The current scale of agroforestry area per farm ranges from 22% to 100% of farm land (median of 54%). Intercrops of fruit trees (e.g. longan, mango and plum), annual crops (e.g. maize, achira and cassava) and fodder grass were the most common agroforestry designs in the area.

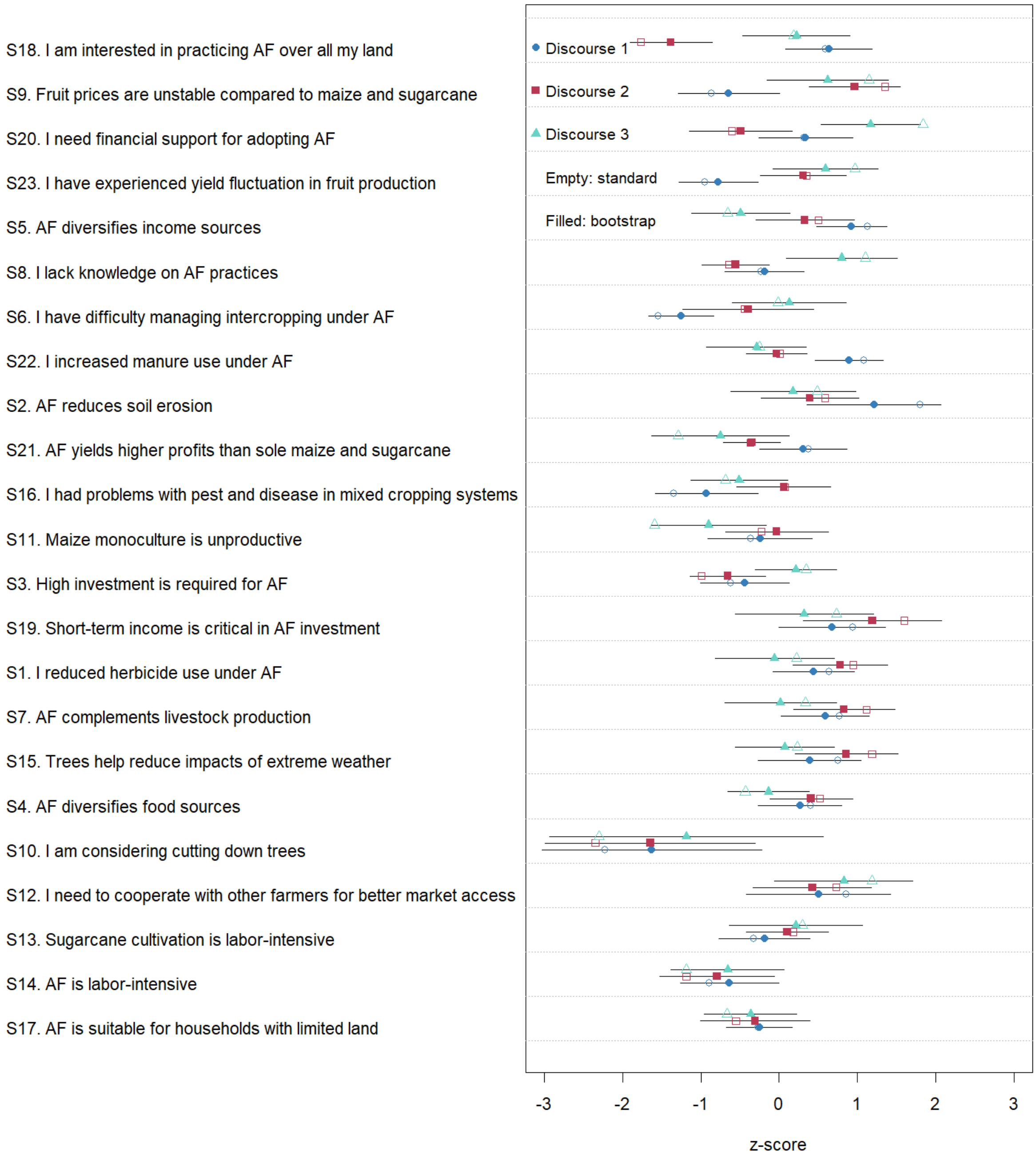

Fig. 5 Z-scores of statements on farm-level impacts of agroforestry (AF). The statements are ranked based on the descending difference in z-scores of three factors (distinguish to consensus). Error bars represent 95% confidence intervals (CIs) of z-scores

3.1. Discourses among farmers on agroforestry adoption

Three main discourses were identified by the Q analysis, explaining 50% of the variance in farmers' rankings of statements. Discourse 1 explained 20% of the variance and was contributed by 14 participants. Discourse 2 explained 17% of the variance, corresponding to 12 farmers. The third discourse included 8 respondents and explained 13% of the variance. Z-score (Fig. 5) and factor scores (Table S3, Supplementary) were compared to identify those statements that characterize the discourse and distinguish each discourse from the others.

In general, there was a strong consensus among farmers that they are unlikely to abandon integrated trees (S10) since they perceive trees as a long-term investment. Farmers also agreed that agroforestry is not a labor-demanding practice (S14) compared to sugarcane (S13) and that cooperation among tree-growing farmers would benefit market access for their fruit products (S12). By contrast, major distinctions in farmer perspectives refer to the scale of intended land use for agroforestry (S18), perceived stability of fruit price compared to prices of maize and sugarcane (S9) and the need for external assistance to support adoption (S20).

Discourse 1. The first discourse represents farmers who display a strong belief that their households have benefited from agroforestry adoption. This discourse emphasizes the role of agroforestry in reducing soil erosion (+3, S2) and diversifying sources of income (+3, S5). Farmers have applied more manure (+2, S22) with the presence of trees and they benefit from high availability of manure from increased livestock production as a result of agroforestry adoption (+1, S7). They do not have trouble with complex management in agroforestry or pests and diseases in their mixed-cropping systems (-3, S6 and -2, S16), and they do not see agroforestry as a labor-demanding practice (-1, S14) compared to sugarcane (0, S13). They consider earning short-term income from annual crops as a strategy in agroforestry investment (+2, S19). They can afford the investment level of agroforestry (-1, S3), and they have a neutral attitude toward external financial support to adopt the practice (0, S20). They show little concern about the fluctuation in prices and yield of fruits (-2, S9 and S23 respectively), which might imply that they have adaptive strategies. Seeing opportunities from agroforestry rather than its obstacles, the farmers in discourse 1 would likely scale up agroforestry over their land (+2, S18) and are unlikely to abandon the planted trees (-3, S10).

Discourse 2. The respondents associated with discourse 2 perceived benefits from agroforestry to some extent but also emphasized challenges of the practice. They assigned the greatest importance to short-term income from an agroforestry investment (+3, S19). They could afford the investment level of agroforestry (-2, S3) and were therefore not in strong need of external support to adopt the practice (-1, S20). Agroforestry provides fodder for animal husbandry (+2, S7), reduces herbicide use (+2, S1) and dampens the impacts of extreme weather conditions (+2, S15). Farmers associated with discourse 2 did not perceive agroforestry as a labor-demanding practice (-2, S14) compared to sugarcane (0, S13) and were quite confident about their knowledge and experience about the practice (-2, S8). They are unlikely to cut down trees (-3, S10), but unlike farmers in discourse 1, they expressed a lower intention to expand agroforestry to the whole farm (-3, S18) because they perceived fruit prices to be unstable compared to other cash crops (+3; S9). They also perceived the profits from agroforestry as not being higher than those from the two alternatives of maize and sugarcane (-1; S21).

Discourse 3. Discourse 3 assembles farmers who emphasized stronger views about the challenges of agroforestry adoption rather than its benefits. From their point of view, monocultures of maize are still productive cropping systems (-3, S11). These farmers rely on external support to adopt agroforestry (+3, S20), since the practice requires higher levels of investment than they can afford (+1, S3), and they do not consider agroforestry to be profitable compared to the alternatives (-2, S21) due to the perceived fluctuations in both fruit yield and price (+2, S9 and S23). They have a strong belief that cooperation with their peers would bring benefits in market access for their products (+3, S12). They reported a lack of knowledge on agroforestry practices (+2, S8). Discourse 3 agreed with the other two discourses that agroforestry is not a labor-demanding practice (-2, S14) compared to sugarcane (+1, S13) and pest and disease issues are not a concern in mixed agroforestry cropping systems (-2, S16). They are unlikely to abandon the planted trees (-3, S10) and intend to expand agroforestry areas (+1, S18).

3.2. Discourses and farmer characteristics

Discourses were related to some observed characteristics of respondents, such as location, gender, age, land area, level of adoption (% land occupied by agroforestry), livestock production (number of cattle owned), crop diversification (number of crop settings), and livelihood diversification (number of livelihood activities). The established associations reflect correlation and not necessarily causal relations. Due to the small sample size, the analysis should also be considered exploratory.

We used the X2Y metric, an alternative to correlation coefficients, which works in the presence of both categorical and numeric variables (Ramakrishnan 2021). X2Y is inspired by the mutual information concept (Learned-Miller 2013). The metric quantifies the relative reduction (in %) in prediction error between a baseline model of Y without knowing X and a model predicting Y given knowledge on X. The baseline model is determined as the average of Y when Y is continuous and the most frequent value when Y is categorical. Classification and regression tree (CART) is applied for predicting Y given X. The relative reduction in prediction error is then calculated using mean absolute error and misclassification error for continuous Y and categorical Y, respectively. A detailed description on the approach and R script for the metric implementation can be found in Ramakrishnan (2021). Table 1 shows the results for only the pairs of variables with non-zero X2Y.

In general, no association between farmers' discourses and the tested variables appeared to be substantive except for location, age and land area, for which the 95% confidence intervals of X2Y did not include 0.

Table 1. Association between farmer discourses and farmer characteristics.

X	Y	X2Y	Bounds of 95 % confidence interval	
			Lower	Upper
Location	Discourse	35.0	10.9	70.0
Age	Discourse	35.0	8.9	58.9
Land area	Discourse	30.0	4.4	53.8
Livestock	Discourse	25.0	-3.4	50.0
Level of adoption	Discourse	20.0	-7.7	40.0
Gender	Discourse	10.0	-16.4	20.0
Crop diversity	Discourse	5.0	-28.5	10.0

Table 2 presents characteristics that appeared to correlate with discourses. Each discourse is dominated by farmers in specific locations which, in this study, represent geographic proximity within the two villages. The location variable may characterize farm structure, farming style or peer influence. Farmers in discourse 1 are older and own less land than those in discourse 2 and discourse 3. Gender and livestock showed insignificant association in the analysis, however they showed some patterns in relation to discourses (Table 2). Discourse 1 assembles more men than women while the opposite is true for discourse 3 where the number of females is higher. Farmers in discourse 1 and discourse 2 own more cattle than farmers in discourse 3.

Table 2. Discourse characteristics. Median and mean (in parentheses) values are provided for age, land and livestock.

Discourse	Gender (no. respondents)		Location (no. respondents)			Age	Land (ha)	Livestock (head)
	Male	Female	L1	L2	L3			
Discourse 1	10	4	1	4	9	54 (48)	1 (1.3)	3 (2.7)
Discourse 2	6	6	7	3	2	45 (44)	1.4 (1.7)	2.5 (3)
Discourse 3	2	6	1	5	2	43 (44)	1.3 (1.6)	1 (1.6)

3.3. Discourses and farm models

Causal Loop Diagrams were generated from systems thinking sessions for discourse 1 (Fig. 6), discourse 2 (Fig. 7) and discourse 3 (Fig. 8) to illustrate the dynamics of farm processes and farmers' actions in response to the changes in land use configuration in the context of agroforestry adoption. Farmers identified all elements within the boundary of farm operations and two elements outside as having significant impacts on the system. The two external elements were the farm-gate price of fruits and climate change impacts (bold text in Fig. 6 & Fig. 7 & Fig. 8). The main components (shaded boxes and bold text in Fig. 6 & Fig. 7 & Fig. 8) can be considered decision variables, which may change and interact with other parts of the system.

Various livelihood activities including crop production, livestock husbandry and off-farm activities happen simultaneously and interactively to complement or compete for farm resources. The common share in the mental models of the three discourses are the dynamics that lead to agroforestry adoption (balancing loop B1) and land allocation in the context of adoption (reinforcing loops R1, R2, R3) as well as impacts on soil erosion and household income. The number of causal links and their importance perceived by each discourse are the major differences.

For all discourses, severe soil erosion due to a long period of maize cultivation on slopes has led to the adoption of alternative cropping practices such as sugarcane cultivation or agroforestry. Sugarcane contributes significantly to the income of farmers in the study area. The contribution of sugarcane to household income is perceived more important in discourse 2 (Fig. 7) and discourse 3 (Fig. 8) than in discourse 1 (Fig. 6). However, sugarcane requires high labor input experienced by all three discourses (balancing loop B2). The labor intensity of sugarcane production was emphasized by discourse 1 and discourse 3 who therefore expressed their desire to expand agroforestry area in the Q study. However, high adoption expenses (B4) and unstable farm-gate prices for fruit prevent them from expanding agroforestry on their land. Farmers reallocate land for different alternatives to secure their cash flow. This was considered as an adoption strategy by all discourses. The adoption of agroforestry reduces soil erosion through reduced soil disturbance and increased soil cover due to the tree canopy. The practice also sustains feed supply for livestock production, and it diversifies income through intercropped products and fruits. High feed availability in agroforestry systems frees up labor for other income-generating activities. Farmers in discourse 1 and discourse 2 have increased their herd size, given sufficient feed supply from agroforestry, thereby raising their income through cattle sale. This dynamic may explain the higher number of cattle owed by discourse 1 and discourse 2 compared to discourse 3 (Table 2). The importance of these pathways, however, was perceived differently among discourses. Discourse 1 (Fig. 6) highlighted the importance of income diversification pathways through livestock, off-farm activities and other agroforestry products beside fruit benefits while discourse 2 (Fig. 7) and discourse 3 (Fig. 8) rely on and expect more from fruits than from the other diversification pathways. This could be an explanation for the strong view held by farmers in these discourses on the statements regarding fruit yield and fruit price. The association between discourses and age and land area (Table 2) imply that older farmers and farmers with little land (discourse 1) tend to appreciate the diversification benefits from agroforestry. In addition to livelihood benefits, discourse 2 also mentioned other benefits from agroforestry, such as reduction of herbicide use and effects of tree shade that have impacts on both climate and human health (Fig. 7). Discourse 1 and discourse 3 did not perceive such benefits.

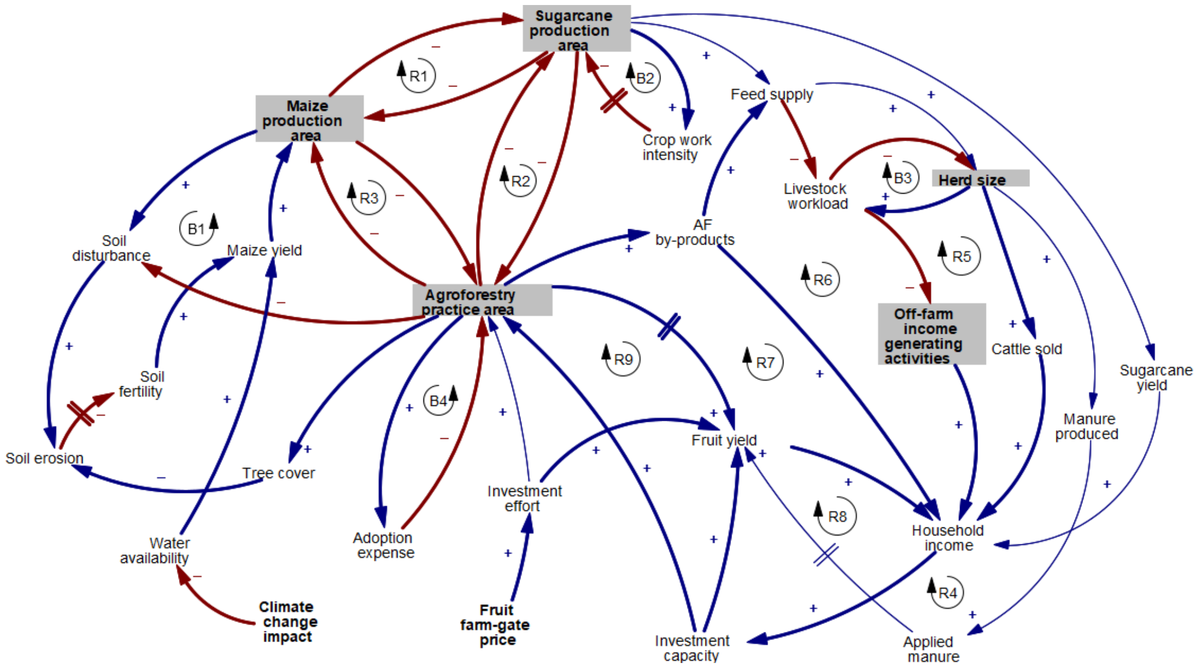

Fig. 6 Mental model of discourse 1. Blue arrows with "+" imply the same direction of change of two linked variables, whereas red arrows with "-" indicate a change in the opposite direction. Arrows with "||" indicate a delay in the impact between two variables. Bold arrows represent important links highlighted by the discourse. "R" indicates a reinforcing feedback loop with an even number of negative links. "B" represents a balancing feedback loop with an odd number of negative links

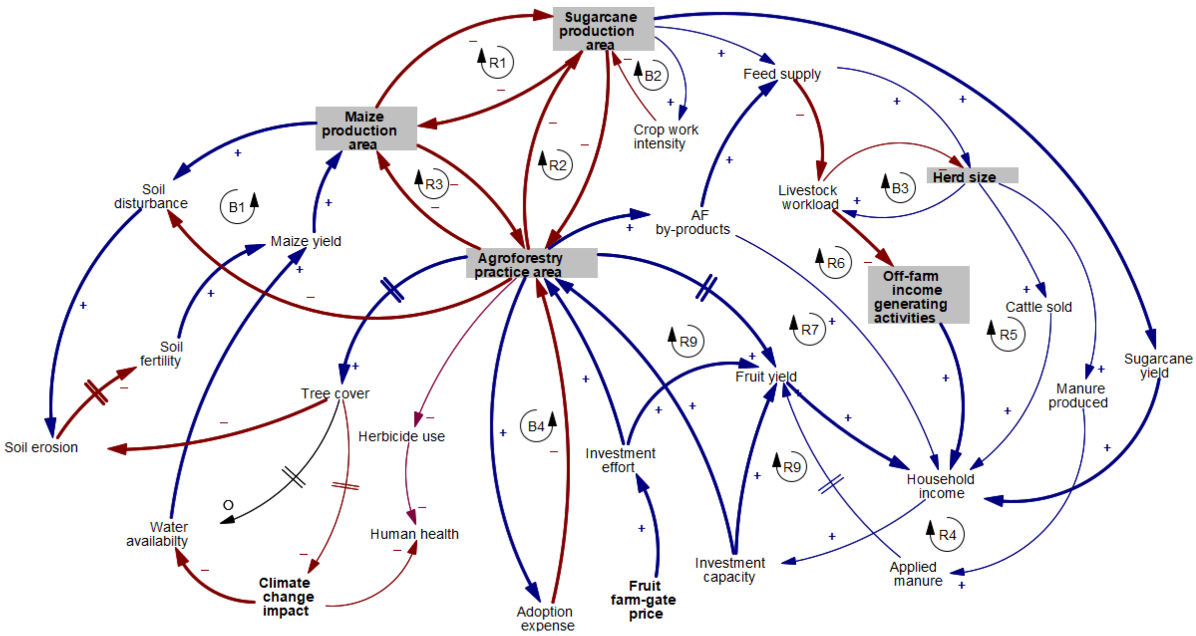

Fig. 7 Mental model of discourse 2. Blue arrows with “+” imply the same direction of change of two linked variables, whereas red arrows with “-“ indicate a change in the opposite direction. Black arrows with “O” indicate an unclear relationship. Arrows with “||” indicate a delay in the impact between two variables. Bold arrows represent important links highlighted by the discourse. “R” indicates a reinforcing feedback loop with an even number of negative links. “B” represents a balancing feedback loop with an odd number of negative links

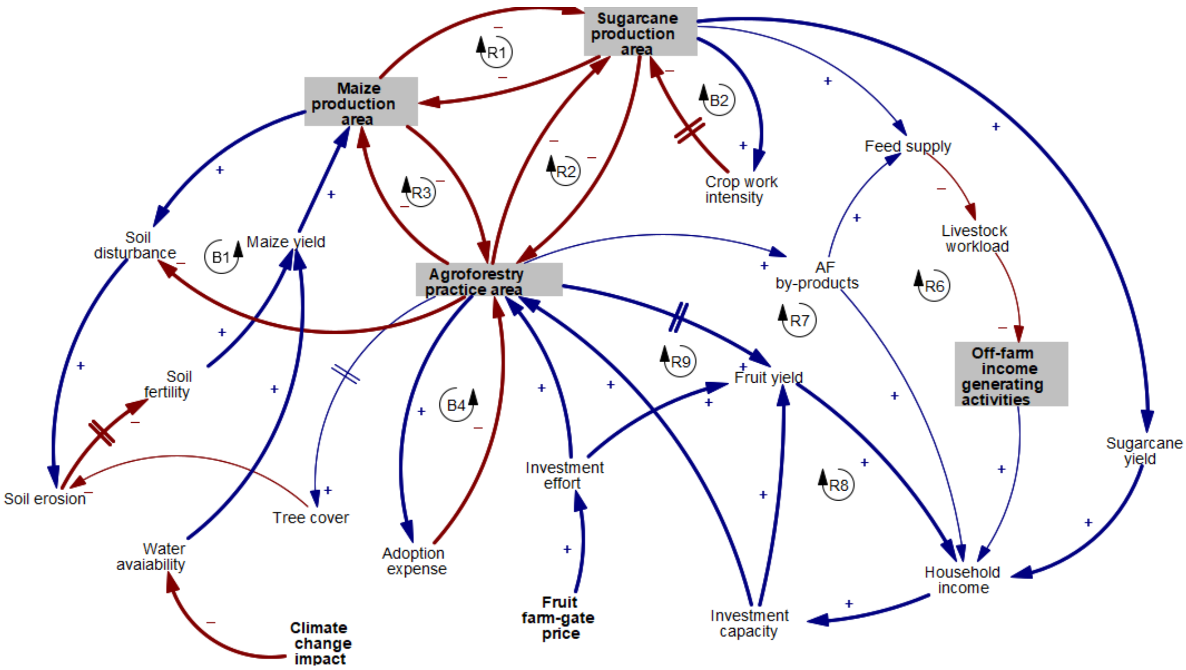

Fig. 8 Mental model of discourse 3. Blue arrows with "+" imply the same direction of change of two linked variables, whereas red arrows with "-" indicate a change in the opposite direction. Arrows with "||" indicate a delay in the impact between two variables. Bold arrows represent important links highlighted by the discourse. "R" indicates a reinforcing feedback loop with an even number of negative links. "B" represents a balancing feedback loop with an odd number of negative links

3.4. Development pathway of agroforestry farmers

To provide a generalized and concrete story of the local farming system, we unified the three models by highlighting common and important interactions that are responsible for system behavior given the adoption of agroforestry (Fig. 9).

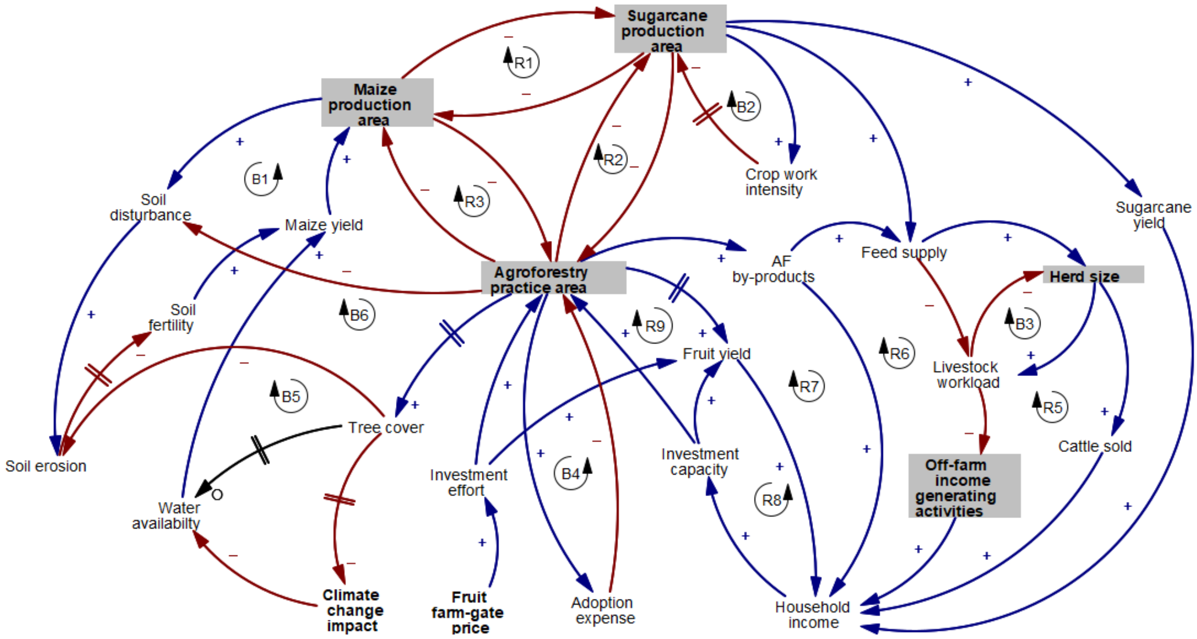

Fig. 9 Dominant feedback loops responsible for emergent behaviors within farming systems in the context of agroforestry adoption. Blue arrows with "+" imply the same direction of change of two linked variables, whereas red arrows with "-" indicate a change in the opposite direction. Black arrows with "O" indicate an unclear relationship. Arrows with "||" indicate a delay in the impact between two variables. "R" indicates a reinforcing feedback loop with an even number of negative links. "B" represents a balancing feedback loop with an odd number of negative links.

The balancing loop B1 presents an intervention point initiating changes in local land use. Expansion of maize monoculture over long periods is associated with frequent soil disturbance and loss of vegetative cover. This causes severe soil erosion problems. Depletion in soil fertility reduces maize yield substantially and thereby decreases household income. As maize yields decrease, farmers reduce the land area for maize cultivation to avoid losses. They re-allocate land to alternative crop settings such as sugarcane and tree-based systems. The new land-use configuration induces emergent behaviors by interacting with other elements within farms.

Sugarcane has played an important role in poverty reduction in recent years by increasing farm income. Given the expansion of the production scale of sugar manufacturing companies, which secures stable farm-gate prices, sugarcane remains dominant in terms of cultivated area and contribution to income generation in the region. Biomass from sugarcane also helps to sustain the feed supply for livestock production during the dry season. However, the production level for sugarcane is constrained by the intensive labor requirement of the practice, which forces many farmers to reduce production levels in the long run. This is partly due to the aging of those doing agricultural labor, illustrated with the balancing loop B2.

Farmers agreed that they adopted agroforestry as an intervention to reduce soil erosion and improve farm productivity. However, introducing this practice reduces the available area for maize and sugarcane production. This leads to a constraint on land resources, which is reflected in the negative reinforcing loops R1, R2 and R3 (Fig. 9). Tree-based systems incur costs for setting up tree stands (adoption expenses). Trees are expected to provide direct products (fruit yield) for income generation, which may allow re-investment in trees in order to enhance fruit yield or plant more trees (R7 and R8). This contribution is delayed, however, with a time lag until positive net returns from fruit trees are generated. The delayed impact makes the future behavior of agroforestry hard to predict. Without action, the reinforcing loops R2 and R3 might lock in farm operations given continuous investments without earnings for the first several years. In this case, full adoption may lead to system collapse. As a strategy, farmers may choose to transit slowly so that they can afford the adoption-related expenses (B4). Meanwhile, they create short-term income in various ways. These immediate incomes help enhance the investment capacity of farmers and allow them to further expand tree areas or improve tree productivity. This is demonstrated by the positive reinforcing loops R5, R6 and R7 (Fig. 9). Instead of a large-scale transition, farmers retain parts of their land distributed among other crops such as sugarcane, to maintain annual cash flows. In tree covered land, they integrate annual and fodder crops to earn direct income (R7) and increase feed supply during the rainy season. The increase in feed availability reduces the time they spend on collecting fodder and herding cattle. With the additional free time, farmers get more housework done or participate in off-farm activities, which can add to household income (R6). On the other hand, given feed abundance, farmers tend to increase herd size, thus increasing the number of cattle available for breeding, household consumption and income generation (R5). Increasing herd size leads to higher manure availability for trees (Fig. 6 & Fig. 7) or for cash through sale to peers. The extension of livestock production is, however, constrained by labor availability, as illustrated by balancing loop B3. Instead of increasing herd size proportionately with the availability of fodder, farmers may balance the herd size at the level that they can manage with their household's labor resources.

Farmers perceived positive environmental impacts of agroforestry through enhanced soil cover with trees and other vegetation, which played a major role in reducing soil erosion. Participants also recognized several services contributed by trees, such as providing shade for farmers working in the field and dampening heat stress during hot days. In the long run, tree covers can alleviate the impact of climate extremes and conserve soil fertility through reduction of soil erosion. Over longer periods, soil fertility builds up in agroforestry systems, which can then secure yields of conventional crops. There is a chance for dis-adoption, where farmers abandon agroforestry and return to conventional crops (B6 and B5) given well-established markets for those crops. However, a long delay and lack of clarity on the impacts of tree-based systems on soil quality and the climate imply large uncertainty on this emergent behavior.

4. Discussion

We explored how farmers evaluated the use of agroforestry by analyzing their perceptions of the practice and its effects within their farming system. Through application of the Q method, we extracted dominant discourses among local farmers focusing on impacts of agroforestry. The systems thinking approach enabled learning and elicitation of comprehensive understanding of farm management decisions through which adaptation strategies to overcome adoption challenges could be highlighted. Farmers acknowledged multiple benefits of agroforestry adoption. They navigated adoption challenges and found ways to overcome the challenges by drawing on their understanding of local farms and the farm environment.

Agroforestry has been favored by local farmers due to various positive impacts on the environment and on livelihoods. Reduction in soil erosion was mentioned by participants as one of the most beneficial environmental impacts of agroforestry. This implies that farmers who have experienced serious soil erosion and believe agroforestry could improve the situation are particularly likely to adopt the practice (Hoffman et al. 2014; Hastings et al. 2021). The underlying mechanism of the impact on soil was reflected in the Causal Loop Diagram generated in this study and also supported by plot-level experiments by Do et al (2023). The authors reported a significant reduction in the amount of soil, soil organic carbon and other soil nutrient elements that was eroded from fruit tree-based agroforestry systems compared to their monoculture counterparts. According to the Q study, farmers in our study area also perceived a reduction in labor input after adopting agroforestry. The result does not support the popular belief that agroforestry is more labor-intensive than monocropping (e.g. due to tree management operations and difficulties in the use of machines (Graves et al. 2017)), highlighting the importance of context. In monoculture settings of annual crops, labor demand is highly seasonal, especially at high cropping intensity, with peaks clustering around specific operations of sowing and harvesting (Kotir et al. 2022). The peaks constrain the area that can be managed by a unit of labor (Kotir et al. 2022). During the systems thinking session, farmers discussed that more types of crops can be managed in agroforestry than in monoculture given the same amount of time. They therefore believed that agroforestry has higher labor productivity. This belief aligns with the findings of other studies that agroforestry had higher returns to labor (Ajayi et al. 2009; Armengot et al. 2016). Farmers also discussed the temporal distribution of agroforestry-related work over the year, which made farm work less intense, particularly for elderly farmers. This finding reflects a suggestion by Ajayi et al (2009) for a modification to the agronomic management of agroforestry-based soil fertility management practices. They suggested to shift some of the labor inputs away from the main cropping season to the "off-peak" labor demand season, thereby enhancing acceptability among farmers when labor is limiting (Kotir et al. 2022). In addition, farmers elaborated further on the complementary effect of agroforestry (see discourse 1 and discourse 2 in Q method S7, Fig. 5). Fodder from agroforestry sustains livestock production and reduces labor needs for feed collection and herd supervision, freeing up time for other livelihood activities, which may have social implications (Kiptot and Franzel 2012) in addition to direct economic benefits.

We found that the most frequently mentioned challenges were related to high uncertainty about farm-gate prices and yields of fruits. The findings support previous work which emphasized the importance of these two factors in a prediction model of the economic performance of agroforestry in different settings (Do et al. 2020a). Our results show that the levels of uncertainty were perceived differently by farmer groups, distinguishing discourse 1 from discourses 2 and 3 (S9 &S23 in Fig. 5). The presence of reliable markets for alternative crops, in addition to bio-physical compatibility, is an important requirement when introducing farming practices that include new crop components (Roesch-McNally et al. 2018). Such markets are still missing in our study context. The absence of reliable markets increases farmers' uncertainty about selling prices, which generally leads farmers to reduce the use of production inputs (Assouto et al. 2020). Farmers are reluctant to commit to investing in trees if they perceive high fluctuation in fruit prices (investment effort, Fig. 9). Cost control was employed by smallholder rice farmers in Tanzania as a strategy to guarantee their income margin in years with low market prices (Mgale and Yunxian 2021). Nevertheless, perennial fruit trees often demand unwavering investment (in terms of both plant nutrition and overall management effort) to ensure good yield performance in the long run (Carranca et al. 2018). Some farmers abandoned trees during two years of the Covid-19 pandemic when the market for fruits largely collapsed due to restricted transportation and lack of access to the Chinese market, the main market for fruits. Another challenge mentioned by discourse 3 in the Q study was that agroforestry requires a high level of investment. This has been highlighted in earlier research (Do et al. 2020a, b), which suggested financial incentives to promote adoption. However, the high complexity and diversity of agroforestry are causing many complications for policy-makers trying to develop a supporting framework for farmers who adopt the practice. Subsidies have been provided in the form of seedlings and fertilizers, but these measures were limited to short-term pilot projects. The private sector has taken part in providing tree seedlings and securing output markets for only a narrow range of tree species. Such profit-oriented activities by the private sector may encourage a spread of large-scale agroforestry that compromises the biodiversity-supporting nature of the practice. This may lead to a poor agroforestry transition, which may strengthen and institutionalize agribusiness practices that harm the environment and reduce social equity (Ollinaho and Kröger 2021).

Farmers often have little power to address structural challenges, such as uncertain farm-gate prices in this case, which may require interventions at higher levels, yet many have engaged in attempts to adapt and maintain system functions. Although financial incentives are highly appreciated, most farmers did not put a high weight on the need for incentives to adopt agroforestry (discourse 1 and discourse 2). During the systems thinking workshops, farmers rather focused on discussing how they have managed the adoption and overcome its challenges. To reduce the pressure from the high investment requirements of agroforestry, farmers implemented the transition at temporally and spatially slow rates. During the transition, they made use of the multiple benefits of the practice that were mentioned in the outcomes of systems thinking. The slow transition allowed for adaptive management of the adoption, minimizing the risk of failure given a range of uncertainties regarding the innovation (Klerkx et al. 2010). Such a gradual transition has been suggested as a means for making agroforestry feasible for resource-poor farmers (Do et al. 2020a). Farmers also maintained a diversity of crop settings across farm plots to enhance their ability to adapt to market and climate shocks. A diversified portfolio of crop production has proven to help spread risk and thus enhance the resilience of farming systems (Sulewski and Kłoczko-Gajewska 2014; Petersen-Rockney et al. 2021). Therefore, some farmers preferred allocating land for a diversity of crop settings to converting the whole farm to agroforestry. They were satisfied with having income spread over their land across the year.

For the majority of farmers in our study, spot markets where prices are decided at the time of selling were the dominant channel for fruit sales. In this arrangement, farmers usually rely on informal networks (farmer-to-farmer) to acquire market information such as price, buyers or product standards. These networks equip them with bargaining power and reduce their uncertainty when making deals with buyers (Mgale and Yunxian 2021). For farmers living near local markets, self-retailing is also a common strategy whenever farmers disagree with the prices offered by regular traders. This strategy offers local women opportunities to participate in income-generating activities. Many women, during the discussion, reported additional income from the collection of fruits and other agricultural products on their land for sale on local markets. Some also diversify their product portfolio with prepared traditional food to earn additional cash and make the best use of their self-retailing time. Thereby, women can contribute to household income and possibly enhance their role in decision-making processes (Antman 2014; Arthur-Holmes and Abrefa Busia 2020). In some cases, forward-contracts are available, but this mainly applies to large fruit production farmers with intensive monoculture plantations, since such farmers can promise reliable supply. Small-scale agroforestry farmers may be able to ensure reliable supply by cooperating with their peers for pooling their capital resources and product outputs (Fernando et al. 2021). Farmer-driven cooperatives with good marketing strategies and service functions could eliminate the involvement of intermediaries in agroforestry supply chains and help improve farmers' returns from their products (Islam et al. 2018). Farmers in all three discourses considered cooperation as a key strategy to overcome structural market barriers. Farmers believed that by participating in farmer cooperatives, they could exchange knowledge and be provided with sufficient market information and potential involvement in certification schemes, thereby gaining access to and bargaining power in forward-contracts and securing a fair price. However, attempts to set up cooperatives are often unsuccessful due to cumbersome administrative procedures and a lack of business skills and trust among farmers. This may present a possible intervention point for the government, which may provide technical and financial assistance during the establishment and development of agricultural cooperatives. It is also essential for the government to stay engaged and maintain its authoritative role in examining and enhancing the capability of such cooperatives in their operational and decision-making management (Fernando et al. 2021). Engagement in other networks that include different stakeholders such as industry representatives, public agencies and policymakers may also expand the options available to farmers and thereby reduce structural barriers (Roesch-McNally et al. 2018).

Farmer-to-farmer networks are common channels for farmers to exchange and disseminate technical knowledge. None of the discourses concerned technical issues of agroforestry (S6 and S16, Fig. 5), since farmers were able to access relevant and timely information from their peers. The association between location and farmer discourse in our analysis suggests an influence of social networks on farmer perceptions as an important driving factor of farmer actions. The location in our study represents both geographic proximity and similarity in farming style, experience and cultural identity. These dimensions may be referred to as geographical proximity, cognitive proximity and social proximity, as defined by Kabirigi et al. (2022), who reported significant relationships between the different forms of proximity and the likelihood that farmers share and ask other farmers for information. Our findings may have implications for interventions to integrate and promote informal networks in the existing formal extension system for effective knowledge exchange and social learning. However, formal research should be conducted on proximity aspects to provide nuanced recommendations within local contexts.

5. Conclusion

This study adds a new dimension to the assessment of agroforestry considering both consensus and disagreement in farmers' views on the practice within the whole-farm context. Benefits and challenges of agroforestry were perceived differently by farmer discourses in the Q study. There was, however, high consensus among the mental models elicited from the systems thinking reflecting similarity in farmers' adaptation strategies and expected impact pathways within local farms. Farmers leveraged the synergistic impacts of agroforestry on other farm components to overcome the challenges and better integrate agroforestry into the farm operation. It appeared that farmers think in systems, which highlights the importance of taking a whole-systems approach to assessing the implications of introducing new components into farm operations. The combination of the two research approaches offers a robust tool for agricultural development research, especially in the field of resource management where multiple stakeholder groups with conflicting interests and different expectations are often involved. The Q-method detects characteristics and severity of conflicts between the views of different stakeholder groups on certain topics. Systems thinking then elucidates the dynamics explaining the different discourses, providing useful guidance for coordination and action.

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Authors' contributions Conceptualization, H.D., E.L., C.W., and N.L.; Methodology, H.D.; Investigation, H.D., and N.L.; Data analysis, H.D., Writing—original draft, H.D.; Writing—review & editing, C.W., E.L., H.S., and N.L.; Funding acquisition, H.D., E.L., N.L., H.S., and C.W.; Supervision, E.L., C.W., N.L., and H.S.

Data availability All generated or analyzed data is included in the Annex.

Consent to participate and for publication The authors confirm that all the participants provided informed consent to participate in the study and agreed on publication of the results.

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Chapter 5. Agroforestry adaptation by farm households in northwestern Vietnam: who needs what and implications for practice and policy

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Abstract

Agroforestry, a multifunctional land use practice that integrates perennial trees into agricultural land, is practiced across a wide range of ecological regions. In northwestern Vietnam, agroforestry is promoted to enhance environmental sustainability and support livelihoods, especially in resource-constrained situations. Agroforestry adoption is hindered by farm-level and structural barriers, necessitating interventions tailored to the diverse needs of farmers. Employing a participatory approach, we developed a farm typology to capture the diversity in farm structure and adoption behaviors among agroforestry farmers by analyzing data from 101 households through archetypal analysis. This analysis identified three distinct agroforestry archetypes, each reflecting unique resource constraints. Archetype 1 and Archetype 2 represent small-scale farmers with limited agricultural labor and diversified livelihood activities. Archetype 1 farmers manage consolidated land and maximize land and labor use efficiency by integrating agroforestry systems with a high diversity of crops and trees. Archetype 2 farmers manage highly fragmented land and small plot sizes, which together restrict the diversification of agroforestry systems. Archetype 3 farmers operate the largest farms, relying for their livelihood on annual crops. They have the lowest agroforestry adoption level and moderate species diversity in their agroforestry systems. We used these archetype profiles to discuss potential intervention strategies aimed at enhancing farmers' adoption and sustained

engagement in agroforestry. Farmers identified strategic interventions including improving market access, providing financial support for production inputs and tree seedlings, and establishing irrigation systems for agroforestry. Practical interventions involve diversifying agroforestry systems and enhancing technical knowledge. To meet the identified diverse needs and contribute to the co-creation and design of farming systems, we discussed potential socio-technical solutions, as well as challenges and opportunities for their implementation. Our study emphasizes the importance of tailored solutions and facilitated learning from varied farmer behaviors and strategies to ensure the practicality and local relevance of possible solutions.

1. Introduction

Northwestern Vietnam features agricultural production on steep slopes with relatively infertile soils, making cultivation challenging (Hoang et al. 2017). Shifting cultivation of staple crops such as upland rice (*Oryza sativa* L.), maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz) has traditionally been the primary livelihood for several ethnic minority groups living in the area (Catacutan et al. 2017). Widespread shifting cultivation has been a significant contributor to deforestation, forest fires and environmental degradation (Catacutan et al. 2017). Government policy interventions, initiated in the 1960s, aimed to promote sedentary agriculture and reforestation, significantly impacting local livelihoods and farming structures (Catacutan et al. 2017). These policies, along with the relocation of lowland people to mountainous areas, have reduced the area available for shifting cultivation and shortened fallow periods (Catacutan et al. 2017). As a result, upland agriculture has transitioned toward settled cultivation, characterized by more intensive use of labor and external inputs such as agrochemicals. This intensification of agricultural production, coupled with unsustainable land management practices, has led to severe soil erosion and soil fertility depletion (Wezel et al. 2002). The productivity of annual monoculture has been under threat, further exacerbated by extreme climate conditions, jeopardizing local livelihoods (Keil et al. 2008). There is an increasing demand by farmers and local authorities for land-use systems and management practices that can provide a wide range of services, including soil and biodiversity conservation, food production and high resilience to climatic disturbances (Wezel et al. 2002).

Agroforestry, a land-use and management practice that integrates trees and other crops or livestock, is widely recognized for its potential to enhance environmental sustainability and support livelihoods, particularly in resource-constrained situations. In Vietnam, local authorities in several northwestern provinces, supported by international organizations such as World Agroforestry (CIFOR-ICRAF), have actively promoted agroforestry (La 2019). To increase adoption rates, farmers who participated in agroforestry projects often received tree seedlings, fertilizer and initial training to establish their agroforestry systems. However, agroforestry adoption is an ongoing and dynamic process in which farmers modify agroforestry to align with their specific needs, resources, knowledge and strategies (Do et al. 2024). This adaptation process presents an opportunity to support farmers in refining and redesigning agroforestry, recognizing the role of practitioners as active participants in the development of agricultural technologies (Glover et al. 2019). Understanding the modalities of farmers' adaptation and the underlying motivations is essential for designing effective interventions.

Therefore, it necessitates a holistic approach that facilitates local adaptation of agroforestry practices, fosters continuous learning to improve and refine the techniques, and strengthens community ties to ensure collective engagement and support. These processes are crucial for building resilience and ensuring that agroforestry adoption leads to sustainable impacts rather than just short-term expansion (Périnelle et al. 2024).

Supporting farmers in modifying their practices presents a challenge for researchers and policy-makers who seek to avoid entering a case-by-case process while ensuring effective intervention strategies (Stevenson et al. 2019). This difficulty arises from the high heterogeneity of smallholder farms in terms of farm resources, development trajectories and livelihood orientation (Tittonell et al. 2020; Innazent et al. 2022). This heterogeneity stems from the wide range of environmental and socio-economic factors unique to each farming context, which complicates the development of broadly applicable solutions (Glover et al. 2019). Effectively categorizing the heterogenous farming community into manageable types can facilitate more targeted and effective support. "Farm typology" has been used as an umbrella term for various categorizations that aim to capture this agricultural diversity (Huber et al. 2024). As a tool for in-depth farming system analysis, typologies integrate quantitative, participatory, and statistical methods to condense the large, heterogeneous population of individual farm households into a few coherent, homogeneous farm types (Alvarez et al. 2018). Farm households within the same farm type typically manage their farms similarly, share common strategies, face similar constraints, and have comparable opportunities (Innazent et al. 2022). Developing farm typologies with farmer participation can enhance understanding of farmers' decision-making processes, enabling them to relate their behaviors to those of their peers. This process can facilitate the exchange of concerns, identification of development pathways and transfer of technologies and strategies (Alvarez et al. 2018). Moreover, a well-defined typology facilitates pinpointing opportunities and constraints, guiding farm advisory services and policymakers in targeting or adjusting policy interventions (Alvarez et al. 2018; Huber et al. 2024).

This study aimed to bridge the gap between understanding farmer heterogeneity through farm typology and targeting farming interventions to support diverse agroforestry adoption patterns in Son La, a northwestern province in Vietnam (Fig 1). Our objective was to categorize smallholder agroforestry farmers, based on their farm characteristics and agroforestry adoption behaviors. Through this categorization, we aimed to identify their constraints and envisage cost-effective, locally relevant interventions to address challenges faced by farmers.

Fig 1 Mosaic landscape in Son La shaped by diverse agroforestry adoption patterns among smallholder farmers in the region. The landscape covers fields managed by different farmers, with monocultures of sugarcane and annual crops and various agroforestry settings

2. Methods

2.1. Study context

Our study was conducted in three villages in Hat Lot Commune, Son La province in northwestern Vietnam, located within areas targeted by a two-phase agroforestry project run by CIFOR-ICRAF (Fig 2). These villages are predominantly inhabited by people of the Thai ethnic group, who were the intended beneficiaries of this study. The primary agricultural activities for both food and income generation include the cultivation of staple crops including maize and cassava, sugarcane (*Saccharum officinarum* L.) and fruit trees, supplemented by livestock production and occasional paddy rice. The study area is particularly vulnerable to soil erosion due to the prevalence of steep land and a long history of monoculture of staple crops and sugarcane. Therefore, agroforestry was introduced by the project as an alternative land management system. Agroforestry systems in these villages are characterized by a high diversity in structure and system management. Farmers had adopted fruit tree-based agroforestry practices since 2014 in response to market signals and to mitigate the adverse effects of soil erosion associated with the land management practices in annual crop monocultures. Farmers intercrop key fruit trees such as longan (*Dimocarpus longan* L.), mango (*Mangifera indica* L.) and plum (*Prunus salicina* Lindl), in some cases nut trees such as macadamia (*Macadamia integrifolia* Maiden & Betche), and coffee (*Coffea arabica* L.) as the main cash crops, along with other annual crops like maize, cassava, achira (*Canna edulis* Ker.), vegetables and fodder grass (*Pennisetum purpureum* Schumach. and *Panicum maximum* Jacq.). This variation in agroforestry practices provides a robust foundation for our study, offering an established context for exploring the diversity in farmers' implementation of agroforestry.

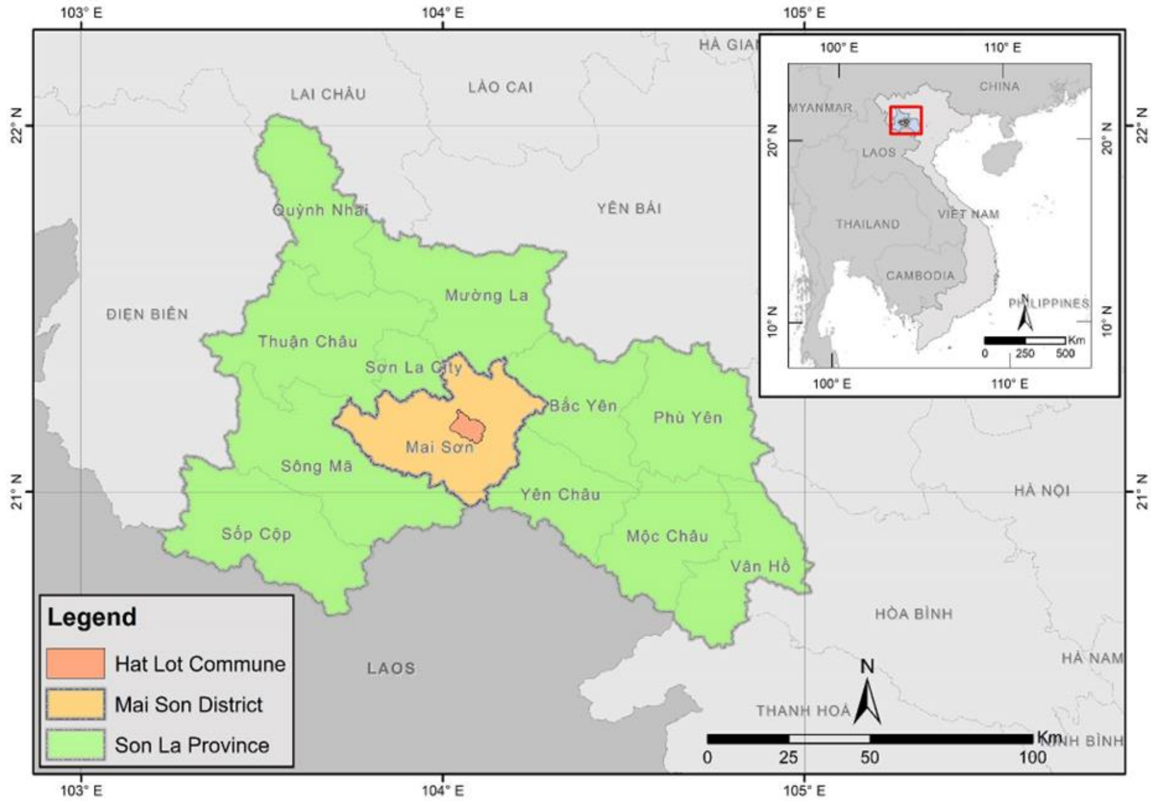

Fig 2 Map of the study area in Son La province, one of the focal areas of the two-phase CIFOR-ICRAF agroforestry project (2011 - 2021), funded by the Australian Centre for International Agricultural Research (ACIAR) and the CGIAR Research Program on Forests, Trees and Agroforestry. Adapted from Do et al. (2024)

2.2. Archetypal analysis to study farm heterogeneity

Studies aiming to understand farm heterogeneity often use unsupervised learning algorithms, commonly principal component analysis, multiple correspondence analysis or factor analysis combined with clustering (Furnari et al. 2021). These methods identify groupings within a dataset by clustering around "average" individuals, which then serve as prototypes for each group. These techniques tend to focus on the most typical and central cases, possibly overlooking extreme cases that could reveal novel behaviors or strategies (Tittonell et al. 2020).

Archetypal analysis, proposed by Cutler and Breiman (1994), provides an alternative approach that searches the periphery of the data, focusing on extreme or distinctive types, called "archetypes" (Epifanio et al. 2013). In this context, "extreme" refers not to statistical outliers but to boundary cases that define the range of variation within the dataset. Such extreme cases can provide a wider lens on the diversity of practices and outcomes, enabling a deeper understanding of what works under different conditions (Necula et al. 2024). The goal of this method is not to classify all data points but rather to identify archetypes that define the extremes of the dataset, allowing the learning of lessons from marginal or uncommon cases (Necula et al. 2024). Archetypal analysis has been used in benchmarking and market research (Li et al. 2003), in studying the diversity of practices in conservation agriculture (Ferdinand and Baret 2024), in assessing heterogeneity among rural actors in responses to disturbance (Tittonell et al. 2020), and for characterizing adaptation responses to climate change among large-scale arable farmers (Necula et al. 2024). In archetypal analysis, each farm is expressed as a convex combination of archetypes, i.e. a linear combination of the resulting archetypes (Eugster and Leisch 2009). This results in a fuzzy segmentation where each farm is not strictly categorized into a single archetype but can partially belong to multiple archetypes (Tittonell et al. 2020). The archetypes themselves, therefore, do not correspond to the actual farms but should be viewed as idealized examples of farm cases which serve as reference points for grouping real farms into clusters (Necula et al. 2024). An individual farm's alignment with an archetype is quantified by a coefficient (Eugster and Leisch 2009). Farms can fully align with a single archetype, which represents them entirely, or they may show varying degrees of association with multiple archetypes. A practical advantage of archetypal analysis is that it can be applied with a relatively small sample size (Tittonell et al. 2020; Ferdinand and Baret 2024; Necula et al. 2024) without overlooking potentially informative extremes in the sample, enabling the design of adaptive and flexible policies. This advantage of archetypal analysis is particularly beneficial for our study, where access to farmers is often limited. By ensuring that extreme cases within the sample are considered, we can develop more nuanced and inclusive recommendations that are better tailored to meet the diverse needs and circumstances of all farmer groups involved.

2.3. Application of archetypal analysis in studying the diversity of agroforestry farmers

We used archetypal analysis to explore the heterogeneity of agroforestry farmers across three selected villages in Son La (Fig 2). We adapted a participatory framework for farming system typology development proposed by Alvarez et al. (2018). This approach actively involves farmers and local stakeholders in defining objectives, selecting key variables for categorization, and discussing the results. By incorporating their perspectives, the study ensured that the outcomes are both context-sensitive and practically relevant. The four steps involved in the study are detailed in Fig 3 and each step is further explained in the following paragraphs.

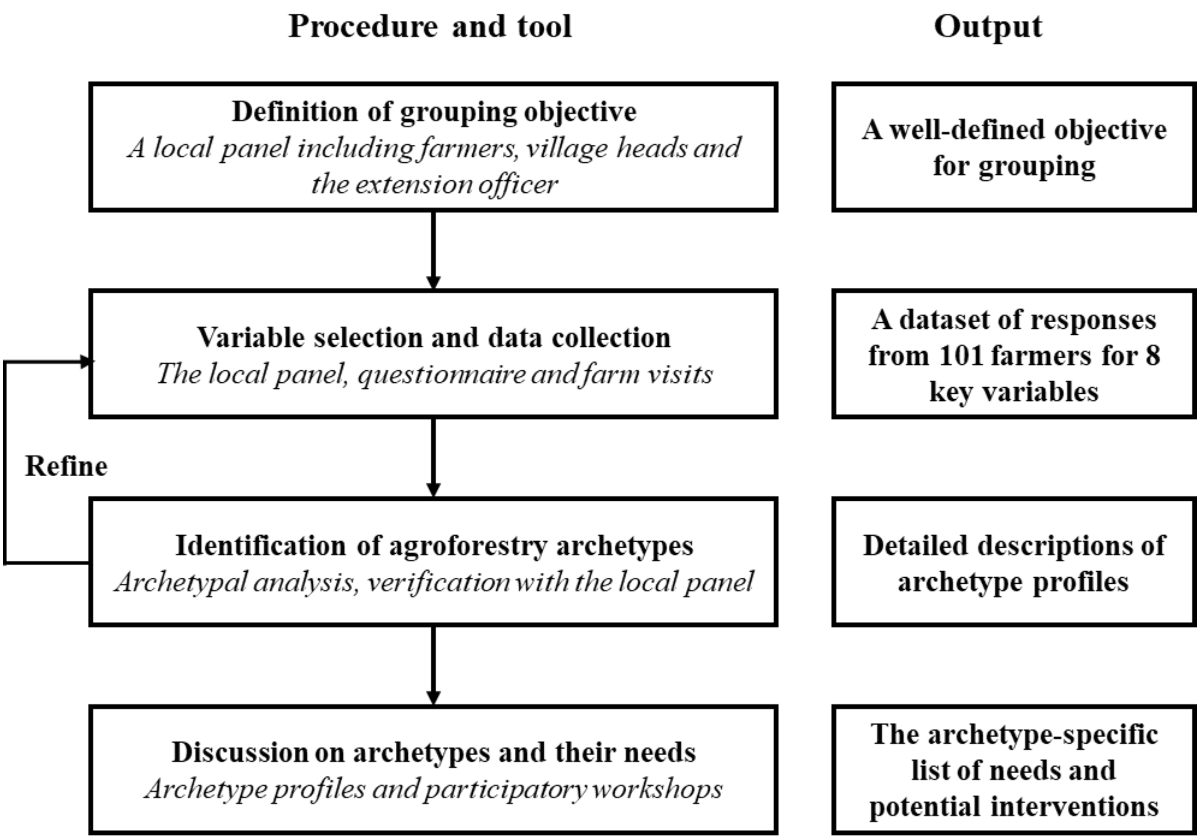

Fig 3 Participatory procedure used in developing an agroforestry farm typology and pinpointing needs of each farm type. The analysis was iterative, allowing refinement of the resulting archetypes through consultations with the local panel until they could map the farms in the dataset and new farms to corresponding archetypes.

Definition of grouping objectives. The motivation and purpose for differentiating farmers came from discussions with a local panel during our previous research which studied a complex web of factors driving farmers' adoption decisions and the diversity of the farms' adoption pathways (Do et al. 2025, under review) and explored dominant discourses on farm-level impacts of agroforestry among adopting farmers (Do et al. 2024). The panel included farmers, the community extension officer and village heads who actively engaged in and supported our activities in the location. Through these activities, we identified farm-level and structural barriers that have hindered the progress of agroforestry. Given the diversity in farm structure and the challenges in farmers' implementation of agroforestry, it became clear that targeted support was necessary. Consequently, we established objectives to group farm households based on their farming structure and agroforestry practices. This grouping aims to pinpoint both the opportunities and the specific challenges and needs of each farmer type.

Variable selection and data collection. The selection of variables was guided by the grouping objective. In collaboration with the local panel, we identified key variables that differentiate agroforestry farmers. These variables included structural aspects of the farms and elements related to the implemented agroforestry practices. The farm structure variables included total cultivated land, land fragmentation, available farm labor, income derived from cropping activities and off-farm activities. The agroforestry-related variables included adoption level, crop diversity of the agroforestry system and farmers' experiences with agroforestry practices. Additionally, we collected information on other socioeconomic variables relevant to the farmer and detailed information on plot-level management practices such as fertilizer and pesticide application, use of irrigation and labor allocation. We conducted interviews guided by a semi-structured questionnaire between June and August 2023.

We used Simpson's index (Ciaian et al. 2018) as a measure of land fragmentation within the farm. Simpson's fragmented land index is estimated as $S = 1 - \sum_{i=1}^{N} a_i^2 / (\sum_{i=1}^{N} a_i)^2$, where a_i is the size of plot i, and N is the total number of plots. The value of the index S ranges from zero to one, with a greater value meaning that land is more fragmented (Ciaian et al. 2018). An S-value of zero indicates that the farming household owns only one parcel or plot of land, showing complete land consolidation, while a value close to one suggests that the household has numerous scattered plots, reflecting significant land fragmentation. We defined the adoption level as the percentage of total cultivated land that farmers allocated to agroforestry. We measured species richness per agroforestry parcel, counting the number of tree and crop species as an indicator of species diversity within agroforestry plots across households. We also inquired about the households' income during the previous year (2022) to balance the ambition of obtaining a comprehensive view of the household's livelihood structure and the challenge of receiving accurate recalls from farmers about past events. We distinguished between income from different livelihood activities, including crops, livestock and off-farm activities. Off-farm incomes included earnings from employment and self-employment, as well as seasonal off-farm work undertaken by household members. This diverse spectrum of income sources illustrates the various livelihood orientations of the households, which affect how resources are allocated and ultimately may influence their agroforestry practices.

Table 1 Surveyed variables and variables used for farmer categorization. These variables include farm structure variables, livestock-related variables, income-related variables and agroforestry-related variables. Values are presented with mean, maximum and minimum values from the responses of 101 farmers.

Category	**Variable**	**Variable used**	**Mean (min – max)**
Farm structural variables	Age of household head (year)		49.6 (29 – 68)
	Number of years of schooling of the household head		7 (0 – 12)
	Number of household members		4.8 (2 – 9)
	Number of household members fully engaged in farming activities	x	2.5 (1 – 6)
	Total cultivated land area (hectare)	x	1.8 (0.3 – 5)
	Number of cultivated land plots		4.5 (2 – 8)
	Level of land fragmentation (Simpson index)	x	0.6 (0 – 0.9)
	Percentage of land allocated to annual crop (%)		12.7 (0.0 – 75.0)
	Percentage of land allocated to sugarcane (%)		37.8 (0.0 - 92.6)
Livestock-related variables	Number of cattle		2.3 (0 – 10)
	Number of poultry		71 (0 – 300)
	Number of pigs		2 (0 – 30)
	Number of small ruminants (i.e. goat)		2 (0 – 41)
Income-related variables	Total income (million VND)		162.7 (5.6 – 435)
	Income generated from cropping activities (million VND)		65.5 (0.28 – 222.6)
	Income generated from off-farm activities (million VND)		74.8 (0 – 264)
	Income generated from livestock (million VND)		22.5 (0 – 327)
	Share of total income generated by cropping activities (%)	x	42.2 (0.0 – 94.5)
	Share of total income by livestock activities (%)		13.6 (0.0 – 87.0)
	Share of total income derived from off-farm activities (%)	x	44.3 (0.0 – 98.3)
Agroforestry-related variables	Percentage of the total cultivated area allocated for agroforestry (%)	x	46.1 (1.3 – 100)
	Number of tree and crop species integrated in agroforestry systems	x	2.9 (2 – 6)
	Farmers' experience with agroforestry practices (year)	x	6.5 (1.0 – 16.0)

We employed a purposive sampling approach to capture the diversity of agroforestry adoption behaviors and key variables. Since input distribution through the project ended in 2019, agroforestry adoption observed by the time of data collection was largely shaped by the farmers' own strategies rather than by direct external support. We included both farmers who had received support from the previous project and those who had not, to ensure the typology reflects a broad spectrum of farm diversity. This approach enhances the applicability of findings to broader policy contexts, extending beyond the scope of a single intervention. Initial participants were identified with the assistance of the local panel who provided insights into the local farming community. We then used snowball sampling (Naderifar et al. 2017) to recruit new respondents based on recommendations from previously interviewed farmers. This strategy ensured the inclusion of a wide range of household characteristics, agroforestry practices, and resource endowments. We also conducted farm visits to verify and assess agroforestry systems described by farmers during the interviews. Characteristics of the 101 surveyed farmers are summarized in Table 1.

Identification of agroforestry archetypes. A dataset consisting of responses from 101 farmers to eight selected variables (Table 1) was subjected to archetypal analysis, following the algorithm described by Eugster and Leisch (2009). This method can be applied to a given n x m matrix ($n = 101$ and $m = 8$) which represents a multivariate data set with n observations and m attributes. For a number k, the archetypal analysis finds the matrix of k x m archetypes. These archetypes, which are derived as convex combinations of the data points, are considered to approximate the data best. The estimation process involves solving systems of linear equations and convex least squares problems as detailed in Eugster and Leisch (2009). This process distills the 101 farmers into a manageable number of k archetypes, each representing a unique combination of characteristics observed among agroforestry farmers. This method facilitates the identification of distinctive profiles, highlighting the diversity of farming practices and strategies.

Practically, the initial step involves selecting a meaningful number of archetypes, k, to retain. To decide on k, we employed the common method of running the algorithm with varying numbers of archetypes and applying the elbow criterion to the residual sum of squares (RSS). This method suggests selecting the number of archetypes according to the point where the RSS curve flattens, which indicates diminishing returns from adding more archetypes (Epifanio et al. 2013). We calculated and plotted the RSS for 1 to 15 archetypes (Fig 4A). A distinct elbow was observed at three archetypes, after which the decrease in the RSS became less pronounced. Accordingly, we conducted the analysis with three archetypes to calculate the model parameters and coefficients. The model parameters provided an estimate of each archetype's attributes, while the model coefficients estimated the degree of association of each farmer with the respective archetype. Following the two-thirds criterion (Tittonell et al. 2020; Necula et al. 2024), farmers were assigned to an archetype if their coefficient for that archetype exceeded 0.66. The model also yields percentile values for each variable, indicating the position of a variable's value within the dataset. In archetypal analysis, these percentile values are instrumental in highlighting how extreme or central an archetype is compared to the entire data distribution. This information is crucial for understanding the defining traits of each archetype. The analysis was executed using the R statistical software (R Development Core Team 2022) with the *archetypes* package (Eugster and Leisch 2009).

We incorporated feedback from the local panel of farmers, village heads and the community extension officer to verify the resulting archetypes and repeated the analysis as needed. In this case, we refined the variables that were initially used for the archetypal analysis. For instance, we initially used absolute values for income-related variables, such as absolute incomes from cropping and off-farm activities. However, the resulting archetypes from this trial were challenging for the local panel to interpret. We shifted to using relative values for these income variables (Table 1), which better reflect the households' livelihood orientations and their resource management strategies. We decided on a final set of archetypes when the local panel could map the farms to corresponding archetypes, including the farms in the dataset and new farms and confirmed that the resulting archetypes were well-suited for the purpose of farm typology development. After defining three archetypes, we examined the distribution of farmers who had received input support and those who had not across archetypes. This step helped in interpreting the relationship between past input support and the identified farm types and their needs.

Discussion on farm types and their needs. In November 2024, a workshop was conducted with 30 participants, including two village leaders, one extension worker and 27 farmers (13 female and 14 male) from three villages. We invited a focus group of participants among those we had interviewed based on their association to archetypes. A focus group ensured a manageable discussion size, allowing for deeper engagement and interactive dialogue while maintaining representation across archetypes. The workshop's aim was to validate the relevance of the identified archetypes based on the participants' experience and to gather insights into the specific challenges and needs associated with each archetype. We used these insights to identify potential intervention points for enhancing farmers' engagement in sustaining agroforestry practices. Interventions to be proposed could involve specific actions, programs or strategies implemented by farmers, researchers or policy-makers to address the needs and challenges identified during the workshops.

During the workshop, we presented the outcomes of the archetypal analysis with three archetype profiles. These profiles were confirmed by participants as effectively representing the local farming community with respect to our intended grouping objective. Participants were then asked to assign themselves to one or more of three groups that represented the three archetypes. Farmers' self-assignment was consistent with the data-driven assignment generated by the archetypal analysis. Some farmers identified themselves with more than one archetype, which demonstrates the practical applicability of a convex-combination approach in archetypal analysis. These farmers were invited to join the group that they saw as the best reflection of their current situation. Discussions within these archetype groups were facilitated by trained facilitators and centered around two guiding questions: 1. "What are challenges and needs for expanding and enhancing your agroforestry practices?" 2. "Which intervention points do you think would have the greatest impact to address your challenges?". Each group was tasked with prioritizing intervention points by grading them for their potential impacts and feasibility. We used a scale from 1 to 10, representing the scale from the lowest impact or feasibility to the highest impact or feasibility. This exercise helped pinpoint immediately actionable interventions. The focus group discussion was followed by a panel discussion where each group shared their findings, which were then further explored through open discussions within the entire group to deepen understanding of each group's circumstances. In addition to workshop minutes, the focus group and panel discussion were digitally recorded and transcribed to support comprehensive interpretation of the results.

3. Results

3.1. Agroforestry archetypes and their farming strategies

Three distinct archetypes emerged from patterns in farm structure and adoption strategies among farmers. A ternary plot illustrates each farmer's proximity to different archetypes, as expressed by their coefficients (Fig 4B). While some farmers are remarkably close to a particular archetype, others are at the intersection of two or all three archetypes. Of 101 farmers, 61.4% (62) were assigned to one of the three archetypes. Among these farmers, 6 (9.7 %) were mapped onto Archetype 1, 31 (50.0 %) onto Archetype 2 and 25 (40.3%) onto Archetype 3. The most representative characteristics of each archetype are highlighted by the percentile values of the respective variables (Fig 5), indicating their relative position within the studied population of 101 farms. Table 2 presents the characteristics of the three archetypes across eight variables, calculated as weighted combinations of farmers positioned near the extremes of the data space.

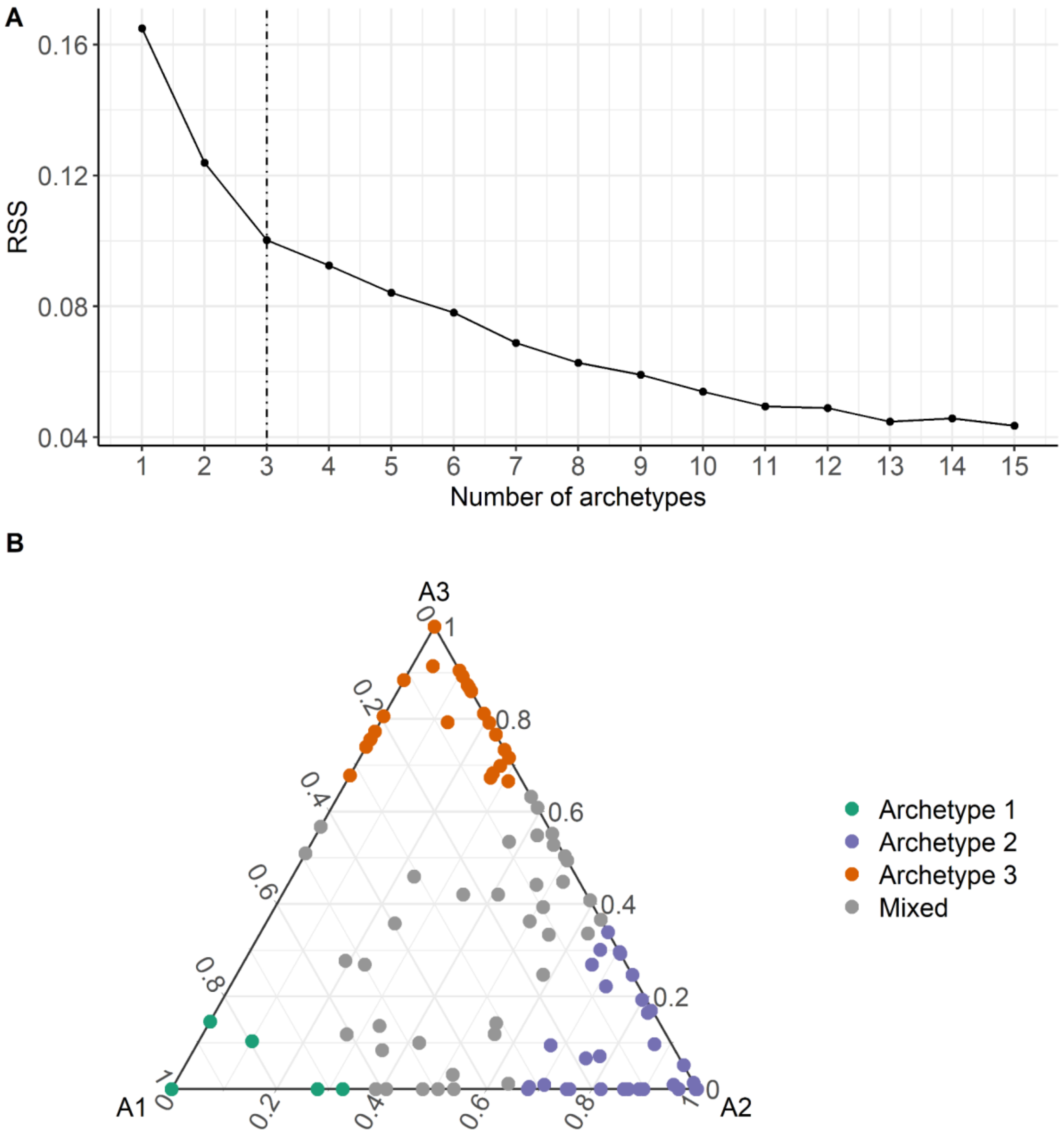

Fig 4 Scree plot (A) showing three archetypes as an optimal number to retain (dashed line), decided based on the elbow rule applied to the RSS values and the interpretability of the resulting archetypes. Ternary plot (B) illustrating the association of farmers with three distinct archetypes. Each point in the plot represents an individual farmer as a combination of these archetypes, with the coefficients associated with each archetype summing up to 1. Non-grey dots signify farmers who predominantly align with one archetype, identified by one of the coefficients exceeding 0.66, a common threshold used in archetyping farms. The grey dots situated on and near the edges A1A2, A1A3, and A2A3 indicate farmers who exhibit characteristics of two corresponding archetypes. The grey dots positioned towards the center of the plot generally embody attributes of all three archetypes.

Archetype 1. Small-scale diversified farms run by experienced farmers

Archetype 1 (A1) is characterized by a small landholding of 1.0 hectare but demonstrates the highest level of agroforestry adoption. The A1 group demonstrates a strategic approach to optimizing the use of limited resources. The A1 farmers allocate all their land to agroforestry, attributing their high adoption level to limited availability of agricultural family labor (1.8 household members). They perceive agroforestry as less labor-intensive compared to sugarcane production, the predominant alternative cropping system to annual monocultures and fruit tree-based systems in the area. The A1 farmers implement diversified agroforestry systems, which integrate 5.3 crop species including trees and annuals. These systems often feature a diverse mix of trees, including fruit trees, nut trees and coffee, in addition to annual crops and fodder crops. Low land fragmentation, as evidenced by a low S-index of 0.2, facilitates the management of these diversified systems. A1 farmers perceived their agroforestry systems with diverse tree and crop species as a strategy for guarding against market and climate risks. The diversification extends to income sources, with 20.5 % of household income derived from cropping activities, 61.3 % from off-farm employment and the remainder from livestock production.

Despite their strategic approach to allocating resources and leveraging diversified agroforestry practices, the complexity of managing highly diversified agroforestry systems presents significant challenges to A1 farmers. The high diversity of species introduces cultivation difficulties, such as intensive technical knowledge requirements, reliance on multiple sources of agricultural inputs and a need for permanent irrigation facilities.

Table 2 Characteristics of the three agroforestry archetypes detected in archetypal analysis. The table presents values of eight key variables across each archetype calculated as model parameters from archetypal analysis using data from 101 farmers.

Variable	Archetype 1	Archetype 2	Archetype 3
Adoption level (%)	100	39.8	19.7
AF diversity (number of integrated species)	5.3	2.0	3.0
Agroforestry experience (number of year)	8.5	4.9	7.0
Farm labor (number of household members)	1.8	2.0	3.6
Land area (hectare)	1.0	1.1	3.4
Fragmentation index (-)	0.2	0.8	0.6
Share of crop income (%)	20.5	19.4	86.6
Share of off-farm income (%)	61.3	72.2	5.0

Archetype 2. Fragmented resource-poor farms

Archetype 2 (A2) operates on small landholdings of 1.1 hectare, with a high land fragmentation index of 0.8, indicating a high degree of land dispersion and small plot sizes. This group relies on both farm-based and off-farm income, with cropping activities contributing 19.4 % of total household income. Similar to A1, their small landholdings limit their engagement in agricultural labor, with only 2 family members typically involved. Off-farm activities contribute 72.2% to the total income of an A2 household, which underscores the critical role of off-farm employment in sustaining their livelihoods. A2 farmers allocate 39.8% of their land to agroforestry, demonstrating a strong willingness to adopt the practice. However, they are in the early stages of integration, with 4.9 years of agroforestry experience. Their agroforestry systems are characterized by low species diversity, typically one fruit tree species, usually mango or longan, intercropped with one annual crop species. The limited diversity is likely influenced by high reliance on off-farm income, which restricts farmers' time and resources to improve and diversify their systems. Additionally, the high dispersion level of land presents logistical challenges, making effective management of complex and diversified agroforestry systems difficult.

Despite these challenges, the moderate adoption level and the presence of agroforestry on A2 farms suggest significant potential for further expansion and improvement. Farmers in this group expressed a shared interest in increasing the tree diversity in their agroforestry systems given the high risks of market fluctuations and weather extremes. However, their limited experience and knowledge limit their ability to find suitable tree species and to manage more diverse agroforestry systems.

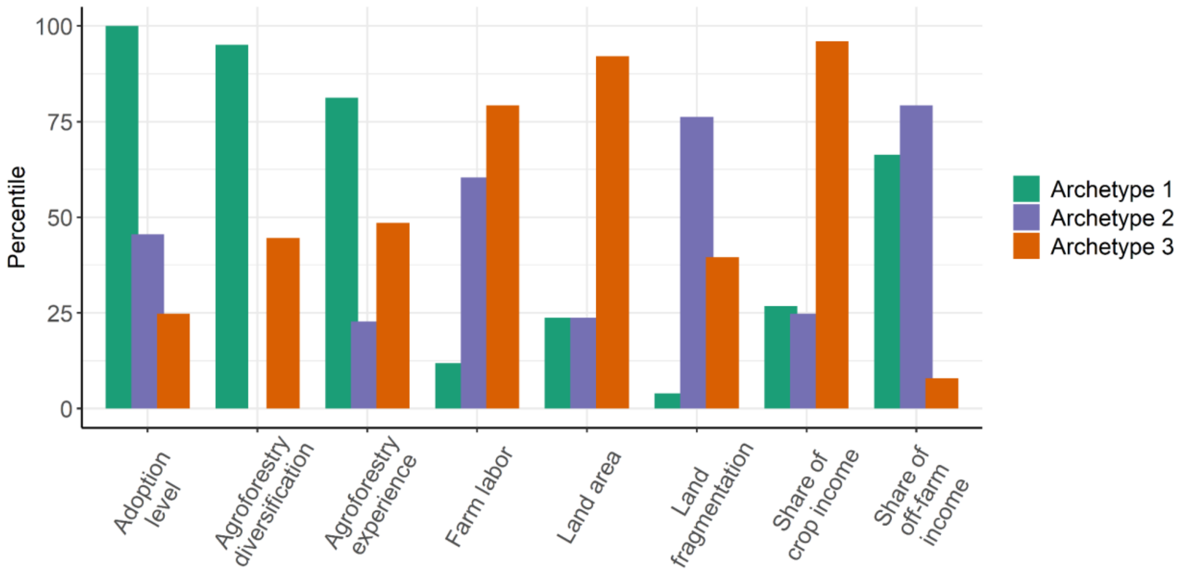

Fig 5 Percentiles of selected variables indicating the relative positioning of a variable's value for a particular archetype compared to the distribution of that variable across the entire dataset.

Archetype 3. Sugarcane-focused farms

Archetype 3 (A3) is characterized by the largest landholding of 3.4 hectares and a primary reliance on farm-based income. Cropping activities contribute 86.6 % of total household income, reflecting a strong focus on cash crops (i.e. sugarcane). A3 farmers allocate substantial labor to farming, with 3.6 household members fully dedicated to agricultural activities. They experience moderate land fragmentation with an S-index of 0.6, reflecting the distribution of their land across multiple plots, often located far apart. Similar to A2 farmers, this dispersion poses logistical challenges for effectively managing diversified cropping patterns. Scattered land plots are more laborious and time-consuming to manage, as farmers must travel between locations to perform routine tasks. Despite their substantial land resources, A3 farmers allocate only 19.7 % of their land to agroforestry. In their agroforestry systems, A3 farmers integrate three species, including trees and annual crops, typically intercropping one fruit species (mango or longan) with one annual crop and fodder grass, or a mix of two fruit species and an annual crop species. The predominance of sugarcane cultivation is driven by its perceived stability as an income source, supported by forward contracts with the local sugar manufacturer. These contracts ensure a guaranteed market for farm produce and provide farmers with production inputs under “delayed payment” arrangements. This system alleviates immediate financial burdens, as farmers are only required to settle input costs after harvest. The high engagement of farm labor on A3 farms enables effective participation in the local sugarcane shared-labor cooperatives, which are essential for managing the intensive labor demand that is typical of the peak sugarcane harvesting seasons.

While benefiting from the economic stability of sugarcane monoculture, farmers registered in this archetype expressed concerns about the long-term sustainability of this system. Issues such as land degradation and the challenges posed by an aging family labor force motivate interest in expanding agroforestry areas. However, this transition is hindered by both farm-level and structural barriers. Key farm-level constraints mentioned by A3 farmers include limited knowledge on the suitability of tree species, the management of diversified agroforestry systems and the need for upfront investments for tree seedlings. The absence of robust agroforestry value chains was also mentioned as a persistent structural barrier.

All three archetypes included both supported and unsupported farmers. However, the distribution of these farmers varied across archetypes. Archetype 1 included three supported and three unsupported farmers. In Archetype 2, the number of supported farmers (22) was more than double that of unsupported farmers (9). In contrast, in Archetype 3, the number of unsupported farmers (17) was twice as high as that of supported farmers (8). The mixed group consisted of 24 supported farmers and 14 unsupported farmers. This uneven distribution suggests a bias in project support allocation. Since the CIFOR-ICRAF project aimed to demonstrate large-scale agroforestry within a designated area, farmers with land plots in close proximity were more likely to be selected for support. This highlights how logistical and spatial planning considerations can shape support allocation and its inclusiveness.

3.2. Expressed needs across the three archetypes

Intervention points, defined as specific places within a system where intervention can be most effectively applied, were discussed and evaluated to address the challenges faced by each archetype, focusing on potential impacts and feasibility (Fig 6). This analysis revealed several common themes, highlighting shared needs across the three archetypes. These common needs included improved market access, financial support for agrochemicals, irrigation systems for agroforestry and enhanced technical knowledge of agroforestry. The unique needs of each archetype were also identified. The needs of Archetype 1 (A1) farmers were the same as the identified common needs, without additional specifications. Archetype 2 (A2) farmers were motivated to diversify their existing agroforestry systems, while Archetype 3 (A3) farmers needed financial support with tree seedlings, which they considered critical for expanding their agroforestry areas. Based on farmers' rankings of these intervention points, we identified two intervention groups: strategic interventions and practical interventions. Strategic interventions are those seen as having significant potential to drive the expansion of agroforestry but are challenging to implement. In contrast, practical interventions are those that can be implemented immediately and are likely to have a direct and tangible impact on farmers' practices.

Among strategic interventions, improved market access for agroforestry products was the most universally recognized need across all archetypes. In the study area, positive signals from fruit markets initially encouraged the transition to fruit tree-based agroforestry systems. However, these markets have since deteriorated, failing to provide stable and secure prices for farmers. While A1, with its highly diversified agroforestry systems, is better equipped to buffer against the market risks associated with a narrow range of products, this issue is particularly significant for the A2 and A3 farms. For these farms, the lack of effective market schemes has been a primary barrier to wider adoption of agroforestry. Farmers noted that measures to improve market access are currently lacking due to the small-scale and fragmented nature of local production, the weak linkages between farmers and market agents and a lack of market information. To address this, farmers suggested establishing collective marketing by forming farmers' cooperatives. However, they expressed concerns about weak community leadership, which could hinder the development of strong and effective cooperatives.

Support for production inputs was identified as the second major area requiring attention, though the underlying concerns varied among archetypes. The A1 farmers expressed a need for input support through delayed-payment arrangements, similar to the system used in sugarcane production. This need arises from the requirement for the intensive input investments necessary to sustain tree productivity in the highly diversified agroforestry systems they manage. The A2 and A3 archetypes tied their needs for input support to the high risk of market failure. Current low fruit prices often fail to cover input costs, leading to net losses on agroforestry plots. As a result, farmers in these groups expressed a need for direct financial incentives to buffer against these risks. A3 farmers also highlighted the need for subsidized tree seedlings given their large potential for expanding agroforestry areas. This need aligned with the finding that a greater proportion of A3 farmers did not receive input support from the previous project compared to those who did. Given that most A3 farmers lacked prior support, their collective reflection on the need for subsidies was likely influenced by this shared experience.

The establishment of irrigation systems was another strategic intervention mentioned by A1 and A3 farmers. In upland farming communities, agricultural production is primarily rainfed. Changing climate patterns have resulted in increasingly frequent droughts. These conditions led to crop failures in conventional monocultures and premature fruit and nut drop in agroforestry systems. Farmers perceived irrigation systems as critical for ensuring the long-term productivity of tree-based systems. Nevertheless, they were aware that financial support in any form for both production inputs and establishment of irrigation systems is limited. They noted that such support is typically available through funded projects, which are often restricted in scope and fail to reach many of them. Additionally, the feasibility of irrigation is impaired by other factors such as limited water sources, inadequate storage facilities, land fragmentation and geographical challenges of field plots.

Farmers identified practical interventions, including improved technical knowledge and diversification of the existing agroforestry systems, as both highly impactful and feasible. Technical assistance was highlighted as crucial for improving existing agroforestry practices (A1 and A2) and expanding household agroforestry areas (A3). The perceived high feasibility of improving technical knowledge is due to the variety of accessible sources of assistance, including peer-to-peer exchange, agencies or companies promoting specific crops like sugarcane, macadamia or coffee, and various online sources. Public extension services, while not as frequent as farmers might prefer, remain accessible. Farmers can request training on certain farming aspects via their village leaders. The requests are then considered, and training is provided if needed. In addition, diversification of the existing agroforestry systems, especially by A2 farmers, was seen as a measure in response to the deterioration of the fruit market. Farmers viewed diversification as highly feasible since it is affordable without requiring the substantial investments that are incurred when establishing new tree-based systems.

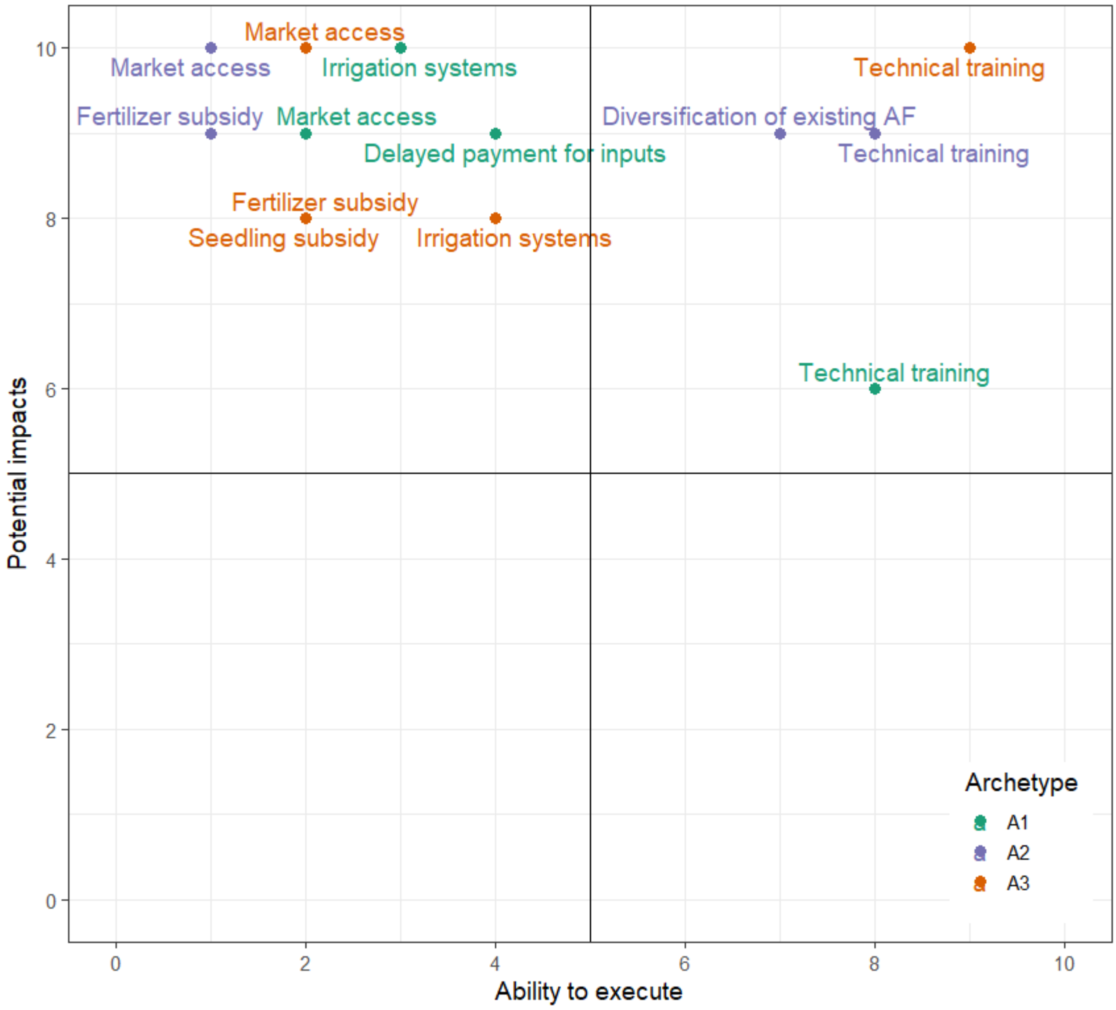

Fig 6. Priority matrix of potential intervention points as suggested by three archetypes. The x-axis displays the feasibility of executing the interventions while the y-axis indicates potential impacts of the interventions. A scale from 0 - 10 is used on both axes, ranging from the lowest to the highest impact or feasibility. This matrix categorizes strategic and practical intervention points, in the top-left and top-right quadrants, respectively. The strategic interventions are characterized by high impact but low feasibility, while practical interventions are noted for their high feasibility and impact.

4. Discussion

We characterized the predominant adoption behaviors of agroforestry farmers in relation to their resource endowments and constraints. All identified archetypes highlighted a critical need for financial support to cover production costs and mitigate market risk. While prior studies, such as Simelton et al. (2017), often emphasize the role of governmental policy incentives, implementing these incentives typically requires extensive strategic planning, which can be cumbersome and slow to adapt to local needs. Furthermore, in some cases, the level of funding required to achieve substantial adoption might be higher than the amount that can be justified by the resulting environmental benefits (e.g. Pannell 2001). This situation underscores the limitation of heavily relying on government-driven incentives and suggests a shift towards adjusting management practices for both short- and long-term economic and environmental benefits without requiring excessive subsidies.

The characterization of farm types in this study has clarified the unique constraints, opportunities and specific needs of the agroforestry archetypes. This comprehensive knowledge informs our approach to identifying possible socio-technical solutions that do not solely rely on extensive strategic government planning. Instead, we focus on actionable solutions that farmers can implement to address their own needs or that can be supported by social agencies who commit to fostering sustainable agroforestry. These insights are relevant to the local context and applicable to other regions facing similar challenges. They can help overcome common barriers and leverage opportunities for advancing progress towards sustainable agroforestry transitions. It is important to note that our discussion integrates strategic and practical intervention points within a holistic agroforestry framework. This approach targets systemic change and provides tools and methods that are aligned with the socio-economic realities of agroforestry communities.

Market access and production input costs are interconnected challenges. The two challenges of market access and input costs, mentioned by all archetypes, are interconnected. Market access with secure prices for agroforestry products encourages farmers to invest in their systems, while reducing reliance on costly external inputs can ease the pressure on farmers to achieve high market prices. Addressing one of these concerns can help alleviate the other, creating positive feedback.

Farmers have developed strategies to address challenges related to markets and input costs. The A1 archetype has diversified agroforestry systems to mitigate the risk of market prices associated with a narrow range of fruit tree species. The A1 and A2 archetypes also rely on off-farm income to offset input costs for agroforestry plots while the A2 and A3 archetypes diversify household income sources by growing a range of crops. However, persistent low market prices might threaten the long-term viability of agroforestry transitions, potentially undermining farmers' confidence in the economic returns from such systems.

Agroforestry systems with high species diversity were perceived by A1 and A2 farmers as an economically viable solution in the context of market and climate risks and difficult access to productive resources, especially land. This implies that future market incentives should support the diversification of agroforestry supply chains to avoid investments driven solely by profit, which often favor a narrow range of tree species (Ariza-Montobbio et al. 2010; Costa et al. 2018). Dual-crop agroforestry systems, practiced by A2 and A3 farmers, often focus on one or two major commercialized fruit tree species and feature high reliance on costly agrochemicals and low functional diversity. Such systems may offer limited ecosystem services and sometimes cause negative overall impacts, which underscores the need to explore strategies that enhance the overall functionality of agroforestry systems (Ollinaho and Kröger 2021).

Diversification and integrated management of agroforestry practices can enhance agroforestry functionality. Current agroforestry practices are vulnerable to market and climate conditions, as highlighted by farmers during the participatory workshop. Diversified agroforestry systems are increasingly seen as viable solutions to improve the economic viability of agroforestry, evidenced by their adoption by A1 farmers and the willingness to diversify by A2 farmers. When well-designed and well-managed, diversified agroforestry practices can support a wider range of ecosystem functions, such as enhancing biodiversity and offering soil and water-related services (Ollinaho and Kröger 2021). Such systems have the potential to transform degraded land or areas challenged by water scarcity and specific climate conditions into productive agroforestry systems with low capital costs for irrigation, chemical fertilizers or pesticides (Andrade et al. 2020). These potential benefits make diversified agroforestry systems practical solutions for addressing concerns related to the cost of external inputs across all archetypes and the financial challenges associated with establishing irrigation systems for A1 and A3.

A diversified agroforestry system, when managed effectively, can reduce farmers' dependence on external inputs and enhance system resilience against external shocks by leveraging ecological interactions between species and recycling on-farm resources. External inputs can be reduced by recycling resources available within the system, e.g. through pruning and mulching (Matos et al. 2020; Froufe et al. 2020) or from animal manure. Most farmers (84 out of 101) use livestock manure to return nutrients to the field. However, limited availability of manure and transportation challenges often prevent the application of sufficient manure to meet the trees' nutrient needs. In-situ mulching, using pruned biomass from trees, presents a practical solution, offering an alternative nutrient source for agroforestry systems. Steinfeld et al. (2023) suggested that major macronutrients such as N, P, K, Ca and Mg can be effectively recycled from in-situ biomass into plant-available soil pools across a wide range of soil conditions, from very sandy to very clayey, in the humid subtropical climate of São Paulo, Brazil. Nutrient cycling is particularly effective in densely planted systems with high species richness, including pioneer trees (Steinfeld et al. 2023). Using pruned tree branches as surface mulch can also preserve soil moisture and regulate soil temperature, which could reduce the need for irrigation (Tang et al. 2022).

Establishing irrigation systems, as specified by A1 and A3 farmers, remains financially and logistically challenging in upland farming contexts due to weak financial capacity, land fragmentation and the topographic characteristics of the area. Of the 101 interviewed farmers, only 15 reported having irrigated agroforestry plots, which are typically located near their homes and close to water reservoirs. A promising solution can be drawn from the existing farming practices, where rainwater is harvested using small wells that are dug on-site. These facilities, typically used for herbicide and pesticide spraying, could be expanded into collective pond systems for irrigation. In the study area, community ponds exist, however they are currently leased to larger-scale farmers to irrigate their intensive fruit plantations. Rainwater harvesting ponds for irrigation, which have been successfully implemented by upland farming communities in Thailand (Landicho et al. 2022), provide a low-cost and practical model suitable for adoption and adaptation in northwestern Vietnam. This method also minimizes the risk of groundwater overexploitation while effectively leveraging the recycling of local water resources. However, implementing such interventions often requires community collaboration in allocating resources such as land and labor for establishing and maintaining these facilities (Landicho et al. 2022).

Local challenges and opportunities reveal insights for putting diversification and integrated management of agroforestry into practice. The emphasis on diversification and natural processes of nutrient recycling requires profound changes in current technical systems, which make the implementation of such systems both knowledge- and labor-intensive (Willmott et al. 2023; Steinfeld et al. 2023). Farmers need to be well-informed about which tree species are suitable for different land topographies and soil types, and how to design and manage a system with a high diversity of annual and perennial species to optimize the economic and ecological interactions among the components. Robust scientific knowledge and tools are available for identifying appropriate species for effective diversification through functional diversity and niche complementarity (Santos et al. 2021; Willmott et al. 2023). Practical implementations of diversified and integrated system management are evolving under different models such as successional agroforestry (Bouffartigue and Weckenbrock 2016) or syntropic agroforestry (Andrade et al. 2020), which integrate indigenous knowledge of intercropping multi-purpose species, modern agroforestry techniques and assisted natural regeneration, emphasizing biodiversity, adaptive management, and the use of ecological succession to establish a productive system (Young 2017). These models provide strong evidence of the practical feasibility of diversification and integrated management of agroforestry systems. The intensity of labor requirement tends to decrease as systems mature, when natural processes take over. Similarly, the demand for specialized knowledge may decline over time as farmers gain more experience and familiarity with the system (Ollinaho and Kröger 2021). In addition, the reduction and possibly exclusion of externally produced inputs empower farmers to become less reliant on external inputs and gain autonomy in their production (Ollinaho and Kröger 2021).

Economically, agroforestry with high biodiversity is unlikely to achieve the profitability of monoculture plantations, which highlights the need for changes in the economic incentive structure through well-designed policies (Grass et al. 2020). The relatively lower profitability of agroforestry compared with monocultures and short-term rotation has often discouraged farmers from implementing diversified agroforestry systems. This tendency is reflected in farmers' preference to manage simple systems focused on a few profitable tree species, such as longan and mango (A2 and A3). Nevertheless, the shifting of consumers' preferences toward more sustainably produced products presents significant market opportunities for products from diversified agroforestry systems. Domestic consumers in Vietnam are increasingly willing to pay price premiums for products that are produced in chemical-free, highly diversified and environment-friendly systems (Khai and Yabe 2015) or for products with effective traceability systems (Dang et al. 2019). Therefore, chances to enhance product commercialization and improve the integration of diversified agroforestry into value chains are increasing.

Limited and fragmented land access generally presents challenges in agricultural production, as it often leads to high production costs and low economies of scale (Lu et al. 2018; Zhou et al. 2024). However, a fragmented structure may provide opportunities for promoting diversification and integrated management of agroforestry systems, particularly in areas with small land sizes (A1 and A2), which may make system management more feasible and approachable for farmers. The dispersion of cultivated land plots (A2 and A3) may even facilitate diversification of cropping systems (Van Hung et al. 2007; Ciaian et al. 2018), and it offers farmers opportunities to trial new ways of managing agroforestry systems while maintaining cash flows from other plots (Do et al. 2024).

In Vietnam, diversification and integrated management of agroforestry systems have been practiced by farming communities across the country, either spurred by their own interest or supported by social networks and agencies such as the Agroecology Learning Alliance in Southeast Asia (ALiSEA) and ADRA International (ADRA Vietnam 2023). The existing complex agroforestry systems practiced by A1 farmers and the willingness to diversify of A2 farmers provide strong justifications for introducing such agroforestry settings into practice.

Strengthening community capacity and collaboration are crucial. Diversification and integrated management of agroforestry typically emerge from grassroots initiatives, driven by farmers, consumers and their respective networks, who foster niches or pathways to diversification and its associated social and environmental benefits (Blesh et al. 2023). Therefore, the success of such approaches relies strongly on local motivation and collective action within communities. To support effective diversification of agroforestry in the study area, governmental initiatives alone may not be sufficient. It is crucial to strengthen capacity and collaboration within the community, enabling it to address both technical and structural challenges successfully.

Farmers proposed establishing an agricultural cooperative to enhance market access through collective marketing strategies, especially for small-scale A1 and A2 farmers. Extensive research shows that cooperatives can provide market access, education, training and technical assistance, reduce certification costs, provide seed bank and nursery access, provide microcredit for investments, and improve local infrastructure for the processing and transporting of goods (Jacobi et al. 2017). These benefits make cooperatives promising solutions to the challenges associated with diversifying agroforestry systems. Moreover, the presence of cooperatives could reassure consumers seeking traceable, sustainable products and potentially increase farmers' access to fair-trade markets (Willmott et al. 2023). Such network pathways have been identified as the primary mechanism facilitating the emergence of niches for agriculture diversification (Blesh et al. 2023). These pathways have also been the foundation for other sustainable agricultural initiatives, such as the Participatory Guarantee System (PGS), a locally-focused quality assurance system in organic agriculture that involves stakeholders along the value chain in the monitoring process (Grovermann et al. 2024). Similarly, the Community-Supported Agriculture (CSA) movement fosters long-term partnerships where a community of members supports small-scale farmers using agroecological practices by covering production costs in exchange for a share of the harvest (Parot et al. 2024). However, previous attempts to establish farmer cooperatives in the study area have failed due to farmers' weak institutional capacity and lack of commitment and trust among farmers. This failure underscores the crucial role of enhancing community capacity to collaborate effectively.

All farmers in the focus group emphasized the need for regular hands-on training sessions to reinforce their skills and confidence in handling complex agroforestry systems. As stated by farmers, there is currently a notable lack of engagement from extension officers in the study villages, particularly in providing agroforestry-specific guidance. Conversely, farmers often benefit from their peers by sharing knowledge and motivation. Feedback from our workshop highlighted that sharing experience helps farmers learn about the behaviors and strategies of others, whether in similar or different circumstances. This suggests that peer-to-peer agroforestry training could serve as an effective alternative extension model, potentially fostering a transition toward more sustainable agroforestry practices. For instance, A1 farmers with their diversified and complex systems could share their experiences through community field schools (Rahman et al. 2017). Within this framework, agroforestry land plots could act as "living labs" where farmers learn firsthand about how and why something works under certain conditions. This model promotes mutual learning and may encourage the formation of shared-labor cooperatives, akin to those found in sugarcane cultivation, to address labor intensity challenges. The community-based education and capacity-building model could also enhance awareness of the benefits of sustainable management of local resources and create niches for the transition to more diversified and integrated management of agroforestry within the community (Blesh et al. 2023).

The role of collective action is highlighted in the decision-making of A2 and A3 farmers, who allocate their land between intensive monocropping (e.g. sugarcane) and agroforestry. The transition from sugarcane to tree-based farming practices is an individual decision and a collective community choice, especially due to specific management requirements of crops like sugarcane, where residue burning is common. While farmers believe that residue burning helps control pests and diseases and promotes regrowth, this practice complicates the integration of tree-based systems in neighboring fields. Some farmers have experimented with sugarcane cultivation without burning residues and successfully integrated trees into sugarcane systems, suggesting a potential model for sugarcane-based agroforestry that merits further scientific investigation.

Changes in policy frameworks can support broader-scale mechanisms for a sustainable agroforestry transition. Agricultural specialization with strong dependence on external inputs, emphasizing monocultures and short-term rotations, has become deeply entrenched in modern production systems, driven by national policies, government subsidies and corporate influence over research and development (Hendrickson 2015; DeLonge et al. 2016). Such structural barriers often constrain individual farmers' ability to engage in farm diversification (Ollinaho and Kröger 2021; Blesh et al. 2023). Consequently, structural changes in national policy frameworks are essential to facilitating broader-scale mechanisms for sustainability transitions in agroforestry. Supportive policies could include the development of structured markets that align goals for environmental sustainability with those for food and nutrition security, facilitated through local businesses and markets that support diversified supply chains. Additionally, increasing funding allocated for participatory research and education on socio-ecological systems is vital. Mobilizing such funding would enhance opportunities for co-creation and design of farming systems, ensuring sovereignty and sustainability of transformative efforts through local leadership (Blesh et al. 2023).

5. Conclusion

Through a participatory farm typology development process, we differentiated farmers based on their farm structure and agroforestry adoption behavior. The three resulting farmer archetypes reflect diverse implementation patterns tailored to farm resource endowments, such as land and labor, and livelihood orientations. These archetypes articulated their needs, identifying intervention points that could enhance their engagement in agroforestry. Improving market access, providing financial support for input costs and establishing irrigation systems are perceived by all three archetypes as crucial for expanding their agroforestry farming, however, external support remains limited. Farmers suggested actionable interventions such as diversifying existing agroforestry systems and enhancing technical knowledge on agroforestry to improve the economic viability of these systems. Based on these suggestions, we envisioned solutions that consider the challenges and opportunities of each archetype. Diversification and integrated management of agroforestry systems could be a potential direction for sustaining agroforestry farming systems for which strengthening community capacity and collaboration is crucial. Our study underscores the importance of understanding farmers' adaptation behavior when introducing new farming practices. This approach facilitates learning from varied farmer behaviors and strategies, which contributes to the co-creation and design of farming systems that are both innovative, resilient and locally adaptive.

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Data availability Codes and data used for the analysis in this study are available in the repository https://doi.org/10.5281/zenodo.15099703

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Chapter 6. Conclusion

This dissertation investigates the adoption of agroforestry as a dynamic and multifaceted process, focusing on northwestern Vietnam as a case study. Drawing on multiple studies that employed a mixed-methods approach for both data collection and analysis, it advocates for a context-sensitive and farmer-centric approach in promoting agroforestry, which not only respects but also leverages the diversity of farmer circumstances and perspectives.

Although the introduced agroforestry options promise positive returns in the long term, agroforestry requires high investment for establishing tree stands, often resulting in an economic lag of more than three years, a challenge for many smallholder farmers. The high upfront costs, coupled with market uncertainty, make agroforestry systems less economically appealing in the short term compared to maize monoculture, which provides faster returns. However, maize monoculture is increasingly unsustainable, as it depletes soil nutrients and accelerates erosion, leading to a decline in projected annual profits over time. This raises concerns about its long-term viability, particularly in the context of escalating climate change impacts in the region. Despite this, small-scale farmers must often prioritize immediate household needs and cannot afford short-term income losses. Therefore, to make agroforestry a more attractive and feasible alternative for local farmers, financial support and improved market access for agroforestry products are needed.

Our Bayesian Network model offers further evidence for the need for supporting agroforestry by mapping the decision-making landscape at specific time points. The model identifies market security and incentive availability as key drivers that significantly increase the likelihood of farmers adopting agroforestry, suggesting them as priority areas for potential interventions. Favorable market opportunities for agroforestry products foster positive attitudes among farmers, thereby increasing their intention to adopt agroforestry. Similarly, financial incentives help realize adoption by alleviating the burden of high initial investment costs. The likelihood of adoption is further enhanced when these factors are supported by strong extension services and farmer cooperation, crucial channels through which farmers access technical knowledge. Access to knowledge not only builds farmers' confidence in taking up the new practice but, when combined with favorable market conditions, also sustains farmers in long-term integration. As farmers progress through the adoption process, they perceive, learn and adapt the practices to suit their specific circumstances. Follow-up observations reveal that different segments of the farming population follow distinct adoption pathways, underscoring the diversity in how agroforestry is adapted to the local farming context. For instance, farmers have modified initial system designs by increasing fruit tree density, diversifying species, rotating annual crops, integrating or discontinuing fodder crops and phasing out intercropping of annual crops in agroforestry after a few years. These adjustments reflect farmers' efforts to respond to changes in market and climate conditions, which highlights the critical role of farmers' adaptive capacity and flexibility in sustaining agroforestry adoption.

The diversity in agroforestry adoption pathways is closely tied to how farmers integrate agroforestry into their farm operations, shaping three main discourses around its benefits and challenges. Two of these discourses are supportive of agroforestry, emphasizing its benefits through household income diversification and soil erosion control. However, unstable farm-gate prices continue to pose structural barriers to achieving high profitability, which suggests the need for high-level interventions. Despite variations in perspectives, there is a high level of commonality in farmers' mental models, reflecting similarities in their adaptation strategies and their anticipated impact pathways on local farming systems. Farmers harnessed the synergistic effects of agroforestry across various farm components to address investment challenges and short-term income needs, thereby facilitating more effective integration of agroforestry into their operations. This systemic and adaptive approach to managing farm resources underscores the importance of a holistic view when assessing the implications of introducing new practices into existing agricultural systems.

The three agroforestry archetypes, defined through participatory farm typology development based on farm structure and adoption behavior, reflect diverse implementation patterns tailored to each farm's resource endowments and livelihood orientation. Farm households with the same archetype typically have similar farm management with common strategies, have comparable opportunities and face similar constraints. Across all archetypes, common intervention points include improving market access and financial support for input costs and enhancing technical knowledge. Additionally, the archetypes specifically emphasized the need to diversify agroforestry systems and establish irrigation infrastructure to improve economic viability. However, not all interventions are immediately feasible since they may need strategic planning. Drawing upon a systemic view of archetype profiles and their specified needs, we discuss potential solutions that farmers and supporting social agents can implement. These suggestions center on diversification and integrated management of agroforestry systems, with a strong emphasis on the importance of strengthening community capacity and collaboration.

In summary, to effectively support the adoption and sustainability of agroforestry, comprehensive programs that provide continuous assistance, market access and technical training tailored to the dynamic nature of agroforestry adoption are essential. These programs should integrate local knowledge and context, ensuring that interventions are culturally accepted and relevant. Designing support strategies based on distinct farmer archetypes can address specific needs, enhancing the appeal of agroforestry practices.

Overall, this dissertation underscores the importance of holistic and farmer-centric approaches in agroforestry development. Such processes enable the identification of target groups and facilitate a deeper understanding of their adaptation behaviors. This learning is crucial for the co-creation and co-design of innovative, locally responsive farming systems, an approach that has gained growing support in contemporary agricultural innovation efforts.

My dissertation has several limitations that underscore the need for cautious interpretation of the findings and suggest avenues for future research to enhance the understanding and support of sustainable agricultural practices in diverse contexts. First, the decision model of seven agroforestry options (chapter 2) mostly accounted for the direct economic benefits, which we assumed to be primary drivers of farmers' decisions. However, such models may overlook other impacts of agroforestry. Future impact assessments should further clarify the profitability and risks of diverse agroforestry practices under various scenarios. Second, in the studies of farmers' adoption and adaptation (chapter 3 – chapter 5), the representativeness of the sample specific to Son La as case study, may limit the generalizability of the results to other regions with different socio-economic dynamics. Temporal dynamics also play a critical role, as the adoption and outcomes of agroforestry practices evolve with changing socio-economic, climatic and policy contexts, potentially outdating our findings. Future research should focus on cross-regional and longitudinal comparative studies to assess long-term impacts and optimize agroforestry systems for resilience against climate change and market risks. Additionally, while the study benefits from a mixed-methods approach, integrating participatory methodologies, it inevitably faces challenges in fully capturing the range of behavioral, cultural and psychological factors that influence farmers' decisions. Employing participatory action research methodologies will enhance the practical application and success of agroforestry initiatives by involving farmers directly in the research process, promoting iterative learning and co-creating knowledge, and designing systems that are attuned to local needs and constraints.

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Annex

Supplementary Material for Chapter 4

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This document provides additional information for chapter 4 “Adapting agroforestry to upland farming system: Narratives from smallholder farmers in Northwest Vietnam”.

Table S1. Characteristics of 70 interviewed farmers. Land area, land plot, adoption level and cattle owned are presented as ranges marked by minimum and maximum values with medians in parentheses.

Gender (no. of farmers)	Male	39
	Female	31
Age (no. of farmers)	≤ 40	22
	41 – 59	39
	≥ 60	9
Education background (no. of farmers)	Illiterate	7
	Elementary	26
	Secondary	25
	High school	10
	Higher education	2
Land area (ha)		0.4 – 5.1 (1.2)
No. of land plots		1 – 8 (5.5)
Adoption level (% of total land area)		7.3 – 100.0 (52.9)
Cattle owned (head)		0 – 8 (3.0)

Table S2. Comparative analysis for different choices on the number of factors to be retained in the Q study.

No. of factors	Factor	No. of respondents	Explained variance (%)
Two factors	F1	19	22.23
	F2	15	19.30
	Total	34	41.53
Three factors	F1	14	19.90
	F2	12	17.25
	F3	8	13.02
	Total	34	50.17
Four factors	F1	11	18.11
	F2	11	16.12
	F3	7	12.00
	F4	8	10.68
	Total	37	56.91
Five factors	F1	9	14.81
	F2	6	13.68
	F3	6	12.84
	F4	4	11.76
	F5	5	10.01
	Total	30	63.10

Table S3. Factor scores assigned to statements for the three factors.

Statement	F1	F 2	F 3
S1. I reduced herbicide use under AF	+1	+2	0
S2. AF reduces soil erosion	+3	+1	0
S3. High investment is required for AF	-1	-2	+1
S4. AF diversifies food sources	0	+1	-1
S5. AF diversifies income sources	+3	+1	-1
S6. I have difficulty managing intercropping under AF	-3	-1	0
S7. AF complements livestock production	+1	+2	0
S8. I lack knowledge on AF practices	0	-2	+2
S9. Fruit prices are unstable compared to maize and sugarcane	-2	+3	+2
S10. I'm considering cutting down trees	-3	-3	-3
S11. Maize monoculture is unproductive	-1	0	-3
S12. I need to cooperate with other farmers for better market access	+1	+1	+3
S13. Sugarcane cultivation is labor-intensive	0	0	+1
S14. AF is labor-intensive	-1	-2	-2
S15. Trees help reduce impacts of extreme weather	+1	+2	0
S16. I had problems with pest and disease in mixed cropping systems	-2	0	-2
S17. AF is suitable for household with limited land	-1	-1	-1
S18. I am interested in practicing AF over all my land	+2	-3	+1
S19. Short-term income is critical in AF investment	+2	+3	+1
S20. I need financial support for adopting AF	0	-1	+3
S21. AF yields higher profits than sole maize and sugarcane	0	-1	-2
S22. I increased manure use under AF	+2	0	-1
S23. I have experienced yield fluctuation in fruit production	-2	0	+2