

A SOCIO-ECOLOGICAL UNDERSTANDING OF ECOSYSTEM SERVICES AND THEIR
BENEFITS TO LIVELIHOODS: INSIGHTS FROM SEMI-ARID WEST AFRICA AND
SOUTHERN ARIZONA

by

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To all the women in my life, past and present, who have inspired me in small and big ways to choose my own path.

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ABSTRACT

Land degradation, the result of both climate change and other anthropogenic factors, is a complex environmental problem of serious concern in arid and semi-arid regions of the globe. Land degradation reduces land productivity and leads to losses of ecosystem services which threatens the long-term ecological and economic resilience and adaptive capacity of the ecosystem and the populations who depend on it. This issue is particularly acute in semi-arid regions where land constitutes the most important socio-economic and cultural resource for rural populations. Thus, managing the land in a sustainable manner is critical to people's livelihood. Sustainable land management practices offer a range of techniques to reverse land degradation and enable land users to maximize the economic and social benefits from the land while maintaining the ecological functions of the land resources. In this dissertation I examine 1) the causal links between the ecosystem services provided by agroforestry and their contribution to livelihood resilience in semi-arid regions of West Africa; 2) the factors influencing smallholder farmers' decision-making regarding the adoption of sustainable land management practices in northern Ghana to understand the complexities of farmers' decision making and identify the barriers and constraints they face; 3) the steps necessary to build an on-the-ground network of stakeholders that can fulfill the functions of an early warning system to identify climate-induced tipping points to the socio-economic and ecological system they depend on. Through the lens of the co-production of ecosystem services, this dissertation contributes to our understanding of the multidimensionality of livelihoods of rural communities in semi-arid regions of West African and Arizona and highlights the need for more engaged modes of research to build networks of societal partners to respond to tipping points through early warnings and identifies knowledge gaps that require future research.

CHAPTER ONE: Introduction

Semi-arid regions are highly vulnerable to the impacts of climate change. Higher temperatures, interannual rainfall variability and extreme weather events such as prolonged droughts have negatively affected agricultural production and the livelihoods of rural communities in these regions (Mirzbaev et al., 2022; Stringer, 2017). Climate change exacerbates land degradation which leads to losses of ecosystem services (ES) including biodiversity and food production. Land degradation, or desertification in arid and semi-arid regions, results in a loss of vegetation cover leading to an increase in bare soil, loss of soil nutrients, loss of water holding capacity in soils, and shifts in vegetation composition. Land degradation is often permanent and irreversible if mitigation strategies are not implemented (D’Odorico et al., 2013). Land degradation is not only driven by climate change but also by anthropogenic factors such as expansion of cropland, deforestation, unsustainable land management practices, urban expansion, and population growth (D’Odorico et al., 2013; IPBES 2018).

Land degradation negatively impacts human well-being and livelihood resilience leading to disruption of the entire socio-ecological system. Rural populations in dryland regions are highly vulnerable to the effects of land degradation and climate change because their livelihoods mostly depend on agriculture, one of the sectors most susceptible to climate change (CGIAR-RPDS, 2014; Rosenzweig et al., 2014).

As ecosystems are increasingly transformed by human intervention, the understanding of co-production of ecosystem services is becoming essential. The co-production of ES is understood as the process through which human inputs impact the different stages of the production and the flow of ES (Palomo et al., 2016)

This dissertation uses a socio-ecological systems approach that defines ES benefits as the outcomes co-produced by the interactions between the social and ecological components of such systems (Reyers et al., 2013). In this context the co-production of ES makes explicit the complex interactions between the social and ecological structures and processes associated with the production of ES and their interactions (Palomo et al., 2016; Reyers et al., 2013). This contrasts with the traditional view of the unidirectional flow of services from ecosystems to people. The ES co-production approach helps move beyond just measuring the supply of services to understand the actual benefits obtained by people. The co-production of ES is also influenced by several factors such as values, perceptions, institutions, and power relationships among the producers and beneficiaries of these services that can modify the natural ecosystem, its functions, and the interactions between the different ES (Reyers et al., 2013). In addition, the co-production of ES impacts the resilience of the socio-ecological system in which it occurs. Resilience, in this context, is the capacity of socio-ecological systems to continue providing the desired ES in the face of ongoing changes or unexpected shocks (Biggs et al., 2015).

Rural livelihoods depend on the range of ecosystem services for food security and resilience to environmental shocks (Kuyah et al., 2019). Livelihood resilience and adaptive capacity need to be understood in terms of access to capital assets (natural capital, human capital, social capital, physical/manufactured capital, and financial capitals) (Goodwin, 2003; Scoones, 1998) and are shaped by power structures and dynamics. Livelihood practices are the actions people take to meet their needs and well-being. These practices are central to understanding people's resilience because they both shape and are shaped by ecological processes (Goodwin, 2003). The various combinations of the different capital assets involved in the co-production of ES will affect both the quality and quantity of the services produced and often will lead to trade-offs among the different ES as well as the resilience and equity of these services (Palomo et al., 2016). Understanding how natural capital

and other forms of capitals are combined to co-produce different types, quantity and quality of ES can give us a better understanding of the dynamics of social-ecological systems and their implications for policy and interventions. An ES co-production approach is particularly important to understand the multidimensionality of livelihoods and the complex interactions between people and their environments to shed light on the various socio-economic and ecological factors that influence farmers' land management decisions in order to develop appropriate policies to enable the sustainable production and use of ES.

In this dissertation, I use an ES co-production approach to understand farmers' choices of land management options and their impacts on livelihood resilience through three case studies located in semi-arid regions of West Africa and Southern Arizona. In these semi-arid regions, ecosystems and agricultural production are threatened by the impacts of climate change and other anthropogenic pressures. The first two case studies explore the socio-ecological dynamics and drivers of sustainable land management adoption for livelihood resilience among smallholder farmers. The third case study describes the steps needed to build an on-the-ground network of stakeholders that can identify and monitor climate induced tipping points before they negatively impact their environment and their livelihood. This research addresses the benefits and challenges of a socio-ecological approach to understand ecosystem services and their benefits across these regions and highlights the challenges of engaged modes of research.

Land degradation is especially of concern in drylands regions of West Africa, where rural livelihoods are increasingly threatened by declining soil fertility, increasing soil erosion, declining vegetation cover, and extreme weather events (Lasco et al., 2014). Land degradation reduces land productivity through erosion, loss of organic matter, and deterioration of soil structure (Reynolds et al., 2007). Land degradation also threatens the long-term ecological and economic resilience and

adaptive capacity of the ecosystem and the populations who depend on it. Achieving sustainable development for dryland livelihoods requires the prevention of land degradation through the implementation of sustainable land management (SLM) practices to restore the lands that lost their productivity before they reach a tipping point (Mirzabaev et al., 2022). Managing land degradation effectively requires an in-depth understanding of human-environment interactions. SLM practices offer a range of techniques to combat and reverse land degradation (Giller et al., 2009; Power, 2010) and enable land users to maximize the economic and social benefits from the land while maintaining the ecological functions of the land resources (Cordingly et al., 2015). The adoption of land degradation mitigation measures also requires identifying and monitoring early warning signs or indicators of degradation. Even though land degradation is considered an irreversible transition, measures such as SLM practices are known to reverse this process before the system reaches a tipping point.

In West Africa, different ecological and socio-economic conditions have resulted in the implementation of different types of SLM practices. These practices have been shown to enhance ecosystem services such as increased soil fertility, reduced soil erosion, increased water recharge, and enhance biodiversity (Giller et al., 2009). SLM practices, and agroforestry in particular, are increasingly recognized as providing multiple ecosystem services and contributing to rural livelihoods resilience. Agroforestry enhances farmers' ability to mitigate degraded lands because of the multiple ecosystem services it delivers including food provision, supplementary income, and a variety of environmental services (Kuyah et al., 2016; 2019). Despite their benefits in mitigating the negative effects of land degradation and climate change, while increasing food security and enhancing livelihood resilience, many SLM practices are not widely adopted for a variety of context specific factors that are ecological, social, economic, and institutional (Cordingly et al., 2015; Giller et al., 2011; Lokonon and Mbaye

2018). Conventional biophysical and socio-economic research suggests that SLM practices that are the most profitable and less costly to implement will be more easily adopted by farmers (Emerton and Snyder, 2018). However, direct financial profitability is not the only factor that influences farmers' land management choices. This kind of one-dimensional understanding of farmers' decision-making often fails to address the complex socio-economic and ecological factors that influence farmers' decision-making and their willingness and ability to invest in SLM. The complex interactions and feedback between social and ecological systems go beyond the flow of materials or energy between systems that are often described in one dimensional economic and linear ecosystem service models.

The impacts of climate change are also threatening ecosystems, water resources, and agricultural production in southern Arizona. For example, this semi-arid region has seen its viticulture industry grow rapidly over the last decade, both in the number and size of vineyards as well as the number of businesses involved in winemaking with an overall contribution of \$133 million to the state economy. Since 2012, statewide grape acreage as well as the number of wineries has nearly doubled and estimates of economic activities directly associated with wine grape growing, winemaking and wine sales in 2019 are around \$59.8 million (Bickel et al., 2021). Growing grapes and producing wine contribute to local economies, generating economic activity and supporting jobs and income not only in the wine industry but also in other businesses directly and indirectly linked to the wine industry. Wineries play a particularly important economic role in rural areas of the state because the sales they generate often bring money into the local economy from out-of-town visitors (Bickel et al., 2021).

Growing grapes in this region, however, is becoming challenging because of climate change. Projected hotter temperatures will most likely increase the duration and severity of droughts and generate an overall drier regional climate (Gonzalez et al., 2018). As temperatures continue to trend

higher, wine grape growers in this warm-climate viticultural region will increasingly be challenged by the many effects that temperature has on fruit composition. Warmer ripening conditions in recent years have resulted in higher sugar concentrations, less acidity, higher pH, and changes in aromatic and phenolic compounds. The wine industry and the livelihoods that depend on it are very vulnerable to an increasing arid climate and grape growers will need to develop appropriate risk mitigation strategies before the entire system reaches a socio-economic and ecological tipping point.

In the co-production of ES, social capital generally refers to formal and informal networks, mutual trust, shared values and norms, and cooperation within the community. It is a key element for SLM adoption and livelihood resilience in the face of climate change. Through these networks farmers and other stakeholders are able to share their own innovations and learn from each other (Asse and Lassoie, 2011; Binam et al., 2017). These networks are also key for identifying disturbances to the socio-ecological system before they have devastating impacts on that system. Therefore, perception of people in the community plays a crucial role in identifying socio-economic tipping points because effects of regime shifts are context specific and most visible at the local level because climate change may have a greater impact on individuals and communities (van Ginkel et al., 2018). Reaching a tipping point in any system can result in a series of cascading effects across ecological, social, economic, and political systems. Thus, assessing vulnerabilities to tipping points is essential to maintain the provision of ecosystem services and to develop appropriate risk mitigation strategies (Berrouet et al., 2018).

To identify and assess tipping points within a particular socio-economic and ecological system, active observations, knowledge, and experience are necessary. For this to occur a network of stakeholders that can act as an early warning system needs to be established. To build such a network there is a need to engage with stakeholders in a way that develops capacity-building, fosters

social capital, and trust, and ultimately implements actions to address the commonly identified problem. Building an on-the-ground network of stakeholders that can fulfil the functions of an early warning system is key to identify threats to the socio-economic system and develop actions to mitigate its harmful effects.

This dissertation addresses three main objectives in the following three chapters. In Chapter Two, I present the results of a systematic literature review that aimed at identifying the causal links between the ecosystem services provided by agroforestry, an SLM practice, and their contribution to livelihood resilience in semi-arid regions of West Africa. The objective of this chapter was to assess the current scientific knowledge and the gaps that remain regarding the mechanisms by which agroforestry practices and their management contribute to livelihood resilience through the lens of the co-production of ES.

In Chapter Three, I present the results of a study that explored the factors influencing smallholder farmers' decision-making regarding SLM adoption in northern Ghana using an ES co-production approach to understand the complexities of farmers' decision making. The objective of this chapter was to identify the socio-economic and ecological factors that shape farmers' ability and willingness to adopt SLM practices and identify the main constraints and barriers they face.

In Chapter Four, I present the results of a case study based on a climate and viticulture project in southern Arizona that describes the steps necessary to engage with and build an on-the-ground network of stakeholders that can fulfill the functions of sentinels or early warning system to identify climate-induced tipping points in the vineyards of this region. The objective of this chapter was to provide a roadmap for how to build and maintain such a network while highlighting the challenges of engaged research.

Finally, in Chapter Five I provide the synthetic insights from the three case studies and directions for future research.

CHAPTER TWO: The contribution of agroforestry to livelihood resilience: Insights from semi-arid West Africa using an ecosystem services co-production approach

This study is a systematic literature review that examines how agroforestry practices can improve efforts to strengthen and diversify rural livelihoods while maintaining and improving critical natural capital and ecosystem services that are essential for human and economic well-being. The aim of this study was to find evidence in the literature of causal links between the ecosystem services provided by agroforestry practices and their contributions to livelihoods, the socio-ecological factors involved in the production of ecosystem services, and the beneficiaries of these services in semi-arid West Africa. Many studies recognize the multidimensionality of livelihoods, however most research focuses on economic indicators as quantitative proxy contributions to livelihoods and fail to provide concrete evidence on how the interactions and combinations of ecosystem services and capital assets contribute to livelihoods and how the benefits of agroforestry are distributed among different social groups.

CHAPTER THREE: Identifying the factors influencing smallholder farmers' adoption of sustainable land management in northern Ghana: An ecosystem services co-production perspective

This study illustrates how the traditional one-dimensional economic understanding of smallholder farmers' decision-making regarding the adoption of sustainable land management often fails to capture the complex interactions among socio-economic, cultural, and institutional factors that influence their decisions and ability to invest in sustainable land management practices. To address this issue, I applied an ecosystem services co-production approach to identify the complex ways in which farmers perceive and value land management costs, benefits, and impacts in four farming communities in the Garu District of the semi-arid region of northern Ghana. A mixed methods approach that included quantitative, qualitative, and participatory activities was used to assess and identify the multiple factors that shape farmers' decision-making regarding the adoption of sustainable land management practices. The aim of this study was to understand the factors behind the low rate of adoption of these practices by identifying the socio-economic and ecological complexities that shape farmers' ability and willingness to invest in sustainable land management practices and highlight the main constraints they face.

CHAPTER FOUR: Navigating sentinel territory with a stakeholder network: a case study of climate and viticulture in Arizona

Findings from Chapter Two and Chapter Three revealed that social capital that encompasses formal and informal networks, mutual trust, shared values and norms, and cooperation within the community are essential for identifying climate change-induced tipping point to the socio-ecological system before they have devastating impacts on that system. This case study of climate and viticulture in Arizona describes the modes of engagement and the earliest stages of on-the-ground stakeholder network building. Building such a network of stakeholders that can fulfil the functions of an early warning system is key to identifying threats to the socio-economic system and develop actions to mitigate its harmful effects. This approach could be used as a model to monitor early warning signals of socio-economic tipping points in any system.

CHAPTER FIVE: Conclusion

Climate change coupled with land degradation reduces land productivity and results in loss of ES that threatens the livelihood of farmers in semi-arid regions of West Africa and Arizona. Through a socio-ecological understanding of ecosystem services, the objective of this dissertation is to better understand the multidimensionality of rural livelihoods in these two semi-arid regions and the complexities of smallholder farmers' decision-making process regarding the implementation of SLM practices. This research also offers a model for building an on-the-ground network of stakeholders that can identify and monitor early signals of climate-induced tipping points that threaten the livelihoods of these rural communities.

The implementation of SLM practices, particularly in degraded environments, has been shown to increase food production while maintaining and even enhancing other ecosystem services. The objective of Chapter Two and Chapter Three was to understand how SLM practices contribute to the livelihood of rural communities and explore the reasons driving the low adoption rate of these practices by identifying the socio-economic and ecological complexities that shape farmers' ability and willingness to invest in SLM practices, and to highlight the main constraints for their adoption in the semi-arid regions of West Africa.

Chapter Two examines, across the literature, the contribution of the ecosystem services provided by agroforestry to rural livelihoods in drylands of West Africa. The findings show that agroforestry practices contribute to multiple direct and indirect benefits to rural livelihoods by providing a range of ecosystem services such as provision of tree products for consumption, fuelwood and timber, livestock fodder, and socio-economic benefits such as income from sale of tree products, and ecosystem enhancement through increased nutrients cycling, biodiversity, soil

moisture retention, and reduced pressure on natural forests. Even though many studies recognize the multidimensionality of livelihoods, they remain heavily focused on income and other economic factors as evidence of the contribution of woody vegetation to livelihood rather than a combination of non-income generating dimension of livelihood. Because gender, wealth, and ethnicity influence who has access to land and its resources, including trees, more research is needed to understand how gender, social and wealth status influence access to capital assets which in turns influence livelihood choices and opportunities. Further research is also needed to understand how trade-offs between ES and capital assets influence farmers' decision-making regarding the adoption of agroforestry practices.

In Chapter Three, results show that to improve adoption of SLM, there is a need to first address the constraints that limit the farmers' ability to adopt them. Initiatives designed to improve the adoption of SLM need to not only be tailored to the local bio-physical environment but also need to recognize the socio-economic diversity of farmers in terms of resource endowment, farming systems, and the institutional and policy environment in which they take place. This study among others (Emerton and Snyder, 2018; Cordingley et al., 2025) demonstrates that households do not always choose the SLM practices they prefer or even consider to be the most effective at improving crop production. Rather, they choose the ones that they can implement given their economic circumstances and resource endowment at the time.

The main barriers to SLM adoption are labor shortage, lack of cash and know-how, and insecure land tenure, particularly for women and poor farmers. Direct cash transfer or grants to households who want to invest in SLM could help farmers hire extra labor, buy seeds for intercropping, crop rotation, and cover crops, and other inputs ahead of the cropping season. Farmer-led organizations that are supported by local authorities could facilitate co-learning and co-

innovation of land management that are specific to local conditions. Developing SLM practices that are tailored to the end-users' priorities and constraints are more likely to result in livelihood improvement and greater rate of adoption.

The results from Chapter Two and Chapter Three point out that social capital such as formal and informal networks, mutual trust, shared values and norms, and cooperation within the community are key elements for the successful implementation of a variety of SLM. These networks are also essential for identifying disturbances to the socio-economic system before they have devastating impacts on that system. Chapter Four describes the process of intentionally building a stakeholder network among wine grape growers in southern Arizona that fulfills the functions of an early warning system to identify and assess the threats of climate-induced socio-economic tipping points in their community. This study shows that engaged research is not without challenges and barriers in building and maintaining networks because it is a process that takes time, energy, and funds. This long-term, iterative process is not compatible with the current funding structure for most academic projects which function on limited time frame. Engaged research also requires the integration of multiple disciplines and different knowledge systems to generate innovation and inclusive solutions. Despite the challenges, more engaged research is needed to build strong responses to tipping points through early warnings.

This research shows that the process of co-production of climate services is a promising approach to not only help build a network of stakeholders but also create the conditions for the stakeholders to fulfill the functions of sentinels or early warning system to monitor and respond to the threats of climate-induced tipping points. By their active observations, intuition, knowledge, and varied perspectives and experiences, sentinels can be very effective at identifying and interpreting tipping points. The negative impacts of climate induced socio-economic tipping points are more

likely to occur in developing countries where there is less socio-economic resilience against climate shocks (van Ginkel et al., 2020). Future research is needed to explore ways to build such networks in this far more challenging context because of the various financial and institutional barriers as well as power structures.

Because of the many constraints and the lack of supporting institutions, an avenue of research would be to explore building sentinel networks at the landscape level rather than individual communities. Landscapes contain many different resource niches, users and local institutions that are connected to other landscapes through both biophysical and social dynamics (Cordingley et al., 2015). These multiple scales of connectivity create an environment conducive to creating and maintaining sentinel networks. Through existing social networks across the wider landscape, land users can access information and know-how at a much broader scale than their respective communities. Building network on the landscape scale would lead to a more comprehensive understanding of threat to the socio-economic system, even if individual communities do not recognize climate induced tipping points at first. Communities that are part of the larger networks and working in close collaboration with local institutions and agricultural extension agents can then identify concrete evidence of threats and develop solutions to adapt to these threats by developing innovative adaptive measures through knowledge sharing and increased collaboration within and between communities. Government agricultural extension services, local farmers' groups, NGOs, country-based research organizations and agribusiness enterprises can all play a role in supporting sentinel networks. In this context, it is particularly important to include different types of knowledge and take them into account for decision making. The inclusion of non-scientific knowledge can build legitimacy in the process. The issue of equity (gender, marginalized social groups) in decision making and being included in the sentinel network is also crucial to lend legitimacy to the process.

As Mach et al. (2020:4) state it, co-production involves changing how decisions are made by changing who is involved in the knowledge-production processes.

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APPENDICES

**APPENDIX A: THE CONTRIBUTION OF AGROFORESTRY TO LIVELIHOOD
RESILIENCE: INSIGHTS FROM SEMI-ARID WEST AFRICA USING AN
ECOSYSTEM SERVICES CO-PRODUCTION APPROACH**

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ABSTRACT

Agroforestry is a sustainable land management practice that provides multiple ecosystem services and contributes to rural livelihood resilience in many areas of the world. Through a systematic review of research literature, I looked at the empirical evidence regarding the mechanisms linking ecosystem services and the different capital assets that contribute to rural livelihoods, focusing on semi-arid regions of West Africa as a case study. I focused on determining the state of current knowledge on the evidence of causal links between the ecosystem services provided by agroforestry and their contributions to livelihoods, the socio-ecological factors involved in the production of ecosystem services, and the beneficiaries of the ecosystem services provided by woody vegetation. Research to date fails to examine or provide concrete evidence on how the interactions and combinations of ecosystem services and capital assets contribute to livelihoods but rather simply describes the observed relationship. While many studies recognize the multidimensionality of livelihoods, most research focuses on either economic indicators or tree-counting as quantitative proxy contributions to livelihoods. Research gaps remain in understanding the links between agroforestry and livelihood such that future studies need to address how land management trade-offs influence farmers' decision-making regarding agroforestry practices and how the benefits of agroforestry are distributed among beneficiaries.

Keywords: Agroforestry, livelihood, capital assets, ecosystem services, co-production

1. Introduction

Agroforestry is the deliberate integration of woody vegetation (trees and shrubs) into crop and livestock systems. It can help mitigate the impacts of land degradation through the various ecosystem services provided by trees (Bayala et al., 2014). Agroforestry is increasingly recognized as a sustainable land management practice that provides multiple ecosystem services and contributes to rural livelihoods resilience. It enhances farmers' ability to mitigate degraded lands because of the multiple ecosystem services it delivers including food provision, supplementary income, and a variety of environmental services (Kuyah et al., 2016; 2019). The early ecosystem services (ES) literature mostly focused on ecosystem processes and functions. With the incorporation of socio-ecological systems into conceptual frameworks, ES literature increasingly addresses the links between ecosystem services and human well-being (Reyers et al., 2013), recognizing that social and ecological components must be understood jointly as well as taking into account synergies and trade-offs between them (Howe et al. 2014). Research on agroforestry systems needs to move beyond a purely ecological focus and embrace a more comprehensive socio-ecological approach that recognizes the complex interactions between people and their environment to produce food at the local and regional scale (Stafford and Mbow, 2014). Rural livelihoods depend on the range of ecosystem services for food security and resilience to environmental shocks (Kuyah et al., 2019). Mbow et al. (2014a) points out the importance of the human components for the successful implementation of agroforestry systems including the enabling conditions of governance, gender equity, secured land tenure, investment, and markets for agroforestry inputs and outputs. Agroforestry, therefore, must be viewed as a land use system that delivers sustainable improvements to food security and income through integrating trees with other components of agriculture in multifunctional landscapes.

Land degradation and agroforestry are especially of concern in semi-arid Africa, where rural livelihoods are increasingly threatened by declining soil fertility increasing soil erosion, declining vegetation cover, and extreme weather events (Lasco et al., 2014). This pressure on natural resources is a result of population pressure and intensified agricultural production. In Africa in general, different ecological and socio-economic conditions have resulted in different forms of agroforestry. These agroforestry systems have been shown to enhance soil fertility, reduce soil erosion, increase water recharge, and enhance biodiversity. The benefits provided by agroforestry occur over a range of temporal and spatial scales (Jose, 2009). Trees are also an important source of income generation for rural community members through the provision of high-value products such as timber, fruits, medicines, resins, gums, and dry season fodder (Sinare and Gordon, 2015). In rural communities where employment is limited, people collect natural resources for their own use or sell them to supplement household income. This review examines how agroforestry can improve efforts to strengthen and diversify rural livelihoods while maintaining and improving critical natural capital and ecosystem services that are essential for human and economic well-being.

There is limited empirical evidence of how the interactions between the various ES provided by agroforestry contribute to livelihood resilience in semi-arid agroecological regions of West Africa. Some studies solely look at the livelihood benefits provided by agroforestry practices while others limit their scopes to understanding how agroforestry benefits ecosystems. Such studies rarely consider the close relationship between social and ecological factors in the production of ES. Several reviews of ES and agroforestry (Bayala et al., 2014; Kuyah et al., 2016; Kuyah et al., 2019; Sinare and Gordon, 2015; Sileshi et al., 2008) in the Sudano-Sahelian zone of West Africa mostly looked at the role of woody vegetation for direct use and income generation (provisioning services) or quantified the benefits of agroforestry on crop yields, soil fertility, erosion control, and water regulation

(regulating and supporting services). These studies, however, often fall short of recognizing the socio-ecological nature of agroforestry systems (Stafford and Mbow, 2014; Milheiras et al., 2022).

An ES co-production approach highlights the role of human interventions in the production and delivery of ecosystem services and examines how changes in environmental flows and quality of resources affect the services on which livelihoods depend. This approach helps reframe ecosystem services research towards a more social-ecological understanding of ecosystems and their benefits (Palomo et al., 2016). For this study, we first briefly review the theoretical background (of what?) and then focus on agroforestry practices in West Africa's drylands as a case study to assess the current scientific knowledges regarding 1) the evidence of causal links between ES provided by agroforestry and their contribution to livelihood resilience; 2) the socio-ecological factors involved in ES produced by agroforestry practices; and 3) who benefits from ES provided by woody vegetation? Our approach for these later objectives was to conduct a categorized literature review that enabled quantitative data analysis of types of response.

1.1 Theoretical background

In this section, I briefly discuss the various agroforestry practices and the ES they provide, followed by a discussion on the concepts of ES co-production and livelihood resilience.

1.1.1 Agroforestry practices and ecosystem services

Agroforestry, as part of a multifunctional landscape, is a land management option that provides multiple ESs and environmental benefits (Jose, 2009). Agroforestry is promoted by the Intergovernmental Panel on Climate Change report as a key practice to respond to climate change and land degradation while also improving global food security (IPCC, 2019).

Agroforestry may include such practices as alley cropping, parklands, dispersed intercropping, home gardens, improved tree fallow, multi-strata agroforestry, windbreaks, and woodlots (Kuyah et al. 2016: Table A3). Trees are either planted on farmland or are naturally regenerated for specific reasons, and farmers cultivate and manage a mix of exotic and indigenous trees to provide a variety of ES (Kuyah et al., 2016; Sinare and Gordon, 2015). Parklands are a traditional land-use system where farmers maintain some tree species that they find useful and manage them in combination with crops and livestock (Bayala et al. 2015). Parklands are the most widespread farming system in the Sahelian and semi-arid regions of West Africa and play a particularly important role in household economy of rural communities (Binam et al., 2015; Papa et al., 2020). When young trees emerge through natural regeneration and farmers find the species useful, they will protect and manage these trees in the parkland. This process is known as farmer managed natural regeneration (FMNR). The species favored by farmers vary from place to place and the composition of species and the density of trees vary across space depending on the amount of rainfall, topographic location, and soil types (Binam et al., 2015). Fairhead and Leach (1996) documented that farmers encouraged tree growth in their farmlands for generations, contrary to conventional wisdom that stated that farmers were responsible for deforestation as a result of poor farming practices. The socio-ecological importance of the parkland system, however, is being threatened by increasing aridity as a result of climate change and increasing human pressure, new environmental policies, and cash-crop commercial farming encouraging the removal of trees (Bayala et al., 2015).

Several reviews have described the various ES provided by agroforestry practices (Bayla et al., 2015; Sinare and Gordon, 2015; Kuhya et al., 2016). They show that through conservation or planting new trees, the establishment of a tree canopy in farmlands can produce many ES including soil carbon enrichment, biological nitrogen fixation, more efficient nutrient and water cycle,

favorable microclimate, prevention of pest outbreaks, production of valuable tree products, habitat for biodiversity, higher resilience to climate variability, and carbon sequestration (Table 1).

1.1.2 Ecosystem Services Co-production

Research in ES co-production (Biggs et al., 2015; Lele et al., 2013; Reyers et al., 2013; Spangenberg et al., 2014) recognizes the various human contributions to the production and delivery of ES. ES, therefore, are a direct result of the interaction between ecosystem properties (natural capital) and human inputs including social capital, financial capital, human capital, and manufactured capital (Figure 1). The co-production of ES is defined by the varying degree of human inputs within the various stages of the production of ES (Palomo et al., 2016). This is a key concept for understanding not only how ecosystem services are produced, but also how services are distributed, since these services and anthropogenic inputs are unequally distributed across ecosystems and unequally accessible by different socio-economic groups (Lele et al., 2013; Reyers et al., 2013)

An ES co-production approach makes explicit the complex interactions between the social and ecological structures and processes associated with the production of ES and their interactions (Palomo et al., 2016; Reyers et al., 2013). This contrasts with the traditional view of the unidirectional flow of services from ecosystems to people. The ES co-production approach helps move beyond just measuring the supply of services to analyze the actual benefits obtained by people. The co-production of ES is also influenced by several factors such as values, perceptions, institutions and power relationships among the producers and beneficiaries of these services that can modify the natural ecosystem, its functions, and the interactions between the different ES (Reyers et al., 2013). In addition, the co-production of ES impacts the resilience of the socio-ecological system in which it occurs. Resilience, in this context, is the capacity of socio-ecological systems to continue providing the desired ES in the face of ongoing changes or unexpected shocks (Biggs et al., 2015).

The combinations of different capitals involved in the co-production of ES will affect both the quality and quantity of the services produced and often will lead to trade-offs among the different ES as well as the resilience and equity of these services (Palomo et al., 2016). For example, the mechanization of agriculture (manufactured capital) has significantly increased crop yields (provisioning services) but often at the expense of regulating and supporting services (decrease in biodiversity and increase land degradation). In addition, ES are not equally distributed among various socio-economic groups such as women, ethnic minorities, or poor households and when co-production leads to trade-offs between ecosystem services (increasing provisioning services at the expense of regulating and supporting services) , it invariably creates winners and losers by benefiting some social groups at the expense of others (Daw et al., 2011; Pascual et al., 2014). Ultimately all trade-offs have social consequences because different groups value different ecosystem services in different ways, therefore impacts need to be evaluated according to different socio-economic groups (Daw et al., 2011).

1.1.3 Livelihood resilience

Livelihoods are closely shaped by the natural resources in people's environment and the ecological processes which affect them. Land users' resilience depends on the health of their natural environment and the resources it provides. As Tanner et al. (2015:23) state, livelihood resilience is "the capacity of all people across generations to sustain and improve their livelihood opportunities and well-being despite environmental, economic, social and political disturbances". They call for resilience to be central in understanding livelihood strategies and people's adaptation strategies in response to shocks and stressors. A livelihood approach acknowledges that people's circumstances, values and beliefs, perceptions, power relations and institutional environment affect their ability to adapt to changing conditions (Tanner et al., 2015). Important questions are central to investigating

livelihoods, such as “Does the resilience of some livelihoods result in the vulnerability of others? Do specific social institutional processes that encourage social inequalities have implications for the resilience of these groups?” (Cote and Nightingale, 2012:482). The relationship between people and ecosystems is therefore reciprocal and all landscapes are shaped, directly, and indirectly by human activities (Comberti et al., 2015). Land management practices can undermine the functioning of ecosystem processes that underpin the provision of ecosystem services (Sinare and Gordon, 2015). Livelihood practices, therefore, are an essential component of resilience as they shape landscape configurations and associated socio-economic outcomes.

The sustainable livelihood approach (Chambers and Conway, 1992; Goodwin, 2003; Scoones, 1998. Figure 1, p.4) is built upon five capital assets including natural, human, social, manufactured, and financial (Table 2). Sustainable livelihood is viewed as “comprising the capabilities, assets (including material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stress and shocks, maintain, or enhance its capabilities and assets, while not undermining the natural resource base” (Scoones, 1998:5). The ways in which people combine the different capital assets affect the sustainability of their livelihoods. Therefore, the impacts of agroforestry on livelihoods will depend on households’ access to the different capital assets and their particular sets of circumstances. In addition, farmers’ needs and preferences are also part of livelihood practices as well as their perceptions of the utility of a tree species’ value and utility (Haglund et al., 2011).

2. Methods

2.1 Literature survey and criteria for inclusion

To answer the research questions, we conducted a systematic review (Berrang-Ford et al., 2015) that aims at answering specific research questions using pre-defined eligibility criteria for

documents with clearly outlined and reproducible methods, including iterative search methodologies to capture all relevant literature (Gough and Oliver, 2012).

This systematic review includes several methodological steps including: 1) define the research question; 2) identify relevant literature; 3) selection of inclusion and exclusion criteria; 4) critical appraisal of study quality; 5) analyze and synthesis evidence (quantitative and/or qualitative; and 6) present results (Berrang-Ford et al., 2015).

I used Scopus and AGRIS online databases to search for articles published between 2005, the publication of the Millennium Assessment and 2023 (Table 3). The initial searches produced 771 publications of which 27 were duplicates. In addition, 15 references were added through backward reference list checking (Gough and Oliver., 2012) from both the included and the excluded articles. I reviewed the abstracts of the selected 759 articles for the following inclusion criteria: 1) Paper published in peer-reviewed scientific journals; unpublished literature and grey literature were excluded; 2) Studies explicitly looking at woody vegetation on farms or agricultural landscapes in the defined geographic area (semi-arid and sub-humid regions of West Africa including the following countries: Burkina Faso, Benin, Chad, Ghana, Niger, Nigeria, Mali, Mauritania, Senegal, Togo; 3) Experimental studies on plots were not included; 4) Studies with field data or field data combined with modeling are included, but pure modeling studies were excluded; 5) Studies reporting the ES provided or affected by woody vegetation; 6) Studies reporting some elements of socio-ecological systems; 7) Pure reviews were excluded. Through several phases of increasingly in-depths review, we removed articles from the study if they did not provide concrete evidence of the inclusion criteria. In total 37 references were included in this review.

2.2 Data Analysis

From the resulting 37 articles, I conducted content analysis of the articles with MAXQDA software (Table 4). I coded information about the types of ecosystem services, their trade-offs, and synergies. I also coded information about the five capital assets (natural, human, social, manufactured, and financial capitals) as livelihoods are created by people's ability to access and combine these capital assets. Social differentiation and beneficiaries (gender, ethnicity, wealth) from agroforestry practices were coded as well. Provisioning services from woody vegetation were analyzed in terms of the direct or indirect benefits that contribute to livelihoods. Reported regulating and supporting services include the effect of woody vegetation on soil nutrients, carbon concentration, and soil water content when directly related to crop yields.

3. Results

In the following section, I present the results from the systematic literature review I focus first on the capital assets that households have access to and that affect the sustainability of their livelihood. Then, I describe the demonstrated quantitative or qualitative direct or indirect impacts of agroforestry on livelihoods. Finally, I describe results regarding how different social groups' access to land and trees and trade-offs among ES affect their livelihoods.

3.1 Capital assets for livelihood resilience

3.1.1 Natural capital

Natural capital was reported in 23 (62.2%) of the reviewed articles (Figure 2). Many studies illustrate how agroforestry systems such as parklands are central to local livelihoods by providing tree products that can be consumed and sold at markets. The composition of tree species differs across space because of rainfall regime, topographical locations, soil types and farmers' preferences for tree species (Faye et al., 2010). Shea (*Vitellaria paradoxa*), African locust bean (*Parkia biglobosa*)

also known as néré and dawadawa, baobab trees (*Adansonia digitata*) and acacia (*Faidherbia albida*) are dominant species in the drylands of West Africa and are a key part of the diets of rural communities (Kasanga et al., 2020). The number of these tree species has been decreasing rapidly particularly in northern Ghana as a result of demographic and climate pressure as well as aging tree stocks that are not being planted consistently, climate change, and expansion of mechanized farming and monocropping (Kansanga et al., 2020; Lelea et al. 2022). Locust bean tree average population density is between 5-10 trees per hectare (Pehou et al. 2020) while shea trees density averages 27 trees per hectare (Poudyal et al., 2011). Natural regeneration is very low for African locust bean tree despite its nutritional value and income source as a result of ambiguous tenure regime (Pehou et a. 2020) and a lack of conservation programs to protect these trees (Lelea et al., 2022).

The main crops grown in drylands of West Africa include millet, cowpeas, sorghum, sesame seeds, peanuts, maize, and rice. *Faidherbia albida* (acacia) trees are among the most utilized species because they are a leguminous tree species that fixes nitrogen and is an important source of fodder and fuelwood (Reij and Garrity, 2016). Non-timber-forest products (NTFPs) are not only a key part of rural diets, but they also provide income that contributes to households' needs. Both NTFPs and fuelwood are collected by women (Pouliot and Treue, 2013).

West African parklands are facing continued degradation and trees in fields are aging and less productive. Despite the well-known benefits provided by the trees, most farmers do not plant or protect trees if they face many constraints such as insecure land tenure or other food and income priorities (Seghieri et al., 2020). Despite initiatives encouraging farmers to adopt FMNR because of its low cost compared to planting trees, greater efforts and support are needed to expand the implementation of of such agroforestry practice to restore degraded lands (Reij and Garrity, 2016). Parklands are progressively replaced by conventional crops or by mono-culture tree plantations such

as mango and cashew that require less labor and provide higher income but offer a smaller range of ES and products which will negatively affect livelihoods in the long-term (Seghieri et al., 2020).

3.1.2 Human capital

Human capital was reported in 27 (73%) of the reviewed articles (Figure 2). Traditional ecological knowledge is one of the social mechanisms behind traditional use and conservation practices of certain tree species. It is important to consider culturally defined differences in use preferences of certain trees and their products according to ethnic affiliation, gender, and wealth (Heuback et al., 2013). Farmers generally agree that trees and shrubs are part of the agricultural systems, but they will not protect and maintain them if they do not perceive their value.

FMNR is a flexible tree management method that can be tailored to individual preferences which gives farmers flexibility to respond to their needs. For example, a study in Niger show that farmers can decide how many trees to manage, their spacing and which species to select (Abasse et al., 2008). FMNR, however, is being adopted slowly by farmers because of the deeply held belief that trees compete with crops for water, nutrients, and light. The level of farmers' education and lack of technical knowledge is directly related to how much or how little farmers use FMNR and how open they are toward innovation in general (Agundez et al., 2020; Haglund et al., 2011). In many regions, farmers believe that African locust beans and shea trees cannot be planted and can only grow in the wild, despite the declining number of these highly valued tree species (Lelea et al., 2022; Wardell et al., 2022). The cost of FMNR is very low in terms of input and labor as new trees emerge from the soil with little help; occasional pruning is needed for proper establishment and some protection from roaming cattle (Reij and Garrity, 2016).

Women have higher labor and financial constraints than men which make it difficult to practice FMNR, but one study shows that women are more engaged in experimenting with new

ideas and practices if they have access to available land (Akpabio et al. 2009). In general, women do not have full control of their labor as men have priority use of women's labor on farm and off farm (Apusigah 2009). Shea kernels that are processed into butter offer a source of income for women, but the labor requirement is very high. In general, women are the collectors and processors of non-timber tree products. Women are believed to be the ones who have the knowledge about shea tree ecology (Pouliot 2012).

The incorporation and management of trees in farm fields require skills, capacity, and proper dissemination of information (Binam et al., 2017). Also having access to labor is essential to meet both household food requirements and market demand because harvesting leaves, fruits, and pods is time consuming and labor intensive; tasks usually left to women and children. Binam et al. (2015) point out that in Niger the level of human capital (labor availability and level of education) in the household is positively related to the amount of tree products sold at markets.

3.1.3 Social capital

Social capital was reported in 29 (78.5%) of the reviewed articles (Figure 2). Traditional farming, including some agroforestry practices requires extensive social networks of family and kin that can be tapped for labor and land acquisition, and farmers' membership in village credit and labor exchange association, and participation in rural development programs (Asse and Lassoie, 2011; Binam et al., 2017).

Informal networks of neighbors and friends are very effective to share information about agroforestry and help innovate and adapt practices to farmers' own conditions. Farmers tend to trust their peers more than officials when discussing advantages or disadvantages of new techniques and practices. In many countries, local conventions have encouraged the adoption of agroforestry practices and FMNR in particular and there is a growing interest in a bottom-up approach by

strengthening community-based natural resources management (Binam et al., 2017). In Burkina Faso, for example, where local governance institutions and village land management commissions work in collaboration with farmers regarding access and use of natural resources, farmers tend to invest in trees because their interests and concerns were taken into consideration through collaboration. These local natural resources management institutions also acknowledge the sustainability of traditional land management practices and promote practices such as controlled fire, rotational grazing and livestock grazing corridors to protect young trees (Binam et al, 2017). Building trust between farmers and extension services, combined with a transfer of authority to village committees for land and vegetation management, and capacity development would greatly contribute to the protection and the increase of tree cover in this region (Sinare et al., 2022).

New governance structures are needed to increase connections and cross-scale linkages between government entities, local institutions and local communities that have the knowledge, experience, and interest to address land degradation. In Niger, farmers, herders, men and women, researchers from international agencies and government officials are involved in programming, implementing, and monitoring programs that aim at promoting agroforestry practices. The inclusion of all stakeholders in decision making regarding the control and access to managed trees was pivotal for the successful adoption and expansion of FMNR practice (Abasse et al., 2008). These social relations are crucial for negotiating access, conflict management between farmers and herders, and developing locally adapted tree management practices (Ablo et al., 2022). Government programs on agroforestry are often perceived by farmers as government activities targeted at increasing tree stocks focused on timber-yielding tree species rather than trees that provide non-timber forest products. The lack of support for tree-based farming systems has resulted in lack of investments even though many studies have demonstrated that agroforestry practices can enhance rural livelihoods through provision of both ecological and economic benefits. In some countries like

Niger, governments are starting to revise forestry laws that restrict farmers from managing trees on their farmland (Garrity et al., 2010). Across the Sahel, efforts such as the African Regreening Initiative, an alliance of organizations that seek to promote of the benefits of agroforestry, have helped increase the number of trees across parklands (Garrity et al., 2010).

In most of West Africa, customary land tenure is the primary organizing factor in land tenure and is based on a patrilineal intergenerational transfer of land (Asse and Lassoie, 2011). Land tenure arrangements either encourage or discourage tree planting. In addition, in some areas tree planting has an important role in creating private property rights to the land. Those rights dictate who has access to tree resources which depends on the location of trees in the landscape, gender, wealth, and ethnicity (Pehou et al., 2020). Land tenure rights determine the types and number of benefits that farmers can obtain from tree resources, however, there is little incentive to invest time and labor in agroforestry if tenure is insecure because the farmers who planted or managed the trees might not have guaranteed access to their products.

In northern Ghana, the sale of land to external companies including land grabbing have further strained gender inequalities regarding land access and access to tree resources (Lelea et al., 2022). Like land tenure, access to and control over trees is a complex issue. Gender dictates rights to plant, harvest and cut trees and tree tenure vary across species, particularly when they have high value as in the case of shea and African locust beans (Pehou et al. 2020). The male head of the households owns the land and has all the rights to decide which trees to protect, plants or cut (Pehou et al., 2020). Women have the right to harvest tree products, particularly shea and African locust trees on the farmland owned by their husbands or if given permission by the landowner. Unlike shea trees, the right to harvest seed pods from the African locus bean lies with the owner of the land and not those who farm the land; therefore, women need to ask permission to harvest the

Pods (Lelea et al., 2022). Access to trees and their products depends on the relationship between the user and the owner of the trees and it is negotiated among them and are dynamic and evolving in response to both external and internal changes (Pehou et al., 2020).

Restrictions on tree resources usually depend on the value of the tree species and quantity harvested (Binam et al., 2017). Tenure and access vary across tree species, especially high value ones such as African locust beans and shea trees. In one study, cutting and pruning branches of shea trees can be used by anyone, while only 25% had the same rights for locust bean trees, and only 14% could cut the trees with the chief's permission (Poudyal et al., 2011). For a given tree species, tenure rights can vary across space and time and among ethnic groups. Also naturally regenerated trees are treated differently than planted ones as they require less time, labor, and resources to grow (Poudyal et al., 2011).

3.1.4 Manufactured capital

Manufactured capital was reported in nine (24.3%) of the reviewed articles (Figure 2). A study indicates that communal resource management practices are under threat with the increased use of tractors that destroy many trees in order to move across the farmland (Kansanga et al., 2020). The loss of these trees, shea and African locust bean trees particularly negatively affects the livelihood opportunities of women. Access to physical capital such as farming, and transportation equipment is more limited for women than for men. Animal driven plows, seeders, tool carriers, bicycles and donkey-pulled carts are mostly owned by men (Asse and Lassoie, 2011). Access to roads, transportation costs, and distance to markets are major constraints to market participation and commercialization of tree products. Owning transport equipment significantly influences participation in markets for tree products (Binam et al., 2015). Along transportation, the simultaneous efforts to improve market integration through investment in infrastructure,

institutional reforms and predictable linkages to markets are all necessary to develop sustainable value chains for non-timber tree products (Binam et al., 2015). Small holder agriculture is labor intensive and time consuming. Agricultural mechanization and the use of tractors in particular can help free manual labor for other farm tasks and non-farm activities. However, a study in northern Ghana shows that poor training of tractor operators and the desire to plough as many farm fields as possible to earn cash, result in increased soil degradation and other negative environmental impacts. Many trees are eliminated to make room for tractors which directly affects the amount of shea and African locust bean pods women can harvest depending on how many trees have been preserved after the land has been cleared for cultivation (Kasanga et al. 2020).

3.1.5 Financial capital

Financial capital is mentioned in 14 (38%) of the retrieved articles (Figure 2). Many households own livestock including goats, cows, and donkeys. These are very important assets and cattle in particular is often referred to as savings accounts. Another important mean of supplementing farmers' livelihoods and income is seasonal migration (during the dry season) of both men and women to urban areas (Hitomi 2017). In their study Pouliot et al. (2012) observed that for wealthier households, cash income constituted 54% of total household income but only between 40 and 50% for poorer households. They also showed that rural households generate their income from a variety of activities but farm income from crops and livestock were the main source of income, between 53 and 65% of their annual income. The rest of their income comes from non-farm wages, remittances, and private enterprises. Managing and planting trees on farmlands offers an opportunity to increase income diversification through marketing of tree products (Binam et al. 2017). Farmers who adopt agroforestry practices tend to have higher incomes, larger stocks of assets and greater cereal production and higher density of trees on their farms (Haglund et al. 2011). In

addition, the development of markets for tree products incentivizes farmers to invest in trees management including tree planting.

3.2 Impacts and outcomes of agroforestry practices

3.2.1 Income

Income was reported in 30 (81.1%) of the reviewed articles and it is the most investigated impacts of agroforestry on livelihoods (Figure 3).

Where markets are well-developed and accessible, fruit tree cultivation has great potential for income generation (Binam et al., 2017). For example, in Mali, native trees and shrubs contribute between 26% and 73% of farmers' annual revenue (Faye et al., 2010). The products that generated the most revenue were fruits from Baobab and shea trees, wood, and Baobab leaves, followed by shea butter. In Burkina Faso, the sale of tree products including shea nuts and fruits accounts for 28% of an average household income (Pouliot 2012). Shea tree is considered one of the most important tree species in dryland West Africa and significantly improves livelihood of smallholder farmers.

In Niger, the sale of *A. digitata* (Baobab) leaves can represent between US\$27 to USD\$75 per tree. Another study found that one mature *A. digitata* can generate an annual income of 34-75 US\$ per hectare which allows a household to purchase 70-175 kg of grain on the market (Reij and Garrity, 2016).

Binam et al. (2017) show that there is a sharp income increase from marketing tree products when the number of managed trees on farmland ranges from 10 to 40 per hectare. In Mali, the adoption of FMNR increases gross annual household income between 46 and 56 USD per capita which represents an annual increase between 18-24%. This increase appears to result from greater yields of cowpea and groundnut crops grown under trees and wood production (Haglund et al.,

2011). In Senegal, households practicing intensive FMNR earned on average US\$73 per season from selling non-timber products compared to US\$30 for households that did not practice FMNR (Seghieri and Harmand, 2019).

A study in Niger indicates that the annual per capita income from firewood sales ranges between US\$46 and US\$92, a significant contribution to household income given that the average annual income is less than US\$200 per person (Abasse et al. 2008). Another study in Niger estimated the income from the sale of firewood to be between US\$127 and US\$154 per household and the sale of non-timber products and estimated US\$237 per year, a smaller contribution than in other West African countries (Reij and Garrity, 2016). In Ghana, charcoal production is the second most important income source for rural households and makes up to 80% of total annual income in some communities (Ablo et al., 2022). Men are the main charcoal producers and derive higher income from charcoal (up to 90%) than from farming and other off-farm activities. On the other hand, charcoal production is one of the main contributors of loss of tree cover which in turn negatively affects women's capacity to earn income (Ablo et al., 2022).

There are differences among ethnic groups regarding the cash income generated by the sale of tree products. For example, in northern Benin tree products contribute to an average of 39% of farmers' yearly income but nomadic Fulani herders, who do not have formal land tenure, earn far less than other groups as they mostly rely on income generated from livestock (Heuback et al., 2013). In addition, the contribution of tree products to rural income in Burkina Faso, varies significantly between poor and wealthier households, where it represents around 43% of poorer households' income and 18% of wealthier households (Pouliot 2012). However, for all households, income from shea products is an important contributor to household livelihood because shea nut production is at its highest between July and September, the "hungry season" prior to harvest when

stored grain supplies are at their lowest (Pouliot 2012). Women perceive increased income as the major benefit of agroforestry practices (Akpabio 2009) and because women have limited access to land to grow cash crops, they depend heavily on tree products as a source of income and safety net. Also, it takes less labor to harvest tree products than cultivate and harvest crops (Pehou et al., 2020).

The economic contribution also differs significantly according to the tree species. In northern Benin, Heubes et al., (2012) show that income derived from *V. paradoxa* (Shea) is 3.5 time higher (13% of total annual income) than the income generated by *P. biglobosa* (African locust bean) (10% of total annual income) and six time higher than the revenue from *A. digitata* (Baobab) (2% of total annual income).

3.2.2 Nutritional diversity

Nutritional diversity was mentioned in 26 (70.3%) of the reviewed articles, the second most investigated impacts of agroforestry on livelihoods (Figure 3). Woody vegetation produces non-timber products including fruits, nuts, leaves, oils, gums, resins, and honey whose production is dependent on trees. In semi-arid regions of West Africa, the most common indigenous fruit trees are baobab (*Adansonia digitata*), shea (*Vitellaria paradoxa*), and African Locust Bean (*Parkia biglobosa*), also known as néré or dawadawa.

Vinceti et al. (2022) find that there is a significant relationship between the amount of tree cover and dietary diversity in this region. Edible fruits, seeds, and leaves from woody vegetation complement daily diet of rural households both in terms of quality with high vitamin, minerals and nutrients content and quantity, particularly during the lean season (Heuback et al., 2013; Pehou et al., 2020). In a study in Benin, Heuback et al. (2013) indicate that a total of 90 tree and shrub species were highly valued for many uses and that 32% of these species contributed to household consumption needs but *V. paradoxa* is by far the most valued species because shea butter is critical

to household diet and income. The seed of *P. biglobosa* (African locust bean) is the second most valued species as it is used as a highly nutritious condiment.

Across the region, the decline of the number of shea and African locust beans trees could lead to shortages of nuts and seeds that are essential for the nutrition of rural households. Shea butter is the most common fat for cooking and has very high nutritional value (Faye et al., 2010). Locust beans are equally important as a cooking spice and a rich source of plant protein (Derbile et al., 2022). In the Sahel, the contribution of tree products to caloric intake and diet increases with the number of trees on farmland when tree density is above 20 trees per hectare. In the region, deficiency of vitamins and other nutrients is prevalent, but in their study Binam et al., (2017) show that eating 10 g of the pulp of Baobab fruit provides 100% of vitamin C daily requirement for a child.

The rapid decline of fruit trees because of farming expansion, harvest for fuelwood and charcoal production threatens diet diversity and nutrition. Therefore, there is an urgent need to develop rural access to more sustainable energy sources (Sinare et al., 2022). Vincenti et al. (2022) suggest that landscape restoration initiatives with carefully selected locally adapted trees that optimize the availability of edible products could contribute to mitigate nutritional gaps and increase diet diversity. From 56 documented tree species in their study in Burkina Faso, 81 edible items derived from them can be used as food, including fruits, seeds, and leaves.

3.2.3 Medicinal uses

Medicinal uses were reported in 10 (27%) of the reviewed articles (Figure 3). Medicinal use is one of the most important tree-products in dryland West Africa. In Mali, Faye et al. (2010) found that farmers identified 42 tree species that are very important for their livelihood, and that the production of medicine was the most important criteria followed by food production. In Benin,

61% of the most common trees were reported to be used for medicinal purpose including *A. digitata* (treat fever), *P. thonningii* (antiseptic), and *T. avicennioides* (antibacterial). The bark and roots of both Shea and African locust trees are used to treat malaria, inflammatory diseases, and infections by most households in northern Ghana (Poudyal et al., 2011). However, medicinal uses of tree products were found to be more widespread in Burkina Faso than in Ghana which indicates that poorer households that cannot afford allopathic medicine rely on plant-based medicines (Pouliot and Treue, 2013).

3.2.4 Crop yields

Crop yields were mentioned in 16 (43.3%) of the reviewed articles (Figure 3). Improving crop yields is another major benefit of trees on farmland. Most studies focus on farm plot scale and include measurements of the yields of crops cultivated under tree canopies. For example, Binam et al. (2015) found that in Niger crop yields where FMNR is practiced were between 15% and 30% higher than where FMNR was not practiced because trees provide shade and increase soil fertility through nutrients concentration and moisture retention. In a different study, Binam et al. (2017) found a sharp increase in crop yields when the density of trees ranges between 15 and 20 trees per hectare with an increase crop production of 274.25 kg per hectare. Above a density of 40 trees per hectare, crop yields tend to decrease. In Mali, Haglund et al. (2011) estimated that an increase of the number of trees on farmland did not significantly impact the yields of cereal crops such as millet and sorghum but did positively impact the yields of other crops such as cowpea and groundnut. In Niger, crop yields increased even with tree density as high as 150 trees per hectare (Abasse et al, 2008). In Mali, farmers identified two tree species, *Daniellia oliveri* and *Faidherbia albida* as being particularly important for increasing crop yield of pearl millet (Asse and Lassoie, 2011). Unlike other tree species, *F. albida* sheds leaves at the end of the dry which reduces competition for light with

crops and leaf litter provides soil nutrients (Leroux et al., 2020) which in turn improves yields of millet in particular. On the other hand, shea trees were perceived by farmers as negatively impacting maize yields while African locust bean trees had neither positive nor negative effect on crop yields (Poudyal et al., 2011). In their study of FMNR in Senegal and Mali, Seghier and Armand (2019) indicated that yields of millet and peanuts are higher in farm fields under FMNR particularly with the presence of the leguminous *F. albida* trees than in fields where FMNR is not practiced. In their study of FMNR in Niger, Haglund et al. (2011) calculated that the crop yields of farmers practicing FMNR were 60% higher than those not practicing FMNR.

3.2.5 Energy (firewood and charcoal)

Energy was mentioned in 18 (49%) of the reviewed articles (Figure 3). Trees are the main source of energy for both rural and urban areas of West Africa's drylands. Farmers pointed out that charcoal production is one of the best ways to meet daily income needs because it is not as uncertain and does not depend on the weather like farming activities and it is one of the most valuable commodities traded in this region. In northern Ghana, charcoal production is the second largest source of income for rural households and functions as an income gap-filler during the hungry season (Ablo et al., 2022). Most charcoal producers in that region use shea trees from their farmlands to make charcoal because it is readily available on their farmland and because of the burning quality of the wood. Charcoal-making is increasingly becoming an essential livelihood activity in response to declining agricultural yields and rising urban demand for charcoal. Wood for charcoal production is easily and freely obtained from forests and farmland, where 90% is obtained from farmers' own farmlands (Assare et al. 2022). The rest is collected from forests that are considered common property. Charcoal production, however, is contributing to the decline of shea

tree population because it is a preferred species for making charcoal and charcoal production has increased in response to growing urban demand (Derbile et al., 2022; Poudyal et al., 2011).

Women have benefited from agroforestry practices because it improves the supply of fuel wood for cooking (Haglund et al., 2011). Firewood is also sold at markets, and in Niger the income from the sale of firewood has an estimated average annual value of US\$ 127-154 per household (Reij and Garrity, 2016). Most households depend on firewood for cooking and with the declining number of trees there is a deficit of firewood and charcoal in relation to the demand in many areas (Sinare et al., 2022).

3.2.6 Livestock fodder

Livestock fodder was reported in 12 (32.5%) of the reviewed articles (Figure 3). Many trees and shrubs are used by farmers to feed their livestock. Some studies have shown that investment in fodder trees on farmland is associated with higher animal stocks. In Niger, FMNR resulted in greater livestock production because tree leaves and pods provide additional nutrients during the dry season when grasses begin to dry off (Abasse et al., 2008). In Mali, a range of native tree species provide fodder for livestock including *Faidherbia albida*, *Pterocarpus erinaceus*, and *Balanites egyptiaca* (Faye et al., 2010) and allows farmers to keep more livestock that can be sold and provide income during the hungry season (Reij and Garrity, 2016).

3.2.7 Materials from trees

Materials from trees were mentioned in 11 (30%) of the reviewed articles (Figure 3). Trees also provide raw materials for house construction, fences, and handicraft (Akpabio 2009). In Benin, 35 tree species were reported as valuable for constructions and tool craft including mortars, pestles, and farm tools (Heuback et al., 2013). In Ghana, African locust bean trees are used for building

houses and the waxy property of the outer covering of the seeds is used for protecting and water-proofing earthen walls (Lelea et al., 2022).

3.3 Social differentiation

Gender is mentioned in 25 articles (68%), ethnicity in 9 articles (24.3%) and wealth in 10 articles (27%) that were reviewed. Natural endowments play a role in determining resource entitlement. When resources are plentiful women have greater access to natural resources such as Shea and African locust beans trees (Apusigah et al., 2009). Both Shea and African locust beans are culturally designated as women's crops and their products are therefore central to women's livelihoods as their commercialization is one of the few opportunities, they have for generating cash income (Kansanga et al., 2020; Pouliot, 2012). The harvest, processing, and marketing of both shea nuts and African Locust beans have traditionally been women's activities as their livelihood's options are largely determined by the cultural constructs of their labor in relation to the land (Agusigah 2009). Studies have shown that women rely far more on non-timber tree products than men and that agroforestry practices benefit them greatly (Pouliot and Treue, 2013). As Heubes et al. (2012) point out, most non-timber tree products can be harvested in open-access areas, offering the very poor and marginalized groups a source of income.

The ongoing loss of these trees is threatening this major source of livelihood (Derbile et al., 2022) and as parklands degrade, more time are required by women to find and collect shea and African locust bean, further reducing their return to labor (Lelea et al., 2022; Kansanga et al., 2020; Wardell et al., 2022). Women's rights to access land, trees and their products are more and more challenged when resources become scarce and when large land areas are acquired for monocropping (Pehou et al., 2020).

Like land tenure, access to and control over trees is complex and gender influences the right to plant, harvest, and cut trees. Tree tenure can vary across space, ethnic groups, and tree species. Among women, social differentiation based on ethnicity, generation, wealth status, and other factors shape women's access to trees and rights to harvest their products as well as making management decisions (Pehou et al., 2020).

In northern Ghana, men dominate the production of charcoal and the differential access to resources and gender-based roles have made it very difficult for women to enter the charcoal business (Ablo et al., 2022). In a study in Nigeria, women were found to be more favorable than men to adopt agroforestry practices because they perceive an increase of income as a major benefit of these practices (Akpabio, 2009). Women, however, are often hesitant to invest time and labor in agroforestry practices because they do not own the land and have little decision-making power over land management and land resources as well as many other labor demands. Women do not have full control over the use of their labor as men have priority use of women's labor, therefore livelihood options women pursue are subject to men's endorsements (Apusigah, 2009). In addition, differences in access to physical capital such as transportation means is acute between men and women, even though women are the ones responsible for going to markets to sell products such as shea butter and unprocessed shea nuts (Binam et al., 2015).

In an FMNR project in Niger, the inclusion of women and Fulani herders in village land management committees was pivotal to the successful adoption and spread of FMNR on farmlands. Together they discussed natural resource management problems where all points of view were heard, and decisions were made that were mutually beneficial for all the stakeholders involved. This was a major shift in a region where women do not usually play a role in decision making affecting

the whole community even though they are the main collectors of wood and other tree products (Abasse et al., 2008).

3.4 Ecosystem Services trade-offs and synergies

ES trade-offs and synergies were reported in 15 (40.5%) of the reviewed articles. Most studies address the trade-offs between decreased crop yield under trees and the importance of tree products for livelihoods.

Competition between trees and crops is one reason farmers do not want to keep woody vegetation in their fields (Abasse et al., 2008). However, many farmers weigh the negative effects of tree-crop interactions with the broader environmental benefits from trees. In Mali for example, harvesting nutritious fruits from *Cordyla pinnata* during the hunger season offsets the negative effects of canopy shading and potential lower crop yields (Asse and Lassoie, 2011). Light was identified as the most limiting factor affecting tree-crop interaction (Coulibaly et al., 2014). The authors found that African locust bean trees had more negative impact on sorghum yields than shea trees. These negative effects can be mitigated by lower tree density and regular crown pruning, particularly during the growing season. This approach maintains the provision of ES provided by trees which are key for the long-term sustainability of parkland systems (Coulibaly et al., 2014) while growing crops. Trees and crop spatial arrangement on farmlands and their management (pruning) reduces the competition between trees and crops. Also promoting nitrogen fixing tree species like *Faidherbia albida* that not only help increase crop yields but also produces significant quantities of fodder and fuelwood (Reij and Garrity, 2016).

Some studies look at the declining number of indigenous trees and its effects on ES. For example, the production of charcoal has threatened many tree species and has increased the rates of deforestation in many regions of West Africa (Ablo et al., 2022). Shea trees are the most

overexploited species for charcoal production in northern Ghana and their number are declining drastically. The functions of West African parklands are changing as the original parklands are being progressively replaced by conventional crops and by monoculture tree plantations that require less labor because of mechanization and chemical inputs and provide higher income but offer a smaller range of ES and products. Shea parklands have been replaced by cashew tree plantations across West Africa (Seghieri et al., 2020).

4. Discussion

For this review, the concept of ecosystem services co-production was used as a lens to highlight the importance of the human component for the successful contribution of agroforestry systems to livelihoods by including conditions such as governance, gender equity, secured land tenure, and investment in markets for agroforestry products. Throughout this review, agroforestry practices have shown to positively contribute to food security and sustainable livelihood by providing a range of ecosystem services such as provision of tree products for consumption, increase crop yields, fuelwood and timber, livestock fodder, and socio-economic benefits such as income from sale of tree products. However, much of the published studies simply describe the observed relationships between agroforestry practices and livelihoods rather than providing evidence for causal links. Most research also fails to examine the interactions and combinations of ES and capital assets on how they contribute to livelihood.

4.1. Limitations of economic valuation studies

Many studies recognize the complex interactions between people and their environment to produce food and while the multidimensionality of livelihoods is increasingly recognized, studies remain heavily focused on income as evidence of the contribution of woody vegetation to livelihood (Figure 3) rather than a combination of non-income generating dimension of livelihood. Weston et al. (2015) and Haglund et al. (2011) highlight the fact that many claims have been made about the

benefits of various agroforestry practices for improving rural livelihoods, but their studies indicate that most published research focuses on either economic indicators or tree-counting as quantitative proxy contributions to human well-being or just merely describe qualitative benefits.

Contribution to livelihood is generally limited to valuation studies (income, number of trees, crop yields), demonstrating some kind of value of positive effect, however, the results of these studies are difficult to compare because they use different methods to calculate income and crop yields as well as different scales of studies. Agroforestry studies are multidisciplinary by nature and use various approaches and data sources to calculate benefits, trade-offs, and scale effects. As an example, a study in Niger indicates that the annual per capita income from firewood sales ranges between US\$46 and US\$92 (Abasse et al. 2008) while another study in Niger estimated the income from the sale of firewood to be between US\$127 and US\$154 per household (Reij and Garrity, 2016).

Most of the data collected on wild foods or crop yields goes beyond one or a few villages at a single point in time. In addition, data on crop yields are difficult to generalize because yields are highly variable from year to year and from field to field. There are also seasonal and interannual variations in yields because of rainfall variability. Results are also difficult to compare because tree density and species composition of woody vegetation vary greatly from farm plot to farm plot and regionally (Sinare et al. 2022). The amount of tree products that contribute to livelihoods are not described precisely in the literature, which makes it difficult to know what percentage they contribute to the daily diet and for how many months of the year.

To really understand the contribution of tree products to household income studies should include: 1) detailed description on how tree products are used, either as a source of cash, direct

consumption by the household, or both; 2) Information on the quantity of tree products harvested, their value (price per unit/kg) and their share of the total household income portfolio.

There is much evidence of agroforestry systems positive contribution to livelihood in drylands of West Africa, but developing and monitoring relevant indicators of successful agroforestry systems is essential to ensure the applicability of different practices to different ecological and social local contexts. Studies show that for agroforestry to support sustainable livelihoods, it requires that tree species be carefully selected to respond to local priorities and biophysical conditions to optimize benefits and environmental services and that the proper management techniques be applied to prevent competition with other elements of the farming system (Mbow et al., 2014a).

4.2 Ecosystem Services co-production and livelihood

The ES provided by woody vegetation are the results of multiple human inputs that can enhance livelihood resilience. Therefore, there is a need to better understand the role of these non-natural capital assets and their contribution to the production of ES, and particularly provisioning services provided by trees. For example, crop yields can increase with the right kind of tree species, optimal number of trees per hectare and proper spacing which involved knowledge, technical skills, and labor (human capital) but also access to land and its resources (social capital) (Binam et al., 2015; 2017).

Livelihood is the result of the co-production between natural capital (trees and shrubs) and the other four capital assets and ES (Scoones, 1998). The different capital assets are combined to obtain various ES, including provisioning services provided by woody vegetation (food for consumption and sale) and then regulating services (increase crop yields through enhanced soil fertility, soil water content). Successful agroforestry practices need other capitals such as knowledge

and labor, access to land and its resources, policies to encourage gender equity and trees conservation. Manufactured and financial capitals are the least investigated capital assets (Figure2); however, they are important contributors to livelihood. Owning transport equipment significantly influences participation in markets for tree products, particularly for women (Binam et al., 2015). In addition, efforts to improve market integration through investment in infrastructure and predictable linkages to markets are all necessary to develop sustainable value chains for non-timber tree products (Binam et al., 2015). The development of markets for tree products incentivizes farmers to invest in trees planting and tree management. Yet very few studies look at the nature of the links and causal pathways between ES and the multiple dimensions of livelihoods. In this review, only four articles (10.8%) mentioned the five capital assets while eight (21.6%) articles mentioned four capital assets (Figure 4) in their assessment of the impacts of agroforestry on livelihoods.

Most studies primarily emphasize the economic aspects of livelihood such as households' cash income and crop yields. Other non-economic livelihood benefits are mentioned but their impacts are not systematically measured (Figure 3). Asse et al. (2008) point out that assistance programs for agroforestry have often failed to address the complexities of smallholders' decision-making because they do not explicitly recognize the interconnections, trade-offs and synergies between different ES and capital assets such as farmers endowment, motivations and skills, land tenure and access to tree resources, access to markets, and enabling policies. Ecological and social issues are fundamentally interconnected and so are the options for livelihood support and land management.

4.3 Tradeoffs and synergies

Trade-offs among ES can affect the quantity, quality and the resilience of the ES produced (Palomo et al., 2016). The ways farmers deal with various trade-offs have important implications for

their willingness to adopt agroforestry practices. Trade-offs between decreased crop yields under trees and the importance of trees products for livelihoods is a major factor in farmers' decision-making regarding the management of woody vegetation on their fields. The most common trade-offs among the different ES generated by trees on farms are linked to too much shade (microclimate), competition for nutrients and water which can reduce crop yields, particularly in semi-arid regions during the dry period (Kuyah et al., 2016). Trade-offs usually take place when competition for water, light and nutrients outweigh the benefits of improved yields (Kuyah et al., 2019). Competition between trees and crops, however, can be mitigated with management practices and selection of trees that use less water such as deep-rooted trees that can tap water below the crop-rooting zone (Bayala et al., 2002; Bayala et al., 2015; Mbow et al., 2014a; Tschardt et al., 2011). Other management options include increasing the spacing between trees and pruning the tree canopy to decrease the amount of shade (Kuyah et al., 2016). Crop yields differ depending on tree species, tree density, canopy shape, height, and crop types (Bayala et al., 2014). For example, Sinare and Gordon (2015) report positive effects for grassland production and for millet and sorghum yields when associated with *Faidherbia albida* and *Combretum glutinosum*.

Most studies look at the trade-offs among ES but rarely between ES and capital assets. There is little discussion about the costs of maintaining trees on farm fields in terms of labor and time availability. Often the short-term increase of one ES as the expense of another will greatly affect the resilience of the socio-ecological system in the long term. For example, the increased use of tractors to prepare fields for planting crops to save time and labor input leads to a sharp decline of the number of trees. The long-term effect will have negative impacts on the provisioning services with declining soil fertility and farmland being more exposed to increase erosion from wind and floods (Kansanga et al., 2020). Despite their multiple ES and benefits farmers do not plant or

protect new trees if they face heavy constraints like insecure land tenure or have other food or income priorities.

Bayala et al. (2015) point out that managing trade-offs requires understanding how the different components of the agroforestry system utilize available resources. This knowledge is key for determining species combinations, planting arrangements, tree spatial densities and management strategies suitable for different locations and different farmers' objectives and for the long-term sustainability of the system, which require knowledge and expert support from governmental agencies and both national and international organizations.

4.4 Institutions and Governance

Studies show that institutions (both at the local and national level) are essential not only for increasing the adoption of agroforestry practices but also for strengthening rural livelihoods. The direct and indirect contributions of trees to livelihoods are not always recognized by policy makers and non-timber tree products are often neglected when developing policies and management plans (Faye et al., 2010). Information on economic value of trees and market opportunities of tree products are needed to develop appropriate agricultural policies that promote sustainable agroforestry practices. Policies and institutions that enable the marketing of indigenous tree products encourage agroforestry practices in communities (Akpabio 2009; Binam, 2015). More training programs and capacity building are needed to promote agroforestry practices that are tailored to each region with specific tree species and management practices. In addition, policies need to promote more equitable value chains where women can benefit from high value tree products and promote the diversification of markets for a wide variety of tree products (Binam, 2015;2017).

At the local level, strengthening community-based natural resources management associations is key to increase the adoption of agroforestry because interests and concerns from

different social groups are considered through collaboration and trust building (Asse and Lassoie, 2011). Local and inclusive management of natural resources needs to include measures particularly with respect to the control and access to trees (Abasse et al., 2008). These social relations are crucial for negotiating access, conflict management, and developing locally adapted tree management practices (Ablo et al., 2022).

Research shows that the main barriers to the adoption of agroforestry practices are insecure control of and access to trees, lack of technical skills, lack of sound environmental policies and need to develop business support services for agroforestry related goods and services (Muthee et al., 2022). Mbow et al. (2014a.) state that environmental policies should integrate agriculture and forestry agendas to increase their effectiveness to address food security and resilience. They highlight the fact that the current policy frameworks are misaligned with growing practices such as monoculture and mechanization that threaten parklands. These current policies either do not provide incentives or they discourage parkland maintenance from providing the traditional quality and quantity of services. This is partly the result of a lack of communication and synergies between state and local authorities governing agriculture, trade, energy, forests, and the environment.

4.5 Beneficiaries of ecosystem services

Analysis of who benefits from different ES is essential to provide better investments and interventions to improve livelihoods. Gender, wealth, and ethnicity influence who has access to land and its resources, including trees. As Pehou et al. (2020) point out, more research is needed to understand the social dynamics that drive tree tenure, beyond just gender inequalities in customary tenure regimes. More studies are needed regarding the wealth status and ethnic backgrounds differences among women and how they negotiate access to tree resources. By considering women as a homogenous group, we run the risk of neglecting the specific constraints that different groups

of women face in accessing and using tree resources (Pehou et al., 2020). The social positioning related to access to land resources and labor constraints are critical determinants of women's livelihoods opportunities as their livelihood's options are constrained by the cultural constructs of their labor in relation to the land (Agusigah 2009). Studies need to consider how social and wealth status influence access to capital assets which in turns influence livelihood choices and opportunities (Asse and Lassoie, 2011).

Improving women's access to land and trees could help increase the adoption of agroforestry practices, especially planting economic trees for food and income provision (Akpabio et al., 2009). Most studies cite that tree products are central to women's livelihoods as the commercialization of these products is one of the few opportunities for generating cash income (Pouliot, 2012). The ongoing loss of these trees is, therefore, threatening this major source of livelihood (Derbile et al., 2022).

5. Conclusion

Trees on farms and in agricultural landscape in the semi-arid regions of West Africa contribute to multiple direct and indirect benefits to rural livelihoods. Throughout this review, agroforestry practices have shown to positively contribute to livelihood by providing a range of ecosystem services such as provision of tree products for consumption, fuelwood and timber, livestock fodder, and socio-economic benefits such as income from sale of tree products, and ecosystem enhancement through increased nutrients cycling, biodiversity, soil moisture retention, and reduced pressure on natural forests. For this review, the concept of ecosystem services co-production was used as a lens to highlight the importance of the human component for the successful contribution of agroforestry systems to livelihoods and to show that the impacts of agroforestry on livelihoods will depend on households' sets of capital assets and their particular sets of circumstances.

This review has highlighted the knowledge gaps that remain regarding the mechanisms by which agroforestry practices and their management contribute to livelihood resilience. Even though many studies recognize the multidimensionality of livelihoods, they remain heavily focused on income and other economic factors as evidence of the contribution of woody vegetation to livelihood rather than a combination of non-income generating dimension of livelihood. Because gender, wealth, and ethnicity influence who has access to land and its resources, including trees, more research is needed to understand how gender, social and wealth status influence access to capital assets which in turns influence livelihood choices and opportunities. Further research is also needed to understand how trade-offs between ES and capital assets influence farmers' decision-making regarding the adoption of agroforestry practices.

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Figures

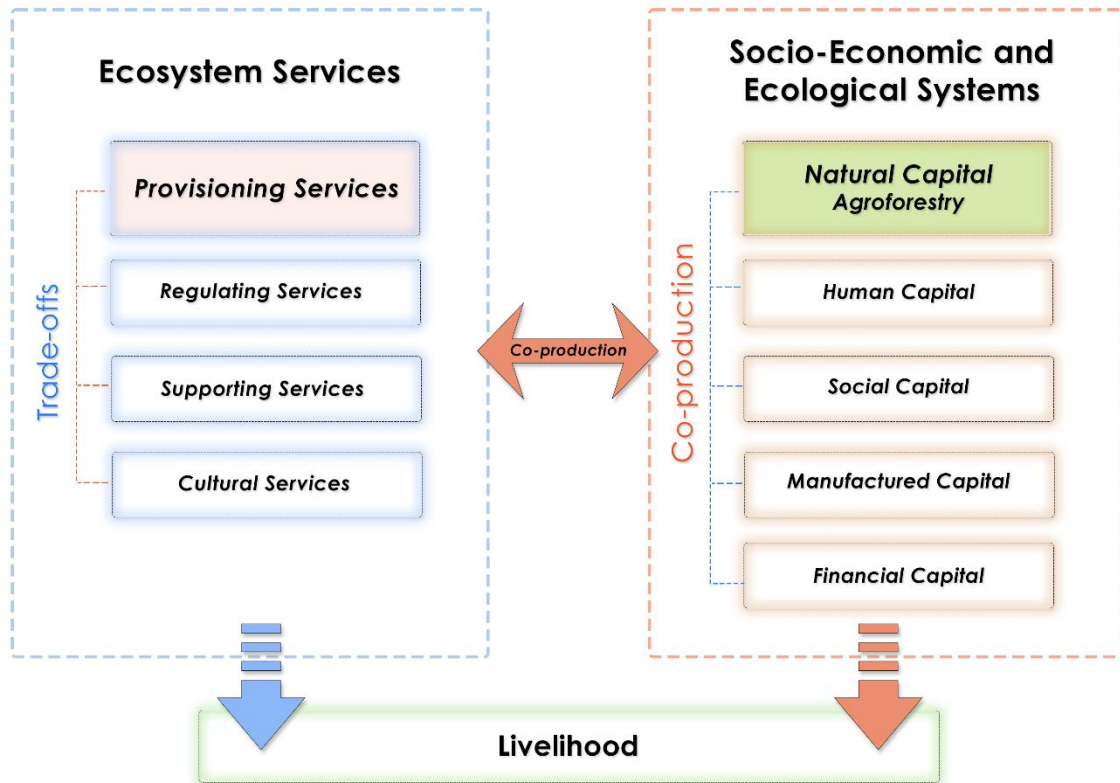


Figure 1. Conceptual framework integrating co-production and trade-offs in ecosystem services assessment in the context of livelihood resilience. Different capital assets are combined to produce ecosystem services. Co-production occurs among capital assets and ecosystem services affecting livelihoods and the ecosystem services delivered. Livelihood is the result of the co-production between natural capital and the four other capital assets. Trade-offs and synergies occur among capital assets and among ecosystem services, affecting livelihood resilience (Adapted from Palomo et al., 2016, Figure 2, p.259).

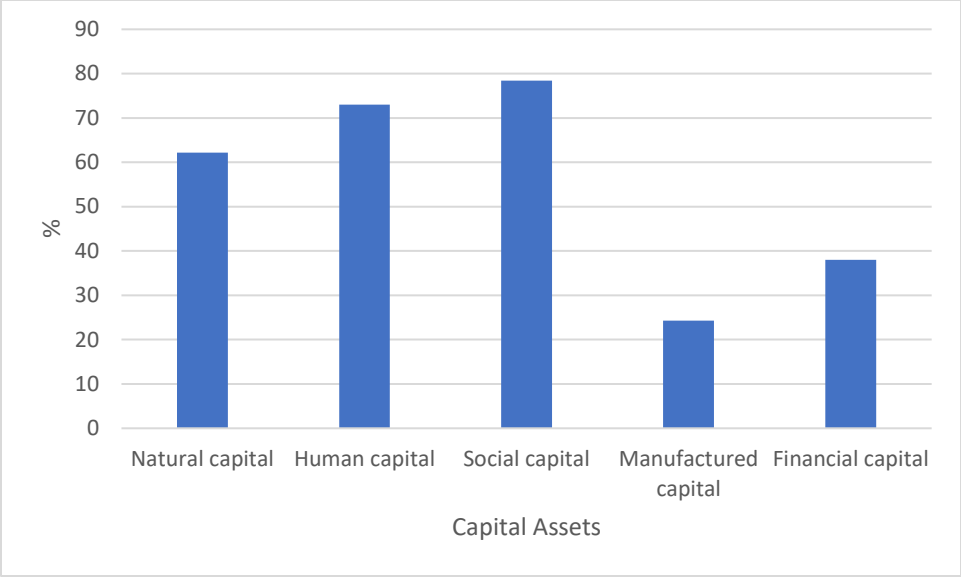


Figure 2. Percent of frequency for the five capital assets across all reviewed studies

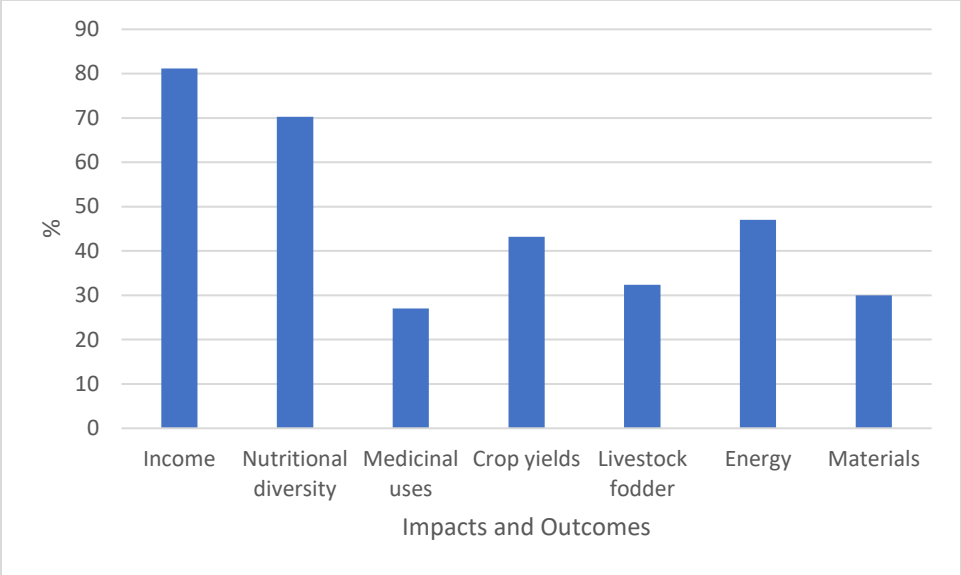


Figure 3. Percent of frequency for the impacts and outcomes across all reviewed studies

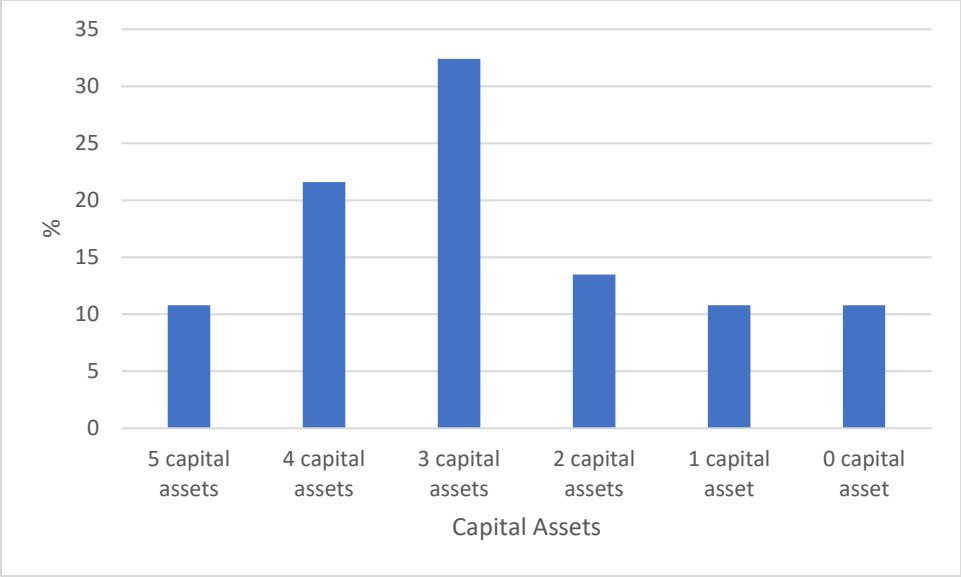


Figure 4. Percent of frequency for the number of capital assets mentioned in the reviewed studies

Tables

Table 1. Ecosystem services provided by woody vegetation

Ecosystem Services	Type of ecosystem services provided by woody vegetation
<i>Provisioning</i>	Food, medicine, livestock fodder, fuelwood, building materials (Kuyah et al., 2016)
<i>Regulating and supporting</i>	Soil nutrients and soil carbon concentration, soil water content, erosion control, shade/microclimate, pest control, positive impact on crop yields, biodiversity (Bayla et al., 2015; Sinare and Gordon, 2015)
<i>Cultural</i>	Shade for community gatherings, religious and cultural identity (Papa et al., 2020)

Table 2. Capital assets involved in sustainable livelihood

Capital Assets ^a	Description
<i>Natural capital</i>	Set of natural resources, renewable and non-renewable including land, water, forests, plants, animals etc. that provide goods and services from which livelihoods can be derived.
<i>Human capital</i>	Includes people's health, knowledge, education, skills, labor, perceptions, beliefs, and motivations essential to well-being.
<i>Social capital</i>	Both formal and informal networks, trust, shared values, and norms needed for enhancing social interactions and for facilitating coordination and cooperation. Also includes Institutions and governance that are the formal and informal institutional processes and organizational structure which mediate access to various capitals and resources as well as the ability of people/groups to carry out livelihood strategies.
<i>Manufactured capital</i>	Includes the fixed physical assets used to produce goods and services such as tools, machines, buildings, and infrastructure.
<i>Financial capital</i>	Refers to the mechanism societies use to trade other forms of capital including savings, credits and cash used for investing in and maintaining other capital assets.

^aThe combination of natural capital and other forms of capital (human, social, manufactured, and financial) co-produce different types, quantity, and quality of ES (Palomo et al., 2016)

Table 3. Search terms used

Agroforestry	Livelihood	Ecosystem	Africa
Agroforest* OR tree cover* OR parkland* OR woody vegetation* OR tree*	AND Livelihood* OR sustainable livelihood* OR food security* OR agriculture production* OR resilience*	Services Ecosystem services* OR AND social-ecological system*	AND West Africa* OR Sahel* OR Burkina Faso OR Benin OR Chad OR Ghana OR Niger OR Nigeria OR Mali OR Mauritania OR Senegal OR Togo

Table 4. Coded variables

Variable	Definition
<i>Location</i>	Country of study and agroecological zone
<i>Ecosystem service type</i>	Provisioning, regulating, supporting, and cultural services provided by woody vegetation
<i>Trade-offs and synergies</i>	Trade-offs occur when trees and crops compete for water, light, and nutrients which in turn affect the quality, quantity, and equity of ES. Appropriate management practices to mitigate trade-offs. Trade-offs among capital assets affect quality and quantity of ES
<i>Capital assets</i>	<p><i>Natural capital:</i> Farmers' access to environmental services and resources (own farmland, size of farmland, diversity of crops, own livestock)</p> <p><i>Human capital:</i> Education level, knowledge of agroforestry practices and benefits, perception and beliefs, preferences, labor availability</p> <p><i>Social capital:</i> formal and informal networks, strength of relationship with neighbors, political influence or power, institutional processes and governance regarding agroforestry practices, land tenure and rights of access to land and its resources</p> <p><i>Manufactured capital:</i> own tools and farming equipment, access to schools, hospitals, roads, markets, irrigation schemes</p> <p><i>Financial capital:</i> access to cash, credit, bank, remittance, own land, own livestock</p> <p>Access to and combination of these assets impact livelihood resilience</p>
<i>Impacts/ outcomes</i>	<p>Demonstrated quantitative or qualitative direct or indirect impacts on livelihoods: 1) <i>nutritional diversity</i> (fruits, leaves and other consumed parts); 2) <i>medicinal uses</i> (leaves, bark, roots, fruits and other parts); 3) <i>livestock fodder</i> (branches and fruits from trees and shrubs); 4) <i>materials</i> from trees and shrubs for construction or handicraft; 5) <i>energy</i> (wood used as firewood or charcoal production); 6) <i>crop yields</i> (increased or decreased yields); 7) <i>income</i> (products from the previous categories that are sold for cash)</p>

Social differentiation

Different social groups (wealth, gender, ethnicity) are affected by ES trade-offs and have differentiated access to land and resources which in turn affect livelihoods

APPENDIX B: IDENTIFYING THE FACTORS INFLUENCING SMALLHOLDER FARMERS' ADOPTION OF SUSTAINABLE LAND MANAGEMENT IN NORTHERN GHANA: AN ECOSYSTEM SERVICES CO-PRODUCTION PERSPECTIVE

Marie-Blanche Roudaut, Katherine A. Snyder, Deborah Bozem-Win Azumah

ABSTRACT

Conventional biophysical and socio-economic research suggests that the sustainable land management practices more easily adopted by farmers are those that are the most efficient to implement and are more profitable and less costly. This one-dimensional economic view of farmers' decision-making approach to understanding sustainable land management practices does not explicitly address the complex interaction among socio-economic, cultural, and institutional factors that influence these decisions as well as farmers' willingness and ability to invest in such practices. To address this issue, we applied an ecosystem services co-production approach to determine the nuanced and complex ways in which farmers view, define, and value land management costs, benefits, and impacts in four farming communities, using the Garu District of the semi-arid region of northern Ghana as our case study. We found that farmers' decision-making was embedded in a complex environment where they must weigh multiple factors when deciding on specific land management options. A co-production approach takes into consideration the wide variation among different farmers' conditions, needs, goals, and constraints in relation to sustainable land management options. This study shows that contrary to common assumptions, direct financial profitability is not the only factor that influences farmers' choices. Rather, farmers opt for sustainable land management practices that provide a combination of benefits that together make a particular land management option worthwhile.

Keywords: Ecosystem services, land degradation, sustainable land management, trade-offs, livelihood, decision-making

1. Introduction

Land degradation and associated desertification is a complex environmental problem of concern in dryland regions globally. Land degradation reduces land productivity through erosion, loss of organic matter, and deterioration of soil structure and is further exacerbated by the effects of global climate change (Reynolds et al., 2007). Land degradation also threatens the long-term ecological and economic resilience and adaptive capacity of the ecosystem and the populations who depend on it. This issue is particularly acute for land resource-based communities such as smallholder farmers and pastoralists, and is exemplified by demographic pressures, land-use intensification as a response to growing demand for food including shorter fallow periods, increased mechanization, fires, felling of trees for firewood and charcoal and changes in the functioning of local governance customary institutions (Mudhara et al., 2016) in northern Ghana. Land is arguably the most important socio-cultural and economic resource in rural northern Ghana, and therefore land use and management are central to food security and overall agricultural production and development, managing the land in a sustainable manner is critical for people's livelihood.

Achieving sustainable development for dryland livelihoods requires the prevention of land degradation through the implementation of sustainable land management (SLM) techniques to restore and rehabilitated the lands that lost their productivity (Mirzabaev et al., 2022). Managing land degradation effectively requires an in-depth understanding of human-environment interactions. Sustainable land management practices (SLM) offer a range of techniques to combat and reverse land degradation (Giller et al., 2009; Power, 2010). These practices enable land users to maximize the economic and social benefits from the land while maintaining the ecological functions of the land resources (Cordingley et al., 2015). The most widely used practices focus mainly on soil fertility and

crop management, soil erosion control¹, water conservation measures², and grazing and forest management. These practices, however, need to be developed within the context of their socio-cultural, economic, and policy environment, which may enable or hinder their adoption (Cordingley et al., 2015).

Although the specific factors that influence adoption of SLM practices remain actively debated, research has shown that adoption of SLM is constrained by a variety of ecological, social, economic, and institutional factors specific to local contexts (Cordingley et al., 2015; Giller et al., 2011). SLM practices are known to help improve soil fertility and prevent soil erosion. The literature indicates, however, that large-scale adoption of SLM is low among Sub-Saharan smallholder farmers (Giller et al., 2011) but the reasons for this low level of adoption have not been widely documented. Conventional biophysical and socio-economic research suggests that the SLM practices that are more easily adopted by farmers are those that are the most efficient to implement and that are the most profitable and less costly (Emerton and Snyder, 2018). However, direct financial profitability is not the only factor that influences farmers' land management choices.

This kind of one-dimensional understanding of farmers' decision-making often fails to address the complex socio-economic and ecological factors that influence farmers' decision-making and their willingness and ability to invest in SLM. In addition, most studies do not address the nuanced and complex ways in which farmers view, define, and value land management costs, benefits, and impacts. For example, production constraints, farmers' objectives, and the expected benefits and costs of implementing SLM are important aspects that influence adoption (Emerton and Snyder, 2018). At the farm level, trade-offs in the allocation of resources, lack of perceived

¹ Including but not limited to: Minimum tillage, crop rotation, maintaining organic cover, intercropping, agroforestry, terracing.

² Earthen or stone bunds, traditional zai, infiltration pits

benefits in the short-term, poor soil fertility, lack of technical knowhow, high labor and capital requirements, unreliable rainfall, land ownership status are important factors in determining how SLM may fit into a given farming system. At the regional level, factors such as market conditions, interactions among stakeholders and other institutional and political dimensions play a role in the adoption of new practices.

Emerton and Snyder (2018) argue that farmers' decision-making is embedded in a complex environment where they must weigh multiple factors when deciding on specific land management options. Farmers generally need to consider practices that match their specific economic circumstances, endowments/assets, requirements, and aspirations (Emerton and Snyder, 2018). They also point out that we need to understand the wide variation among different farmers' conditions, needs, goals, and constraints in relation to SLM.

To address this issue (the one you need to make explicit between here and the preceding text), we (1) provide a general review of the theoretical framework linking ecosystem services and poverty alleviation, and then, using the semiarid-region of northern Ghana as a case study, we 2) identify the socio-economic and ecological complexities that shape farmers decision-making, management of trade-offs, ability, and willingness to invest in SLM practices, and 3) identify the main constraints for adopting such practices. Understanding these factors is a pre-requisite for improving land-based adaptation efforts and reversing land degradation.

1.2 Theoretical framework: Ecosystem Services and Poverty Alleviation

An ecosystem services approach, particularly one focused on poverty alleviation, provides an ideal lens through which to better understand the impacts of farmers' decision-making regarding natural resources management. Such an approach acknowledges the complexities of socio-ecological systems (Berkes and Folke, 1998; Holling, 2001). Because of the multi-scale interactions between the

environment and human wellbeing and the complexity of both environmental and social conditions in the dryland landscapes, the multidisciplinary nature of an ecosystem services approach is necessary (Costanza et al., 2017; Daw et al., 2016; Fortnam et al., 2018; Fisher et al., 2014).

The Millennium Ecosystem Assessment (2005) illustrates how the concept of ecosystem services (ES) provides a particularly useful lens for framing and understanding social-ecological relationships and ecosystem management for poverty alleviation. It has contributed to ideas such as the co-production of ES (Lele et al., 2013; Palomo et al., 2016; Reyers et al., 2013), ES trade-offs (Bennett et al., 2015; Howe et al., 2014; Rodriguez et al., 2006) and multiple human values for ES (Pascual et al., 2014) within governance contexts (e.g. in the Global South; Schreckenberg et al., 2018).

Ecosystem services are broadly defined as “the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being: that is the benefits that people derive from functioning ecosystems” (Costanza et al., 2017:3). Complex interactions and feedbacks are required among built, human, social, and natural capital in order to produce ecosystem services (Costanza et al., 2017:5). The literature increasingly addresses the links between ES and human well-being, recognizing that social and ecological components must be understood jointly, while simultaneously considering the feedback and trade-offs between them. The provision of ES is often assumed to contribute to poverty alleviation, particularly in rural areas of developing countries. On the other hand, degradation of these services is in turn assumed to result in negative effects on human well-being because the livelihoods of the poor rely most directly on the provision of ES (Fisher et al., 2013; Suich et al., 2015). The Millennium Ecosystem Assessment (2005) classifies ecosystem services into the following four categories: provisioning services (products obtained directly from the ecosystem such as food, fiber, fresh water); regulating services (benefits obtained from the regulation of ecosystem process such as erosion, flood control, biodiversity); supporting

services (natural processes that maintain other ES such as nutrient cycling, biological nitrogen fixation); and cultural services (non-material benefits obtained from ecosystems such as recreation spaces, spiritual experiences).

The services provided by ecosystems are a direct result of the interaction between ecosystem properties (natural capital) and anthropogenic inputs including social capital, financial capital, human capital, and manufactured capital (Figure 1). For example, the production of food as provisioning service requires different inputs such as fertilizers, machinery, farmers' labor, and knowledge. This process refers to ecosystem service co-production (Biggs et al., 2015; Reyers et al., 2013). This is a key concept for understanding not only how ecosystem services are supplied, but also how services are distributed, since these services and anthropogenic inputs are unequally distributed across ecosystems and accessible by different socio-economic groups (Lele et al., 2013; Reyers et al., 2013). Most ES are co-produced by a mixture of natural capital and various forms of social, human, financial and technological capitals. Recognizing that ecosystem services are co-produced highlights the role of human interventions in the delivery of ecosystem services and, therefore, help reframe ecosystem services research towards a more social-ecological understanding of ecosystems and their benefits (Palomo et al., 2016). The co-production of ecosystem services is essential for understanding their delivery and distribution across various social groups as well as the impacts on wellbeing on these groups according to their differential levels of access, control and use of assets and labor (Palomo et al., 2016). The complex interactions and feedback between social and ecological systems go beyond the flow of materials or energy between systems that are often described in one dimensional economic and linear ecosystem service models. To fill this gap, a socio-ecological approach to ecosystem services is necessary (Berkes and Folke, 1998). Socio-ecological systems (SES) approaches define ecosystem benefits and wellbeing as the outcomes co-

produced by the interactions between social and ecological components (Liu et al., 2007; Reyers et al., 2013). SES approaches also demonstrate that feedback between poverty and ecosystems, and the resultant trade-offs, are not simple or linear. For example, it is not simply the increased production of provisioning services that causes negative feedback and ecosystem degradation but rather a complex network of factors, including population increase and land use change, which determine the type and magnitude of trade-off among the different ecosystem services (Kafumbata et al., 2014).

Palomo et al. (2016) differentiate two main types of ecosystem services co-production: the physical processes which affect final ecosystem service flows through ecosystem management using anthropogenic assets; and the cognitive processes, which are mainly shaped by social norms, institutions, experiences, and local knowledge, that shape the ways ecosystem services are perceived and used.

ES co-production is most easily identified for provisioning services (Palomo et al. 2016). Research in agriculture underlines the key role humans play in providing provisioning services (Pretty 2008). These human inputs include local ecological knowledge (i.e., human capital), social organizations and networks (i.e., social capital), technological, energetic, and financial inputs (i.e., manufactured, and financial capital). The provision of water also depends on co-production, particularly in semi-arid and arid regions where various water harvesting systems have been used for millennia to provide freshwater (Frot et al., 2008; Oweis and Hachum, 2006).

Regulating and supporting services benefit human well-being indirectly and their co-production is not always easily observable. For example, in agricultural fields the control of soil erosion and run-off has been managed with various techniques including terracing, agroforestry, and

no-tillage systems (Giller, 2011) while practices such as crop rotation and crop residue have been used for centuries in many parts of the world to maintain soil fertility (Zhang et al., 2007).

The co-production of cultural ecosystem services results from close interactions between humans and their natural environment (Palomo et al., 2016), and such interactions, in turn, shape cultural identity (Satz et al., 2013). When components of ecosystems are associated with emotions such as sense of belonging and experiences or local knowledge (i.e., 'cognitive' co-production) they carry symbolic meaning (i.e., sacred places, spiritual value). When natural features (e.g. a tree or a mountain) are perceived as sacred and offer cultural benefits, there is a strong desire among communities to protect these natural resources. For example, in Ghana baobab trees and sacred forests have a human dimension and are regarded as life-generating ancestors that need protection (Ignatov, 2016).

The combination of different capitals (Figure 1) involved in the co-production of ecosystem services affects both the quantity and quality of service delivered and often leads to trade-offs among ecosystem services, where one service increases at the expense of another (Bennett et al., 2009; Butterfield et al., 2016; Hicks et al., 2009; Howe et al., 2014; Reed et al., 2013; Rodriguez et al., 2006). For example, increase in food production is a direct result of the intensification of farming practices through non-natural capital inputs such as machinery, inorganic fertilizers, pesticides, which in turn, have contributed to the degradation of many regulating and supporting services such as water quality, biological control, biodiversity, pollination, and soil fertility (MA, 2005; Baulcombe et al., 2009; Power, 2010). The different forms of farming intensification have also contributed to the decline of traditional and local ecological knowledge associated with agricultural and grazing practices (Pretty et al., 2009). The practice of increasing the quantity of one ecosystem service (increase crop yield with the use of inorganic fertilizers) in the short-term have important

implications for the sustainability of the social–ecological system in the long-term (secure household livelihood) (Power, 2010).

Co-production of ES also impacts the resilience of the socio-ecological system in which it occurs. In this context, resilience is the capacity of socio-ecological systems to continue providing essential ecosystem services when faced with unexpected shocks or ongoing changes (Biggs et al., 2015). Resilience is linked to the maintenance of regulating and supporting services (Biggs et al., 2015) and biodiversity (Mace et al., 2012). If co-production of services contributes to the decline of biodiversity and the delivery of regulating and supporting services, it will adversely affect the resilience of the socio-ecological system. Enhancing the resilience of any ecosystem service often involves trade-offs with other services and, consequently, among different social actors. When co-production leads to trade-offs between ecosystem services, it invariably creates winners and losers by benefiting some social groups at the expense of others (Daw et al., 2011; Pascual et al., 2014). Equity is ultimately embedded in cultural values that are mediated by social institutions of those involved in the co-production of services or benefiting from these services (Pascual et al., 2014). Ultimately all trade-offs have social consequences because different groups value different ecosystem services in different ways, therefore impacts need to be evaluated according to different socio-economic groups (Daw et al., 2011).

Sustainable use and management of ecosystems is therefore key to support efforts at poverty alleviation, which lie at the core of most development strategies. Ecosystem services tend to be particularly important to the livelihoods of the rural poor, and their degradation and loss can have devastating impacts on their wellbeing and the ecosystem on which they depend (Schreckenberg et al., 2018). The key to sustainable development is achieving a balance between the exploitation of natural resources for socio-economic development and conserving ecosystem services that are

critical to people's well-being and livelihoods (Fisher et al., 2013; Suich et al., 2015). Therefore, an understanding of how ecosystem services contribute to livelihoods and of who benefits and who loses from changes arising from development interventions is essential (Schreckenberg et al., 2018).

Recent research has shown that men and women have different socio-cultural perceptions, values, and preferences for ecosystem services. As a result, they use, experience and benefit from ecosystem services differently (Brown and Fortnam, 2018:260). Ecosystem services and their role in alleviating poverty are based on a set of social relations that are inherently based on gender. For example, Agarwal (2000) showed that men prefer trees with high timber value, while women prefer trees that offer a wide range of services such as the provision of fuel, fruits, bark, fodder, and shade. Such studies highlight the fact that men and women value ecosystem services differently, often because of their culturally defined gendered roles and responsibilities. Women often have limited control of or access to land and its associated resources and therefore cannot always fully benefit from ecosystem services. Gender roles and responsibilities are culturally defined and vary from context to context and because of these differences, women and men have different perception and preferences for the use and management of ecosystems (Brown and Fortnam, 2018).

An ecosystem services co-production approach is, therefore, essential to address the nuanced and complex ways in which farmers view, define, and value land management costs, benefits, and impacts. In addition, this approach also takes into consideration the wide variation among different farmers' conditions, needs, goals, and constraints in relation to sustainable land management options.

2. Methods

2.1 Study Area

The Upper East region is one of the most climate stressed regions of Ghana while being one of the most dependent on subsistence farming (Abbam et al., 2018) (Figure 2). It is marked by declining soil fertility and high level of environmental and land degradation as a result of adverse climate conditions, bush fires, land fragmentation, loss of vegetation cover, continuous cropping and overgrazing and urbanization (Yiran et al., 2012) High rates of land degradation reduce agricultural production and exacerbate food insecurity, poverty and vulnerability (World Bank, 2020). In addition, investment in infrastructure such as irrigation, roads, access to market and electricity is minimal in this region and farmers mainly rely on rain-fed, low value-added subsistence farming (World Bank, 2020).

Climate change, land degradation and scarcity of water resources all present major challenges to smallholder farming communities in the drylands of the Upper East region of northern Ghana. These communities engage primarily in subsistence farming and livestock keeping as livelihood strategies. Off-farm activities such as shea and locust bean collection and processing, livestock, charcoal production and firewood sales, small-scale trading, and seasonal migration to urban centres, contribute significantly to the livelihood of households. However, these non-agricultural products are under threat from expanding agricultural production. At the same time, declines in on-farm food production because of decreasing soil fertility and increases in climate variability are threatening current livelihoods and levels of food security.

The four communities selected for this study are situated in the Garu District of the Upper East region of northern Ghana (Figure 2). The Garu District borders Togo to the east and Burkina Faso to the north and lies within the Guinea and Sudan Savannah agroecological zones. These farming communities were chosen because they are representative of the socio-economic and environmental challenges of this region.

In this semi-arid ecosystem, sparse, drought-resistant tree species such as *Adansonia digitata* (baobab), *Vitellaria paradoxa* (shea), *Parkia biglobosa* (African locust tree) or *dawadawa* in the local Dagbani language, and *Khaya senegalensis* (mahogany) dominate the landscape with tall savannah grasses. These wild tree species provide critical economic, social, and cultural benefits for households and their surrounding communities. Woody vegetation, crops and livestock are integrated in an agroforestry system referred to as a parkland system where mature trees are scattered in cultivated or fallow fields (Boffa, 1999).

The topography of the region is characterized by undulating gentle hills and the area is drained by the White Volta River and its tributaries. Soils are developed from granite rocks and are generally shallow, poor in organic matter and coarse in texture, except in valley bottom where soils with higher clay content allow for the cultivation of rice. The low organic matter content coupled with continuous disturbance of the soils weakens the soil structure and makes them susceptible to erosion and leaching (Yiran et al., 2012).

The region is characterized by two seasons; a long dry season from October to April associated with warm and dry harmattan winds and a short rainy season from May to September. The Upper East region receives one of the lowest amounts of rainfall in the country with 1,000 mm of average annual rainfall and experiences the highest temperatures with annual average of 28.9 °C and maxima reaching up to 40 °C (Abbam et al., 2018). Analysis of rainfall indices indicate that mean annual rainfall during the growing season of major staple crops has significantly decreased over the past decades while mean temperature has increased with high interannual variability (Abbam et al., 2018).

Subsistence agriculture is the dominant economic activity with over 80 percent of households in the district engaged in subsistence farming on farms of less than 2 hectares along with livestock and poultry production (Ghana Statistical Service, 2018). The main crops are cultivated during the short

rainy season and include millet, maize, rice, groundnut, cowpea, Bambara beans, and soybeans. During the dry season tomatoes, peppers and onions are cultivated as irrigated crops, however irrigated lands represent less than 1% of agricultural land while the remaining land depends on rainfall (MoFA, 2019)

Even though Ghana achieved the first Millennium Development Goals of reducing poverty by more than half, spatial inequality widened, and poverty and vulnerability became more concentrated in the Northern three regions, including the Upper East region (World Bank, 2020). Since 2012, overall poverty declined by only 0.8 percent where it remains above 70% in the Upper East (World Bank, 2020) and between 2012 and 2016 the poverty rate increased by 12 percent (World Bank, 2020). This concentration of poverty reflects both ecological conditions, disparities in governmental service delivery, and reliance on agriculture as the main sector of employment. According to the World Bank (2020) after 2012 the probability of escaping poverty declined from 29 percent to 18 percent among farming households in this region.

2.2 Data Collection

This research incorporated a mixed-methods approach that included qualitative, quantitative, and participatory methods in an effort to assess the multiple factors that shape farmer decision-making regarding the adoption of SLM practices. We drew on complementary qualitative and quantitative data to address the research holistically (Yin 2013:66). Household questionnaires provided quantitative data while focus group discussions and interviews provided qualitative data. The Evaluating Land Management Options (ELMO) participatory tool provided both quantitative and qualitative information.

A total of eight focus group discussions, four with men and four with women were held in the communities of Denugu, Gbanterago, Pialogo and Kpatia in the Garu District (Figure 2). These gathered essential information on farming, history of land use, constraints and opportunities, land

productivity, and SLM practices. This information was then used to design a household questionnaire that was administered to 120 randomly selected households (30 households were interviewed in each community) with an equal number of male and female-headed households of varying socio-economic status. Data was collected on household characteristics and resource endowments, farm production, SLM knowledge, awareness, and adoption.

In addition, a participatory tool, ELMO, was used to investigate farmers preferences and perceptions of economic advantages, disadvantages and trade-offs associated with different land management options (Emerton et al., 2016). This tool uses participatory techniques such as visualization, sorting, ranking, and scoring to understand farmers preferences and the perceived benefits, costs and attributes associated with different land management options and understand the decision-making criteria of different categories of farmers. A total of 16 ELMOs were conducted in the four communities, with an equal number of females headed and male headed of households. The 16 participants were randomly selected from the 120 households who participated in the household questionnaire.

Finally, community consultations and key informant interviews were conducted with district and village officials and agricultural extension agents to obtain information about the broader context and motivations for SLM interventions and management. All interviews and participatory activities were conducted in Kusaal. The third author is fluent in Kusaal and English and transcribed and translated all the materials.

2.3 Data Analysis

Quantitative data were analyzed using Microsoft Excel to perform descriptive statistics. Qualitative data collected from the various participatory activities were analyzed by the first author using the inductive grounded theory approach (Strauss and Corbin, 1998) to develop themes and

sub-themes with the help of MAXQDA software. Results from both quantitative and qualitative data were then combined and triangulated in an iterative process to obtain a fuller picture and broader understanding of the issue than that provided by a single method (Beebe, 2002; Flick, 2014).

3. Results

The results are based on our two main objectives. Our survey provides some context about household characteristics of survey respondents in the Garu District (Table 1).

3.1 Factors Shaping Farmers' Decisions

3.1.1 Land Degradation

To understand the factors that shape farmers' decisions regarding the management of their land, survey respondents were first asked about their overall perception of land degradation and its effects.

Most farmers observed a loss of soil fertility for the past 10 years leading to low crop yields (77.5%). Farmers also stated that the soil on their farms were too poor as a result of soil erosion (54.2%) to grow anything without the regular addition of manure and external input (22.4% of women and 15.8% of men). Women, however, perceive erosion (58.3%) and poor yields (88.3%) as more problematic than men (50% and 61.7% respectively).

Participants were then asked to rank the main causes of soil infertility in order of severity. Most respondents (86.7% of women and 91.7% of men) are aware that the continuous cultivation of the same crop (lack of crop rotation) without a fallow period causes soil to lose its fertility. The second most mentioned cause was soil erosion (81.67% of women and 66.67% of men). Inadequate manure supply to replace nutrients on soil was the third reason mentioned for loss of soil fertility (41.7% of women and 48.3% of men). Many households do not have access to enough manure to

fertilize soil and cannot practice crop rotation regularly. A small number of farmers (12%) think that a lack of cash to buy inorganic fertilizers is a cause of soil fertility decline.

To increase soil fertility, farmers bury weeds in the fields, apply both organic and inorganic fertilizers in fields near the house to grow maize, millet and groundnut, practice crop rotation, apply compost when they can produce it (but most say it is difficult to prepare and there is not enough to be effective). Some farmers stopped burning crop residue after harvest as extension agents suggested.

Both men and women have similar observations about the long-term impacts of climate on their crop production. Over 80% of men and women mention disappearance of vegetation cover, abrupt changes in season/change in growing season, poverty and food shortages, soil erosion, increase frequency of flooding, lack of potable water, and poor farm yields as the main problem with the decrease of crop production.

3.1.2 Farmers' Perceptions and Use of SLM

Another important factor that shapes farmers' decisions regarding the implementation of SLM practices is how they perceive and understand the benefits of such practices. Over 40 percent of the interviewed farmers are aware of a wide range of SLM practices including use of manure, grass strips, compost, crop residue, contour planting, and tree planting among others. Both men and women seem to be getting most of their information on SLM practices from radio station broadcasts and NGOs' projects. They understand that using a variety of SLM practices on their farms can help mitigate the effect of land degradation, particularly erosion and loss of soil fertility. They state that using SLM practices help increase their farm productivity in terms of increase crop yields, soil erosion prevention, healthy crops production, and increase soil fertility and soil moisture.

Interviewed agriculture extension agents stated that most farmers know about SLM because many of those practices are traditional farming techniques. But most of the farmers say that to increase soil fertility quickly (for the next coming season) inorganic fertilizers are the only way, therefore farmers are relying more and more on fertilizers to increase yields. Only a few farmers implement SLM as their sole practice to increase soil fertility. This minority of farmers have higher income and own their lands, so they are able to pay for the extra labor and materials, and they also have livestock that provide sufficient amounts of manure.

3.1.3 Practiced SLM

Overall, more men are using SLM practices than women. (Figure 3). For women, crop residue (60%), burying weeds (58.3%), and mixed cropping (45%) are the most widely used practices. These three practices are popular because they have no cost and do not require extra labor. For men, burying weeds (66.7%), manure (65%), crop residue (58.3%), mixed cropping (41.7%), and grass strips (38.3%) are the dominant practices.

According to agriculture extension agents, women implement SLM practices less often and instead need more fertilizers because they farm one season at the time as they do not know if they will have access to the same parcel of land the following season. Generally, access to land is tenuous for women and as a result, there is no incentive for them to invest time, labor, and resources to implement SLM since most of these practices show their benefits on the long-term.

Farmers stated that the SLM they choose to implement are the ones that first and foremost will help increase crop yields and income when farmers are able to sell their crops. But they mention that SLM are time consuming and require extra labor which is not always available.

3.1.4 Farmers' Perceptions of SLM Cost, Benefits, and Preferences

Farmers were asked to rank their preferred SLM practices (not necessarily the ones that they implement the most) (Figure 4). Investigating farmers' preferences and perceptions of SLM provides insights for explaining the mismatch between which SLM farmers prefer (Figure 4) and the ones they actually implement (Figure 3). Main costs (Figure 5) and cost burden (Figure 6) and their perceived disadvantages and negative attributes do not necessarily make an SLM option unattractive.

Farmers' responses highlight a mismatch between their preferred SLM and the ones they end up implementing. For example, the three SLM practices preferred (highest percent rank) by farmers are manure/compost (80%), crop rotation (60%), and intercropping (60%) (Figure 4). These practices, however, are only implemented by 49% (manure/compost), 22% (crop rotation), and 43% of the farmers (Figure 3). On the other hand, mulching/crop residue was only ranked at 35% but utilized by 59% of the farmers. Even though composting is highly desirable according to respondents, they state that it is time consuming, labor intensive, and hard to make because a pit needs to be built first. Agroforestry was the fourth highest ranked preferred SLM (37.5%) but was only implemented by 11% of the farmers.

Discussions with respondents shed light on the main attributes that influence their selections of SLM practices that could explain the mismatch between their preferences and the SLM they end up using. These include a variety of monetary and non-monetary factors when they decide which SLM practices would be the most appropriate for their present needs and economic and social circumstances. The main benefits (in order of importance) that farmers seek when selecting SLM practices is an increase in crop yields (which generates higher earnings), increase soil fertility, prevention of soil erosion, conservation of soil moisture, and providing a variety of crops to reduce the risk of crop failure. On the other hand, many respondents emphasized that some of these

practices are out of reach because of their cost burden and require extra labor and technical know-how that they did not have at the time.

The cost of labor (even if family labor is available), the time these practices take, and the costs of inputs often make SLM practices undesirable, particularly for poor farmers and female-headed household (Figure 5). The SLM practices identified by the farmers as the costliest because they are labor intensive are manure/compost, crop rotation, and inter cropping (Figure 6). Respondents said they need to hire labor to implement these practices because there is a shortage of available labor in their households as artisanal gold mining siphons youth labor away from agricultural production, creating labor constraints, particularly for women's head of households.

Even though farmers perceive these practices as costly, manure is used by 36% of farming households, crop rotation by 22%, and intercropping by 43% because of their effectiveness in increasing crop yields.

The use of manure is very popular, however respondents reported that there is never enough manure available to be an effective fertilizer. Transporting manure to fields that are located far from the farmhouse can be very costly and labor intensive, particularly for women (Figure 6). The number of livestock owned is positively related to the decision to use compost/manure on the farm fields. In general, men tend to own more livestock than women; as a result, women have less access to manure (Figure 3). That is one of the reasons why women grow crops such as rice and soybeans that do not require large amounts of fertilizers.

Agroforestry was the fourth highest ranked preferred SLM (37.5%) but was only implemented by 5 % of the women and 17% of men (Figure 3). Farmers are aware of the declining number of trees in their communities as a result of overexploitation for firewood and charcoal production, clearing to make room for agricultural fields, and bush burning. They are also aware of

the various ES provided by trees but point out that planting and caring for tree seedlings is difficult and costly in terms of materials and labor. Seedlings are hard to find and can be expensive. They also need to be protected from free-roaming livestock and tractors with fences made with whatever material is available such as blocks, rocks, thorns, and wood. Respondents also mentioned that timing of planting with the rainy season is critical, and that the survival rate of newly planted trees is low because they need to be watered and protected against livestock and bushfires.

Shea trees (*Vitellaria paradoxa*), one of the most economically valuable trees, are naturally regenerating trees that do not need to be planted; however, these trees take a long time to reach a productive stage. Investing in them, therefore is a long-term enterprise which can be problematic for poor farmers and women who have insecure land tenure. Most planted trees are fruit trees or nut trees, but farmers stated that there are not enough of them to make a difference in people's livelihoods as they consume most of the harvest and sell what is left over. When asked the main reason why they decide to cut down trees in or near their fields, farmers overwhelmingly reply that crops grow better with fewer trees because trees and crops compete for water and nutrients and that crops do not grow well with too much shade. On the other hand, trees in plantations like cashew or mango trees are planted away from crop fields and are not cut down unless they are dead or no longer produce fruits/nuts.

3.4 Main Constraints to the Adoption of SLM

Identifying the main constraints that shape farmers' willingness and ability to invest in SLM practices is another important step in reversing land degradation.

3.4.1 Natural

Precarious environmental conditions and high pressure on resources make this region of Ghana one of the most vulnerable to climate change. Studies found that both daytime and nighttime

temperatures are increasing while average rainfall is decreasing. Climate extreme events such as droughts and flooding greatly affect agricultural production in this region, particularly because it is predominantly rainfed. This high variability in rainfall and temperatures makes prediction difficult (Issahaku et al., 2016). Studies have shown that Ghana's climate during the crop-growing season is becoming drier with more frequent episodes of severe droughts (Abbam et al., 2018; Thornton et al., 2014), particularly in the Upper East region. In addition, an increase in mean temperatures (above 30°C) coupled with drought conditions greatly impact the yields of important staples such as rice, maize, millet, sorghum, and yam. Furthermore, decline in rainfall coupled with high interannual variability of rainfall patterns have potentially devastating effects on the production of major staple crops, and negative impacts on food security and household livelihood.

Farmers utilize different kinds of farming systems, and these differences fall mostly along gender lines (Table 2). In the Garu district respondents practice agriculture in either compound, bush farms or both, of which 79.2% are rainfed while only 20.8% are irrigated. Most men have compound (56.7%) or both compound and bush farms (43.3%) while 43.3% of women have bush farms followed by compound farms (28.3%). This indicates that women's farms are located further away than men's farms and respondents noted that most women who have compound farms have better crop production than the ones who have only access to bush farms. Women who wish to invest in their bush farms face many challenges because of the distance they have to cover to get to the farm. However, women's compound farms are usually smaller and with poorer soils and are mostly used to grow rice, okra, pepper, green leafy vegetables, and groundnuts.

3.4.2 Anthropogenic

Availability of labor/resources

Household assets including availability of labor force, land holding, crop production, distance to farmland, and farm input utilization were found to have an influence on the farmers' choice to use SLM practices.

Labor shortage is a problem for most farming households whose average age is 43.3 years old. Youth in households do not always help in the fields as parents choose to send them to school and older youth prefer to work in artisanal gold mines because they earn more money. Men have greater access to hired labor for labor intensive tasks such as composting, burying weeds, and weeding. Lack of available labor is a major barrier to adopting some SLM practices as well as clearing land to plant crops, planting and weeding which are the most labor-intensive activities on the farm.

In this district, as in the entire Upper East region of Ghana, temporary or even permanent labor migration is widespread. Most households have members (both men and women) who migrate to southern Ghana to work in larger cities for at least six months out of the year. These members send remittances back to their families which increases household income but also creates labor shortages. Very few household members have formal or regular employment while many are involved in various off-farm activities such as trading, sale of wood and charcoal, non-timber forest products, and other items that provide regular or occasional cash earnings.

Access to land and control of resources

Access to land is the most important asset for households that depend on agriculture for their livelihood and a determining factor of farmers' willingness to adopt SLM practices. Unsecured land tenure means that farmers have less incentives to invest in the land. Therefore, farmers' perception that the farmland he/she cultivates will remain his/her own for a certain period affects the decision about the type of land management being practiced. Women who have limited access

and lack security over their plots are less willing to invest in SLM practices because they risk losing all their investment of time, labor and other resources as the landowner may take the land back at any time.

Most farmers cultivate land that they inherited (Table 2). According to the local rules, the land belongs to the father, husband, son, or father-in-law through inheritance. For those who do not own land, access is granted through borrowing, renting or sharing cropping. This differential access to land directly impacts how men and women invest labor and inputs in farm plots. Most women do not own land and must borrow land parcels from their husbands, usually located in the bush, far from the compound farm. As a respondent pointed out “because the house and the land belong to the husband, when a woman marries him, she does not carry her fields with her”.

Women can also farm on compound farms (cultivated fields near the house) if they are widows or if their husbands migrated for work. Respondents stated that women invest in bush farms where they have to most access. On the other hand, men invest in compound farms where land is usually more fertile and closer to amenities such as tractors, hoes, and manure. These are the plots that feed the household. Men also farm on bush farms, and they often give a small plot (usually the least fertile one) to women to cultivate cash crops such as rice, soybeans, and groundnuts. Because of lack of time, labor, and cash to invest in fertilizers, women cannot farm large plots, however these plots are important and are viewed as their “savings” account. Typically, women sell these cash crops to pay for school fees (which they are generally responsible for) and other household expenses. However, if their husbands’ crops are not sufficient to provide food for the household, women will use their crops to feed the household instead of selling them. When they have access to irrigated fields, women will grow onions, tomato, okra, and other greens during the dry season to sell to the market.

Capacity building and aversion to risks

The lack of capacity building regarding SLM practices, proper use of fertilizers, and lack of access to better weather information, particularly the onset of the rainy season, were factors cited as barriers to the adoption of SLM practice. If farmers do not know how to use a technique (the one most cited is intercropping) they are reluctant to try it.

Interviewed agriculture extension agents point that for many farmers SLM practices such as crop rotation is a difficult technique to understand and implement because not every crop is going to help replenish soils (it must be a legume or other plants that release hydrogen). Intercropping is also a challenge because of the need to intercrop with the right plants. Many farmers intercrop maize and millet instead of soybean or other legumes. Implementing new practices requires knowledge and know-how, and if this knowledge is not available these practices are viewed as too risky.

Many households in the four communities are food insecure part of the year and cannot afford to take the risk of implementing or experimenting with new land management options that they are not familiar with. They keep doing what they know, even if new practices could help improve crop production in the future. Overall, most farmers understand the benefits of SLM practices, but they view them as providing long-term benefits and most of them need short-term benefits because they have very little capacities to absorb a shock such as crop failure.

3.4.3 Institutional

In the four communities, inadequate support from either the government, NGOs, agricultural extension service, or local associations is cited as another major constraint on the implementation of SLM practices, even though the government of Ghana has recently prioritized

agriculture as one of the key sectors for development with the aim of alleviating poverty through modernization and improved productivity (Ministry of Finance, 2017). The government strategy includes the provision of improved seeds, building of dams, increasing agricultural extension services, supply of fertilizers, marketing, and encouraging youth participation in the sector.

Less than half of the respondents received external support to implement sustainable agricultural practices. The type of support included extension services for 32.4% of women and 43.3% of men and subsidized farm input for 14.2% of women and 36.7% of men. Financial support was almost nonexistent. NGOs provided various types of support including training, seeds, and tools for 41.7% of women and 21.7% of men. Most respondents (57.5%) said that the support they received was beneficial particularly for improving crop yields and overall support to family needs. Agricultural extension agents provided information on land degradation and SLM practices on a regular basis to 55% of the men, but 56.7% of women stated that they rarely receive this kind of information. In addition to a lack of support, respondents mentioned that the government and the Ministry of Agriculture do not invest enough in this region. They pointed out farmers face a long dry season of about eight months during which most of them are jobless as a result of lack of opportunities. Respondents suggested that investing in expanding irrigation and repairing damaged dams would allow them to continue agricultural production during the dry season.

Another issue raised by respondents is the need for better coordination between NGOs, District Assembly, village chiefs and agriculture extension services regarding project implementation. A village chief explained that for example, an NGO will build a dam and after completion will transfer the responsibility of its maintenance to the village chief without further technical and financial support. NGOs need to work more closely with District Assembly and Agriculture Services to establish clear ownership of these dams and who is responsible for maintaining them. In addition,

many projects funded by various NGOs and governments agencies start irrigation projects but then leave before the work is finished, so farmers rarely see the benefits of these projects.

Respondents also mentioned a lack of coordination among the various players in land management. Each of the government agencies try to implement their specific plans without consulting other agencies or NGOs operating in the area which can lead to delays in some development projects in the district. Efforts at Government's decentralization is very slow, and some agencies are not represented at the local level. As a result, some decisions are made at the higher levels without taking into consideration local needs. Local leaders point out the lack of consultation with the local population and say that their views are never considered, and their concerns never acknowledged by the government.

4. Discussion

Patterns of land use are influenced by culture, governance, wider economic processes, and the natural resources in landscapes. Unfortunately, the literature on ecosystem services, land use and land cover change and agricultural intensification suffer from a lack of attention to the differentiated perspectives, economic endowments, and objectives of different land users.

To fill this gap and point to some solutions, this study was conducted to evaluate the socio-economic and ecological complexities that shape farmers decision-making, ability, and willingness to invest in SLM practices, and to identify the main constraints for adopting such practices in the semi-arid region of northern Ghana. An ES co-production lens (Palomo et al., 2016) was used to frame this study as it offers a holistic and nuanced approach for understanding the complex interactions among livelihood priorities and how trade-offs and synergies among different ES and capital assets (Figure 1) can affect the well-being and the resilience of smallholder farmers and the ecosystem they depend on.

Understanding the factors that drive the adoption of SLM is a pre-requisite for improving land-based adaptation efforts and reversing land degradation. This study shows that farmers understand the benefits of SLM but are only willing to implement such practices if they have the necessary resources such as labor, particularly during the cropping season, access to cash to buy inputs, the necessary knowledge to implement new practices, and access to land.

The literature indicates that large-scale adoption of SLM is low among smallholder farmers (Alamirew, 2011; Cordingley et al., 2025; Giller et al., 2011). Farmers priorities, objectives, and production constraints, resource endowments, farming systems, the expected benefits, and costs of implementing SLM are important aspects that influence adoption. At the farm level, trade-offs in the allocation of resources are an important factor in determining how SLM may fit into a given farming system. At the regional level, factors such as market conditions, interactions among stakeholders and other institutional and political dimensions are important. Research on sustainable land management needs to take into consideration the diversity of farmers regarding resource endowments and farming systems, as well as the broader institutional and policy environment within which they operate. In addition, understanding farmers' priorities and constraints are essential to design incentives that are relevant across the diverse agro-ecological and socio-economic conditions as well as the cultural environment of the farmers at the local level (Ojiem et al., 2006).

The following section explores the factors influencing the farmers' willingness and ability to invest in SLM such as the institutional environment, farmers' priorities and constraints, and trade-offs.

4.1 Enabling Institutional Environment

4.1.1 Governance and policies

Institutions are the formal and informal rules and norms that enable or constrain the actions of individuals and groups (Agrawal, 2001; Leach et al., 1997). The government of Ghana has

developed a battery of macro level policies for broad development planning and natural resource management over the past decade to sustain economic growth and combat poverty. For example, the Ghana Shared Growth and Development Agenda (GSGDA) II (2014-2017) seeks to modernize agriculture and natural resource management, particularly the rehabilitation of existing irrigation infrastructure and promotion of private sector participation in irrigation development, management, and utilization (Government of Ghana. 2014).

Since becoming a party in 1994, the government of Ghana has put into place various policies to achieve sustainable development and meeting the goals of the Convention on Biological Diversity (CBD). Most of these policies are encompassed within the country's National Biodiversity Strategy and Action Plan (NBSAP) whose goals is to enhance sustainable development and biodiversity conservation as well as overall environmental protection (Government of Ghana, 2016). To ensure its effective implementation, the Ghana's 2016 NBSAP has been designed to operate within the country's decentralized system and implementation is carried out by various ministries, departments and agencies, local institutions, traditional authorities, as well as the private sector.

To meet Ghana's international obligation regarding the CBD, the vision of the 2016 NBSAP is to have in place by 2030 "effective systems" that would: "ensure that biodiversity in Ghana is valued, conserved, restored and wisely used to maintain ecosystem services, and sustain life support services for a healthy planet while ensuring continuous and equitable sharing of the costs and benefits arising therefrom, to the well-being, prosperity and security of all Ghanaians" (Government of Ghana, 2016, x). The government of Ghana has also created the Environment and Natural Resources Advisory Council (ENRAC) to oversee and approve all policies on environmental and natural resources relevant for the implementation of CBD. This advisory council includes a variety of stakeholders from academia, civil society, government to traditional authorities (Government of Ghana, 2016:66). In addition, the government of Ghana has been a key participant

in the Reduced Emissions from Deforestation and Forest Degradation (REDD+) agenda and introduced the REDD+ Readiness Proposal in 2010 to help identify and mitigate the causes of deforestation and land degradation in the country. Part of the REDD+ agenda, projects such as the “Tree on farms (ToF) intervention” and Conservation Agriculture” have been put into place to optimize the “productivity and sustainability of smallholder farming systems” through the development of suitable farming technologies (Ministry of Lands and Natural Resources, 2016:73).

Despite these efforts, the CBD Secretariat estimates the current NBSAP has been inadequate in addressing the threat to biodiversity, land degradation, and loss of habitat which are the direct results of deforestation, desertification, mining and quarrying, soil erosion, flooding, drought, bushfire, forest conversion, urbanization, and overall over-exploitation of natural resources (Amoah et al., 2020). In addition, weak legislation, and institutional structures, misguided economic and environmental policies, ineffective institutions, lack of consultation with local stakeholders, the complexity of projects coordination and implementation, and the over-centralization of policies formulation have rendered many of these well-intended policies ineffective (Botchway, 2021; MoES, 2002).

In a country in which land and water resources continue to provide the foundations for most rural livelihood, economic growth focused on large scale private investment and export-oriented agriculture are in direct conflict with the sustainable use of natural resources and equitable wealth distribution. When dealing with low agricultural productivity, the policy framework tends to view small scale farmers as a problem. The dominant solution to low productivity thus appears to be large scale private investment rather than helping smallholders increase productivity through SLM (de Silva, 2012).

4.1.2 Access to Land

Uncertainties over land tenure also constitute a fundamental constraint to smallholder farmers' ability to invest in SLM. In Ghana, land ownership and distribution are one of the most contentious development assets because there was no official land registration until 1986 (GoG 2011). In addition, land allocation and tenure vary from region to region, according to local custom. The distribution, ownership and management of land is still influenced by traditional institutions, especially chieftaincy and its related belief systems and their authority to allocate land rights and its resources (Awuah-Nyamekye and Sarfo-Mensah 2011). Women's rights to land tend to be secondary rights, secured primarily through marriage to the male heads of households who are seen as custodians of the land thorough their lineage. This access to land is not guaranteed or permanent, therefore making long-term investment is not an attractive option for many women. A comprehensive attempt was made for land title registration in Ghana. This culminated in the Land Title Registration Law in 1986. This has been the framework for the land registration policy in the country ever since, but implementation has been sporadic, and this has been attributed to a failure of land policies to adequately integrate traditional belief systems to enhance equitable distribution and optimal use of land (Awuah-Nyamekye and Sarfo-Mensah 2011).

4.1.3 Decentralization and Coordination at the Local Level

Over-centralization of policies formulation, lack of consultation with local stakeholders and complexities of project coordination and implementation among different land management actors have led to a lack of investment and support for sustainable land management initiatives in the Garu District.

Decentralization is key for improving projects implementation because local institutions play a central role in implementing SLM initiatives. Even though the existing institutional framework in Ghana is designed for greater accountability and greater local communities' participation in developing their own natural resources management plans, evidence on the ground suggests otherwise. For

example, the Ministry of Food and Agriculture (MoFA) in Ghana invests on interventions to increase crop production through dissemination of yield enhancing technologies without consulting with District Assemblies and the community at large to understand farmers' priorities and intentions for the management of their lands (Agula et al., 2018). Decentralization is key to empower local communities to develop natural resources management plans that are adapted to the environmental conditions and priorities of their community.

While communities are now expected to drive the development of District development plans, the District Assemblies (the local authorities), lack the fiscal autonomy to generate adequate revenues. Efforts at decentralisation are also inhibited by scarce human capacities both within the local government bureaucracy and the local stakeholders themselves. Stakeholders' ability to participate meaningfully is constrained by the inability of local government to meet the logistical and resource demands of implementing participatory processes. The involvement of citizens in decision making is one of the principles of good governance. Consultation with the people to a large extent determines the acceptance of changes that are made regarding rules, laws and policies affecting them. The Upper East region has the highest proportion (61.5%) of people who said their views are never considered and their concerns never acknowledged by the government before laws or rules are changed (Ghana Statistical Service, 2018).

While the existing institutional framework provides scope for greater accountability, civil society participation in development planning and the opportunity for communities to contribute to their own development plans, a lot more work needs to be done to make this a reality for the farming communities of the Garu District.

Evidence also suggests that the decentralization process is further undermined by how international donors choose to implement their aid programmes, often bypassing District levels and village levels. In addition, the technical, logistical, and human resource burdens created by multiple

projects from multiple donors weaken an already fragile decentralised structure and contribute to making effective and integrated planning and resource governance very challenging (de Silva, 2012).

4.2 Understand Farmers' Priorities and Constraints

Farmers understand the many benefits of SLM but implementing SLM is often not a priority for many of them. In the face of immediate concerns such as poverty, food insecurity and poor agricultural productivity, long-term problems such as land degradation and overall health of the ecosystem are not a top priority for most smallholder farmers.

Smallholder farmers face many constraints that often deter them from adopting SLM practices. The main constraints are access to land, availability of labor at key periods during the cropping season (land preparation, weeding, planting), availability of manure for soil amendment, free-roaming livestock (eat seedling and crop residue), cash to invest in external inputs (seeds for intercropping, herbicides, etc.), and lack of market accessibility to sell produce. Women are particularly disadvantaged as they lack access to family labor compared to men who have priority over women for youth and children as family labor. Women and to some extent poor male farmers, must pay for labor to help them in the fields as labor is no longer, or rarely done in cooperative work groups.

As pointed out by Emerton and Snyder (2018), it is not the absolute cost of a particular SLM practice that is the most important in deciding to adopt it or not; it is how land, labor and time availability, and cash requirements are a match with farmers' endowment and ability to free up these inputs when needed.

4.3 Trade-offs

Ecosystem services are produced by socio-ecological processes where the role of human intervention in their delivery is increasingly being acknowledged (Palomo et al., 2016). The co-production of ecosystem services through the combination of different forms of capital often leads to trade-offs among ecosystem services, where the provision of one ES is reduced as a direct result of increased use of another (Reed et al., 2013; Rodríguez et al., 2006).

Agricultural systems provide provisioning ecosystem services that are essential to human wellbeing. They also provide and consume regulating and supporting services. Maximizing provisioning services from agricultural activities can result in trade-offs with other ecosystem services and adversely affects the resilience of socio-ecological systems. Conversely, careful management can substantially reduce or even eliminate these trade-offs. Agricultural management practices such as SLM are key to realizing the benefits of ecosystem services while reducing disservices from agricultural activities because these practices have the potential to increase food production while minimizing some of the negative impacts on biodiversity and the ecosystem (Power, 2010; Rodríguez et al., 2006). Land management decisions, however, are influenced by the balance between short-term and long-term benefit and many of the benefits provided by SLM practices are only realized in the longer term.

Short-term focus on agricultural production interferes with long-term sustainability of ecosystems. In Ghana, like in other developing countries smallholder farmers are highly dependent on natural resources for their livelihoods and are particularly vulnerable to environmental degradation. These farmers, however, tend to attribute more value to immediate costs and benefits than those realized in the future because of the constraints of production and food insecurity that they face (Suich et al., 2015; Fisher et al., 2013). As Rodríguez et al. (2006) point out, regulating, supporting and cultural services are usually ignored in trade-offs decisions because the negative

impacts of these decisions are not going to be felt for a while or until a critical environmental threshold is reached.

Nevertheless, SLM practices can offset many of the negative impacts of agriculture production while maintaining provisioning services. Regulating and supporting services can be enhanced by nutrient management strategies that capture nitrogen, phosphorus and carbon that are provided by many SLM practices such as cover cropping and intercropping. Crop rotation with legumes promotes nitrogen fixation and phosphorus solubilizing (Power, 2010). Practices that maximize plant cover, such as cover-crops or agroforestry can help decrease runoff and increase infiltration.

At the farm level, production constraints push farmers to make constant trade-offs to ensure sufficient crop production. These trade-offs are often made at the expense of SLM implementation. For example, mulching with crop residue is one of the most effective means to reduce soil erosion, water evaporation, reduce temperatures in the surface layer of soils, and increase water infiltration (Giller et al., 2009; Power, 2010). Crop residues can also help maintain soil organic matter, which assists in water retention and nutrient provision to crops. Soil structure and fertility provide essential ecosystem services to agricultural production and SLM practices can help maintain soil fertility by minimizing the loss of nutrients and keeping them available to crops (Zhang et al., 2007). One major competing use for crop residue, however, is its use for livestock feed. Given the cultural and economic value of livestock (investment and insurance against risk, traction, manure, meat, and milk production), farmers prioritize crop residue to feed livestock instead of using it to mulch. Crop residues are also burned to clear the land from weeds and pests to ready it for the next planting. Weeding is labor intensive and time consuming, and a shortage of labor often leads farmers to choose burning their crop residue as it has the tendency to encourage weed growth. For many

farmers, the cost of using crop residue as mulch is too great in the short-term compared to its potential long-term benefits.

Several studies suggest that tradeoffs between agricultural production and various ecosystem services are not inevitable and that ‘win – win’ scenarios are possible (Pretty et al. 2006; Palomo et al., 2016; Power, 2010). The introduction of SLM practices into resource-poor agroecosystems in 57 developing countries resulted in a mean relative yield increase of 79 per cent (Pretty et al., 2006). In these examples, there was no evidence that the provisioning services provided by agriculture were threatened by implementing SLM practices to improve its ability to provide other ecosystem services. These analyses suggest that it may be possible to manage agroecosystems to support many ecosystem services while still maintaining or enhancing the provisioning services that agroecosystems were designed to produce. Sustainable agricultural production through the management of ecosystem processes has the potential to increase food production while minimizing some of the negative impacts of agricultural intensification on biodiversity and ecosystem services (Baulcombe et al. 2009).

Other studies (Emerton and Snyder, 2018; Giller et al. 2009) point out that the reasons why farmers decide to adopt or not adopt SLM are complex and that efforts to promote such practices need to be tailored not only to the local bio-physical environment but also to the specific socio-economic and cultural conditions of farmers. Farmers differ greatly in terms of resource endowments, capacities, and farming systems. Poorer farmers and women usually farm on degraded and less fertile lands. Their farm plots are usually located in the bush and are often cultivated without fallow period and without inputs. Such farmers are more risk adverse and less able to try new farming practices. Research indicates that SLM practices will be most easily adopted by farmers who have sufficient access to resources such as land, labor, and cash and less likely adopted by the ones who are most resource constrained (Giller et al., 2009; Ojiem et al., 2006). We argue that with

proper incentives, capacity building, community support, and the expansion of regional value chains for local products, SLM practices could be more accessible to all farmers if they wish to implement them.

5. Conclusion

The implementation of SLM practices, particularly in degraded environments, has been shown to increase food production while maintaining and even enhancing other ecosystem services. The aim of this study was to understand the reasons driving the low adoption rate of these practices by identifying the socio-economic and ecological complexities that shape farmers' ability and willingness to invest in SLM practices, and to highlight the main constraints for their adoption in the semi-arid region of northern Ghana.

We have argued that to improve adoption of SLM, we need to first address the constraints that limit the farmers' ability to adopt them. Initiatives designed to improve the adoption of SLM need to not only be tailored to the local bio-physical environment but also need to recognize the socio-economic diversity of farmers in terms of resource endowment, farming systems, and the institutional and policy environment in which they take place. This study among others (Emerton and Snyder, 2018; Cordingley et al., 2025) demonstrates that households do not always choose the SLM practices they prefer or even consider to be the most effective at improving crop production. Rather, they choose the ones that they can implement given their economic circumstances and resource endowment at the time.

As discussed, the main barriers to SLM adoption are labor shortage, lack of cash and know-how, and insecure land tenure, particularly for women and poor farmers. Direct cash transfer or grants to households who want to invest in SLM could help farmers hire extra labor, buy seeds for intercropping, crop rotation, and cover crops, and other inputs ahead of the cropping season.

Farmer-led organizations that are funded and supported by local authorities could facilitate co-learning and co-innovation of land management that are specific to local conditions. Developing SLM practices that are tailored to the end-users' priorities and constraints are more likely to result in livelihood improvement and greater rate of adoption.

Scarce human capacities both within the local government bureaucracy and the local stakeholders themselves inhibit the training of more personnel for natural resource management (Giller et al., 2011). Investing in the training of agricultural extension agents to use appropriate dissemination strategies to promote SLM practices tailored to local conditions and that respond to individual households' livelihood priorities would be a necessary step to increase their adoption. This type of capacity building requires better coordination and collaboration among local authorities. For example, the various District departments need to better collaborate in developing District sector plans that are ratified by the District Assembly and discuss these plans with the community. Strengthening these linkages has the potential to improve stakeholder participation and make the District Assembly more accountable to its rural constituents. This could be a starting point for the implementation of the Decentralization Policy Framework and Action Plan which implies a major re-alignment of roles and relationships at all levels from the local district to the central management agencies (de Silva, 2012).

Ultimately, promoting the adoption of SLM practices to combat land degradation and improve smallholder livelihoods will need to be accompanied by the creation of local and regional value chains through the development of local processes, infrastructure, and private companies for processing local food products. These agricultural products could become the foundation of a regional agro-industry capturing the added value and providing real employment to rural communities. To encourage the

adoption of SLM, there is an urgent need to promote production and exchange of West African agricultural products and build value chains among West African countries (Nubukpo, 2022).

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Figures

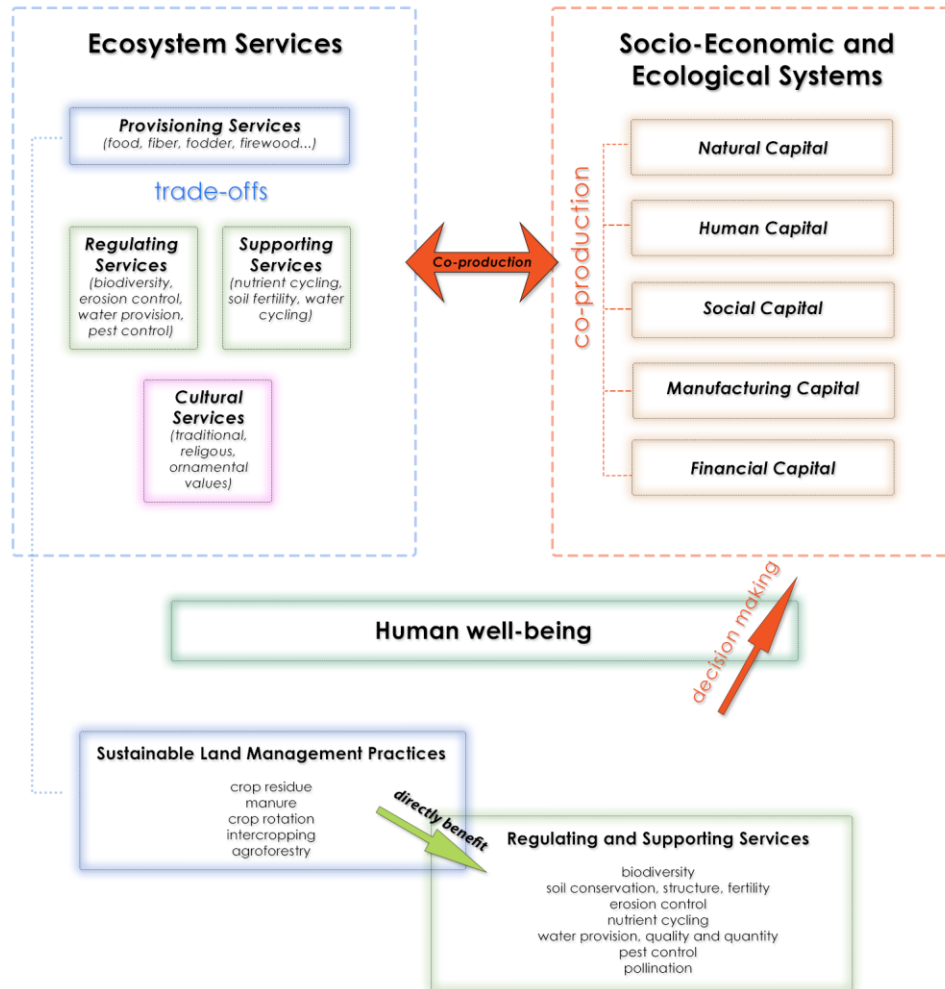


Figure 5. Conceptual framework integrating co-production and trade-offs in ecosystem services in the context of SLM adoption. Capital assets including natural capital are combined to produce ecosystem services. Trade-offs occur among capital assets and ecosystem services affecting human well-being and the resilience of the services delivered. Decision-making regarding the adoption of SLM directly affects the natural capital by benefitting regulating and supporting services. (Adapted from Palomo et al., 2016 Figure 2., p.259)



Figure 6. Map of the study communities in the Garu District, Upper Region of Ghana

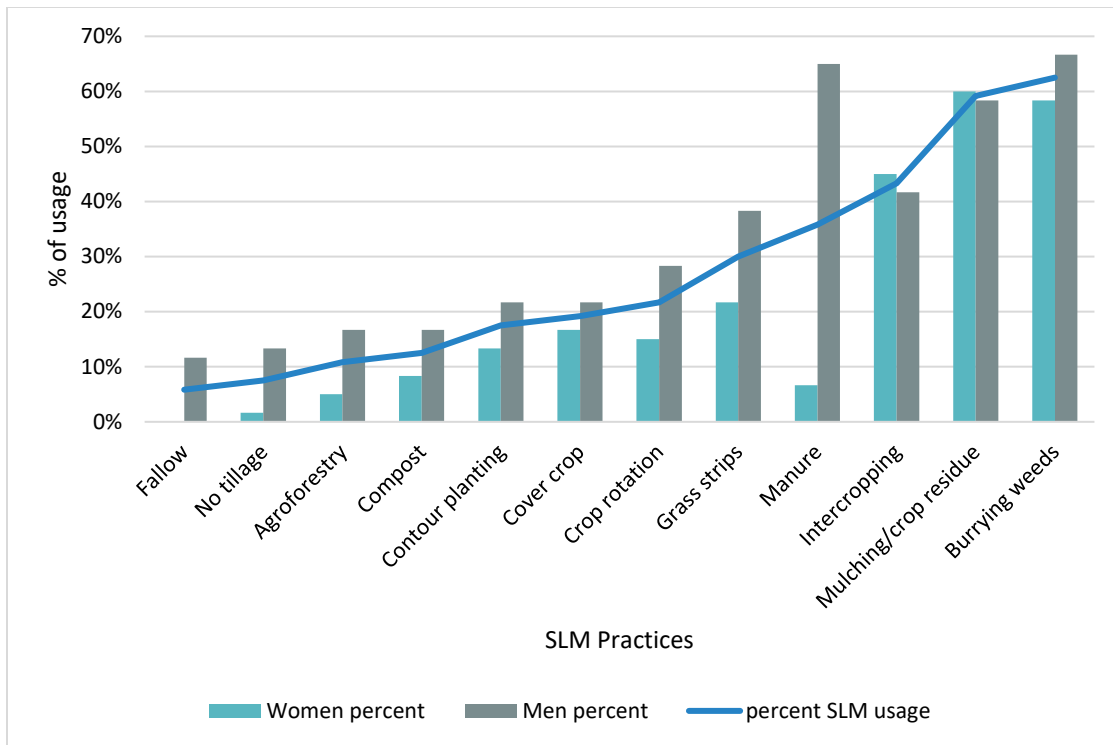


Figure 7. Most common implemented SLM practices

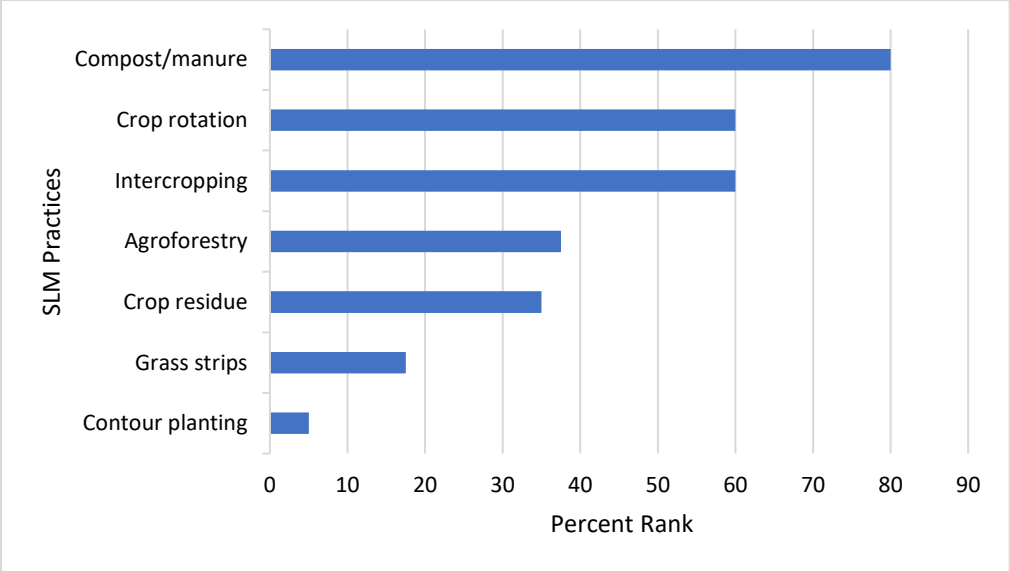


Figure 8. SLM practices ranked by farmers' preferences

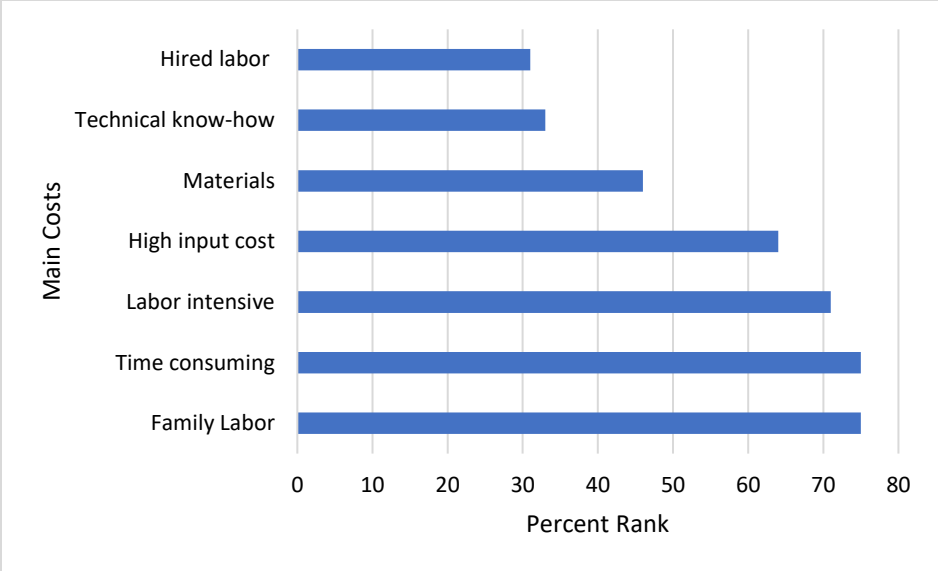


Figure 9. Main cost burden of SLM practices

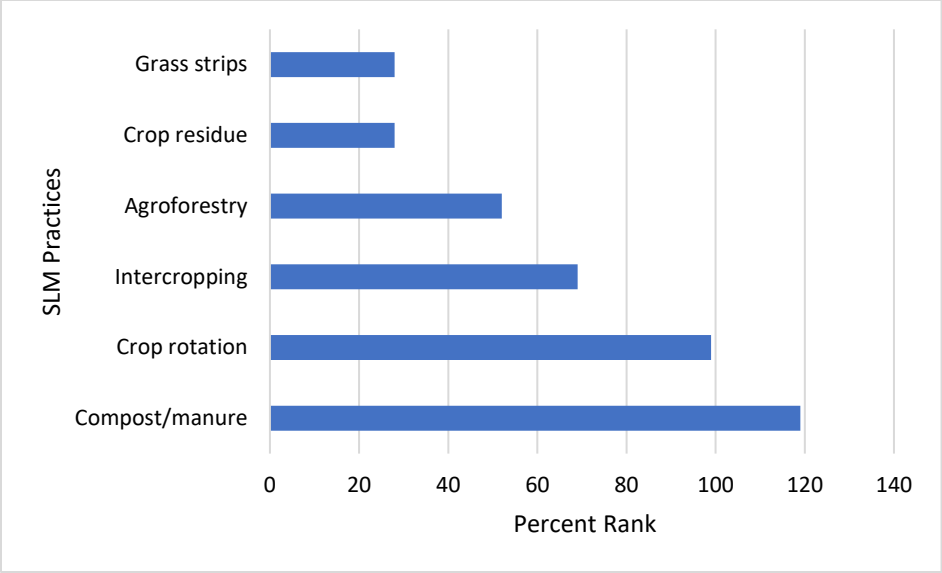


Figure 10. Cost burden of different SLM practices

Tables

Table 5. *Ecosystem Services Categories (Adapted from MEA, 2005)*

Ecosystem Services Categories	Types of Ecosystem Services
Provisioning services (products obtained directly from the ecosystem)	Food, fodder, fiber, fuelwood, timbers, medicine, fresh water, organic fertilizers, genetic resources, gum, dyes, ornamental products
Regulating services (benefits obtained from the regulation of ecosystem processes)	Air quality control, biodiversity, pest and disease control, carbon sequestration and storage, erosion and flood control, habitat connectivity, microclimate, pollination, water regulation and purification, wind break
Supporting services (natural processes that maintain other ecosystem services)	Biological nitrogen fixation, nutrient cycling, photosynthesis, soil fertility, water cycling
Cultural services (the non-material benefits obtained from ecosystems)	Recreation space, tourism, aesthetic, spiritual experiences, sense of places, traditional and religious values (sacred forests)

Table 6. Household characteristics

Participant characteristics	Female (%)	Male (%)
Average age (years)	43.5	43
Education		
Primary	21.6	33.3
Secondary	3.3	28.
None	75	38.3
Household characteristics (n= 120 farming households)		
Average household size: 9.3 persons		
Average land cultivated (acres)	3.2	5.2
Farm assets		
Cattle/Donkey	1.6	46.7
Bullock for plowing	0	48.3
Donkey cart	1.6	8.3
Motor bike	0	58.3
Land tenure		
Inherited	50	75
Borrowed	33.3	16.7
Leased	15	11.7
Farming system		
Compound only	23.3	56.7
Bush farming only	43.3	6.7
Compound and bush	28.3	43.3
Rain fed only	76.7	81.7
Rain fed and Irrigation	23.3	18.3

APPENDIX C: NAVIGATING SENTINEL TERRITORY WITH A STAKEHOLDER NETWORK: A CASE STUDY OF CLIMATE AND VITICULTURE IN ARIZONA.

Marie-Blanche Roudaut, Alison Meadow, and Jeremy Weiss

ABSTRACT

Climate change-induced socio-economic tipping points can result in a series of cascading effects across socio-ecological systems where the state of such systems can abruptly change to a fundamentally different one. The co-production of climate services is being acknowledged as one of the most effective approaches to build an actionable network of stakeholders able to identify vulnerabilities and threats of tipping points. In the literature, however, little attention is given to the processes of establishing partnerships and building stakeholder networks. This paper presents a case study that describes the modes of engagement and the earliest stages of partnership between climate producers and users in the viticulture sector in Arizona. Intentionally building a network through the process of climate services co-production creates the necessary conditions for stakeholders to take on sentinel's functions to monitor the threats of tipping points and act as an early warning system. We argue that this approach could be used as a model to monitor early warning signals of socio-economic tipping points in any sector where the co-production of climate services is critical.

Key words: Climate change, tipping points, co-production, engagement, network-building, sentinels

1. Introduction

The effects of climate change and increasing anthropogenic pressures are driving abrupt and unexpected ecosystem state changes called tipping points. These abrupt changes in the ecosystem result in shifts in its functions and the provision of ecosystem services leading to economic and societally negative impacts (van Nes et al., 2016). Climate change can have great and usually negative impact on ecosystems, societies, and economies and may cause socio-economic tipping points, where the state of the socio-economic system abruptly changes to a fundamentally different state (Dietz et al., 2021; van Ginkel et al., 2022). Such cascading effects create shifts in the functioning of the socio-ecological system (SES) which depends on the provision of ecosystem services. Land management, therefore, needs to prepare and adapt for regime shifts not only from an ecological perspective but also in the context of social and economic systems (Lauerburg et al., 2020).

Regime shifts caused by disturbances to the SES have been widely documented from the collapse of large fisheries to abandonment of agriculture land (Biggs et al., 2018; van Ginkel et al. 2018; Serrao-Neumann et al., 2016). These regime shifts can have devastating impacts on human economies, security, and health (MA 2005; Rocha et al., 2015) because these regime shifts can affect the supply of essential ecosystem services upon which human societies depend on, such as flood regulation and crop production. The full effects of climate tipping points and its implication on SES, however, are still not well-understood (Berrouet et al., 2018; Link and Browman, 2017; Link et al., 2018, Milkoreit et al., 2018).

Stakeholders' perception plays a crucial role in identifying socio-economic tipping points (SETPs) because effects of regime shifts are context specific and most visible at the local level. Depending on the context, different stakeholders have different ways of perceiving tipping points. As van Ginkel et al., (2018) stated, the most obvious SETPs are found on small system scales

because the role of climate drivers is difficult to isolate from other drivers of change and climate disasters may have a greater impact on individuals and communities.

Lauerburg et al. (2020) argue that vulnerability assessments for social-ecological systems lack involvement of stakeholders and interest groups and that a participatory approach is essential to incorporate a variety of perspectives and perceptions of what the relevant tipping points are and at what level they occur. In addition, stakeholder involvement strengthens the link between SES research and management processes (van Ginkel et al., 2022).

Despite stating the need to engage with stakeholders to create more usable knowledge, explicit examples in the literature that describe effective approaches to build and maintain stakeholder networks are lacking. To fill this gap, we present a case study of on-the-ground network-building in the context of climate and viticulture in Arizona where we describe the early stages of engagement to build and maintain a stakeholder network. We show that intentionally building a network through the process of climate services co-production creates the necessary conditions for stakeholders to take on sentinel's functions to monitor the threats of tipping points in their territory (Blanchon et al., 2020). We argue that this approach could be used as a model to monitor early warning signals of SETPs in any sector where the co-production of climate services is critical.

For the purpose of this research, we link the concepts of tipping points in socio-economic systems and sentinels to demonstrate how to create an actionable network of stakeholders able to identify vulnerabilities and threats of tipping points to SES. This paper is organized as follows: first, we present the concepts of tipping points in socio-ecological systems, sentinel territory, and co-production of climate services; second we describe the process of intentionally building a stakeholder network that takes on sentinel functions through a case study of Climate and Viticulture

in Arizona; and third, we then discuss why building such networks is an essential step to identify and assess SETPs and the barriers and challenges in building and maintaining such networks.

2. Theoretical Background

2.1 Tipping points in social-ecological systems

Research on social-ecological systems has contributed to expanding the concept of tipping point by including it as a component of SES. Initially, the term tipping point was used solely to describe regime shift in ecological systems. More recently, researchers have begun to use the term of socio-ecological tipping points to refer to non-linear changes in such systems (Milkoreit et al., 2018). The authors point out, however, that social tipping points are very different from ecosystems and climatic tipping points, even if both systems are subject to rapid change. In socio-economic systems climate change is the driver of tipping points.

There is an emerging field on tipping points research that specifically looks at the coupled socio-ecological systems (Berrouet et al., 2018; Lauerburg et al., 2020; Milkoreit et al., 2018; Reyers et al., 2018; van Ginkel et al., 2020). In this context a tipping point is defined as: “the point or threshold at which small quantitative changes in the system triggers a nonlinear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible. This new state can be distinguished from the original by its fundamentally altered (positive or negative) state-stabilizing feedbacks” (Milkoreit et al., 2018:9). In this context, the regime shift taking place in the social system must be linked one way or another to an ecological system change. Research has shown, however, that in most studies on coupled socio-ecological systems, the regime shift is still mainly investigated in the ecological rather than the socio-economic domain where they have the most relevance for policy in the context of climate change (Biggs et al., 2018; Filatova et al., 2016; Kopp et al., 2016; Lauerburg et al. 2020).

In their review of the literature, van Ginkel et al. (2018) indicate that climate-induced socio-economic tipping points (SETPs) share these characteristics including: 1) *stable states* where state A is fundamentally different from state B; 2) *mechanism* that explains state stability and nonlinear transition; and 3) *rapid and abrupt change* where the state change is rapid compared to the change usually observed in the system. Overall, changes in the socio-economic systems result from the complex interactions between environmental and socio-economics drivers and policy interventions.

These authors identified two types of SETPs: impacts and transformative response tipping points (van Ginkel et al., 2022:2). Impact SETPs occur when the regime shifts as a result of internal causes and insufficient human action such as when climate hazards push people to migrate out of a region (Kopp et al., 2016) or when low altitude ski resorts go bankrupt because of lack of snow (Vaghefi et al., 2021). Transformative response SETPs, on the other hand, refers to situations where the socio-economic structure is deliberately transformed by human actions before the impacts happen. For transformative response SETPs to occur it is imperative to know if and under what conditions SETPs may occur and what can be done to anticipate their causes and effects.

Reaching a tipping point in any system can result in a series of cascading effects across ecological, social, economic, and political systems. Assessing SES vulnerability to tipping points is essential to maintain the provision of ecosystem services and to develop appropriate risk mitigation strategies (Berrouet et al., 2018).

Vulnerability of SES is a result of exposure to a specific threat such as increase temperature, flooding, the susceptibility, or weakness of the ecological, economic, and socio-cultural systems to a specified threat and the system's overall capacity to respond to such threat (Berrouet et al., 2018). The system's resilience is determined by the system's internal susceptibility to specific disturbances and its coping and adaptive capacity (Berrouet et al., 2018; Resilience Alliance, 2010). Assessing the

vulnerability of a socio-ecological system requires the understanding of both the social and ecological vulnerability of a given system (Berrouet et al., 2018).

2.2 Sentinel territory concept

The concept of sentinel emerged from the field of Science and Technology Studies (STS) to develop technologies of preparedness: while modern states have used techniques of prevention to protect their population by the calculation of risks, contemporary global issues such as global pandemic have used techniques of preparedness to mitigate the effects of events with low probability and catastrophic consequences (Lakoff 2008, 2017). Sentinels can be contrasted to indicators and prognosticators as different technologies to anticipate the future and make visible the invisible. While the prognosticator relies on the series of indicators and datasets, sentinels rely on warning signals recorded by people in specific locations (Keck and Lakoff, 2013). Recently, the notion of “sentinel territory” (Blanchon et al., 2020) has been proposed in order to bring together two usually separate understandings of the word sentinel. On the one hand, sentinel devices are apparatuses equipped to monitor environmental change. They can include people who have agency, but they usually play a passive role. On the other hand, sentinels can also be active agents. They can not only raise alarm about incoming threats but also react and take action in order to mitigate risks. Blanchon et al. (2020) define “Sentinel territories” as spaces where early-warning signals of environmental threats/changes can be observed and where the term “territory” includes not only spatial dimensions but also social and moral references (Barreteau et al., 2016). It encompasses a sense of place, which underlines and reflects the agent’s awareness of the environment and of his/her place within it.

Sentinel territories have three characteristics. First, a sentinel territory must face one or more potential threats such as flood, drought, or toxic pollution. These threats, which are a combination

of hazards and vulnerabilities, may endanger one or more elements of the territory such as water resources, human health, biodiversity, or culturally significant places. Second, a sentinel territory must include monitoring devices that gather data and agents aware of the eminent threat. Third, monitoring devices and agents' awareness are not sufficient to create a sentinel territory as they might not translate the gathered information into action to mitigate or adapt to the threat. This happens through the process of "territorialization" (Blanchon et al., 2020:4) where a community is formed and becomes involved around a shared sense of place. A sentinel territory is not only a concept to monitor and identify environmental changes; it can also be a tool to advance environmental policies by making the changes brought by disasters visible to society and transform them into "social problems" by institutions that account for them. For example, Tonnelat (2012) shows how inhabitants of New Orleans have played a sentinel role after hurricane Katrina by rediscovering and monitoring the bayou.

In this paper, we link the concept of sentinel territory to SETPs in two ways. First, through the sentinels' active observations, knowledge, experience, and use of monitoring devices, they can identify and interpret tipping points. Second, sentinels may provide the motivational base for a wide range of stakeholders to act in order to prevent a potential crisis. In this perspective, sentinels are the "crucial link" between an "impending crisis" and "society". Sentinels are not only active observers of tipping points, but they also actively define the tipping points in SES as both are embedded in the social fabric.

Sentinels function in similar ways to an early warning system, defined by Choo (2009:1072) as "network of actors, practices, resources, and technologies that has the common goal of detecting and warning about an imminent threat so that preventive measures can be taken to control the threat or mitigate its harmful effects." The author points out that the detection of threats is often a

function of the expectations of the observer as well as cost and benefits of recognizing such threats. The problem resides in the perception of information by different observers who bring their own background and interests and have different interpretations of the threats.

As a process for gathering, analyzing and sharing information to identify threats before they become a hazard, four key elements for effective early warning system were identified and include: 1) knowledge of the relevant hazards and of the vulnerabilities of people and society to these hazards; 2) technical capacity to monitor threats, to forecast hazard evolution and issue warning; 3) the dissemination and communication of warnings that can be widely understood; 4) knowledge, plans, and capacities for timely and appropriate action by authorities and those at risk. Effective coordination and information flow across these four elements require the participation of many individuals and groups (Basher, 2006). Even though technology and scientific devices can collect, categorize, and process large quantity of data, such a large volume of data is problematic for their interpretation and timely reporting. On the other hand, observers' intuition, local knowledge, and experience are often very effective at seeing patterns in the data and interpreting their significance (Choo, 2009).

Establishing a stakeholder network to navigate a sentinel territory can, therefore, help answer questions such as: What is a tipping point in this particular SES? Can it cause cascading effects within the system? What are the vulnerabilities of this SES? The answers to these questions can then be used for decision making and for developing adaptation strategies to prevent cascading effect and devastating impacts on the provision of ecosystem services. Stakeholders' knowledge and variety of perspectives to define TPs is crucial to figure out management options to adapt to system shifts (Lauerburg et al., 2020; van Ginkel et al., 2022).

As Milkoreit et al. (2018) pointed out, social tipping points require different set of methodological approaches than climate or ecological regime shifts. Social systems are different from ecological systems and are characterized by phenomena such as power and inequality, agency, reflexivity, decision-making, and strategic behavior at both individual and collective scale. These characteristics make social regime shifts far less predictable than ecological ones. Changes in social systems, therefore, cannot be measured the same way and need a different set of methodological approaches (Milkoreit et al., 2018).

Building an on-the ground network of sentinels through the co-production of climate services is a promising approach to engage with stakeholders and foster partnerships between producers of climate information and users to create tailored information that can be used to reduce climate-related losses.

2.3 Climate services

Long-term climate change as well as extreme weather events such as increased risks of flood, drought, and wildfires present complex challenges for society and the agricultural sector in particular. Efforts to address such challenges need to go beyond the traditional modes of knowledge production and include socially engaged research processes to create “use-inspired” knowledge that is both useful for and usable by stakeholders and society at large (Kirchhoff et al., 2013). The field of climate services has been engaging with such efforts through intentional engagement between users and providers (Owen et al., 2019). Climate services is defined as the provision of climate information and knowledge that can be used in decision making to support adaptation and mitigation to climate-related risks at all levels of society (Brasseur and Gallardo, 2016; Hewitt and Stone, 2021). Climate services are particularly valuable in agriculture as climate variability is a constant challenge for producers who often make decisions prior to the growing season with the

assumption that certain climate conditions will occur (Born et al., 2021; Hansen et al., 2019). Climate services can also provide specific recommendations for the growing season such as planting dates, types of cultivars, or irrigation and fertilization schedules. In addition, longer scale forecasts and climate projections are useful for long-term decisions including future land acquisition, infrastructure investments such as irrigation for changing climatic conditions (Born et al., 2021). Climate services can provide crucial information about climate conditions and can be used for decision making when combined with users' knowledge of vulnerabilities and exposure to risks, helping the users to mitigate the risks or adapt to the new conditions (Hewitt and Stone, 2021).

The literature suggests, however, that climate information and services are still mostly being produced by the climate research community and remain disconnected from the needs of the users (Bojovic et al., 2021; Hewitt and Stone, 2021; Owen et al., 2019). In addition, climate science tends to produce data that is difficult to use, either because it is too technical and not comprehensible by non-scientists or because it does not correspond to the specific needs of the users. Thus, just providing climate services is not sufficient; these services need to be salient, credible, and legitimate (Cash et al., 2003; Brasseur and Gallardo, 2016) and need to be driven primarily by the needs and the capabilities of the users (Dilling and Lemos, 2011; Kirchhoff et al., 2013).

Therefore, efforts to increase interactions between climate information producers and users are necessary not only to improve the quality and relevance of such services but also to provide services that are aligned with what users need through interactions and iterative processes (Bojovic et al., 2021; Lourenço et al., 2016; Meadow et al., 2015; Vincent et al., 2018). Co-production has become a common approach in climate services (Bojovic et al., 2021; Meadow et al., 2015) because it is an effective way to produce tailored and targeted climate information through a deliberate

process of collaboration between climate scientists and users; such knowledge is more credible, salient, legitimate, and more likely to be accepted and used (Cash et al., 2003; Meadow et al., 2015).

Co-production is generally viewed as an interactive, collaborative, and iterative process that brings together a range of different knowledge sources to mutually define problems and develop usable products to address these problems (Bremer et al., 2019; Norström et al., 2020). There is a variety of definitions of the term co-production in the literature (Bremer et al., 2019; Jagannathan et al., 2020) and in the context of this study we use Norström et al. (2020:183) concise definition of co-production as an: “Iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context-specific knowledge and pathways towards a sustainable future”.

Co-production approaches produce more than just knowledge; they develop capacity-building, build networks, foster social capital, and trust, and ultimately implement actions to address the commonly identified problem. As a result, co-production is becoming a critical component of many environmental management processes, particularly within climate change adaptation policy, practice, and the development of climate services (Vincent et al., 2018).

Co-production, however, is an incremental process that is achieved through sustained collaboration which requires additional time and resources when compared to standard academic research (Brasseur and Gallardo, 2026; Jagannathan et al., 2020). In the context of this research, we use the term co-production of climate services because this project has not yet reached the stage of new knowledge co-generation. As Mach et al. (2020) pointed out, there are multiple forms of engaged research (Meadow et al., 2015; Cvitanovic et al., 2019) and it is the practice of engagement between science and stakeholders that seem to produce effective results and not any one particular research method.

3. Case Study: climate and viticulture in Arizona; building a sentinel network

3.1 Background

This case study describes the modes of engagement and the early stages of partnership building between researchers, Cooperative Extension, and wine-grape growers to engage in the co-production of climate service in the viticulture sector in Arizona. This climate service project highlights some of the challenges and opportunities in creating a new climate service network of researchers and stakeholders. The Climate and Viticulture project is the result of a research effort aimed at producing climate science for the viticulture industry in the region and providing information to help growers determine which wine grape varieties might be better suited for current and future climate conditions in Arizona. Different wine grapes varieties require different amounts of heat accumulation during the growing season to ripen fruits than do others. Grapes ripen under different conditions which can affect fruit quality.

There is a rich body of literature on stakeholder engagement and participatory approaches (Bojovic et al., 2021; Cvitanovic et al., 2019; Mach et al., 2020; Meadow et al., 2015; Vincent et al., 2018) and a variety of conceptual models of how climate services providers can structure their efforts around a collaborative model, beginning with identifying the actors and building partnerships and moving through a process of co-design and co-development to generate actionable knowledge through those collaboration. For this case study, our approach builds on the co-production for climate services framework proposed by Bojovic et al. (2021) where we emphasize the earliest steps of identifying potential social partners with whom to start the process of building partnership (Figure 1).

This study highlights: 1) the effort and approaches needed to identify potential partners; 2) the barriers in building and maintaining stakeholder networks; 3) the importance of collaboration,

trust, and relationship building between producers of climate information and users; and 4) the potential for the process of climate service co-production for building a network of stakeholders that can function as sentinels to identify the threats of climate-induced tipping points and develop actions to mitigate their harmful effects.

3.2 Building the network

The wine industry in Arizona has grown rapidly over the last decade, both in the number and size of vineyards as well as the number of businesses involved in winemaking with an overall contribution of \$133 million to the state economy. Since 2012, statewide grape acreage as well as the number of wineries has nearly doubled and estimates of economic activities directly associated with wine grape growing, winemaking and wine sales in 2019 are around \$59.8 million (Bickel et al., 2021). By 2019 there were 125 bonded wine producers in Arizona. Growing grapes and producing wine contribute to local economies, generating economic activity and supporting jobs and income not only in the wine industry but also in other businesses directly and indirectly linked to the wine industry. Wineries play a particularly important economic role in rural areas of the state because the sales they generate often bring money into the local economy from out-of-town visitors (Bickel et al., 2021). Growing grapes in this region, however, is becoming challenging because of climate change. Projected hotter temperatures will most likely increase the duration and severity of droughts and generate an overall drier regional climate (Gonzalez et al., 2018). As temperatures continue to trend higher, wine grape growers in warm-climate viticultural regions will increasingly be challenged by the many effects that temperature has on fruit composition. Warmer ripening conditions in recent years for such growing regions around the world have resulted in higher sugar concentrations, less acidity, higher pH, and changes in aromatic and phenolic compounds. Precipitation during ripening additionally can influence wine grape composition by interacting with effects caused by temperature.

3.2.1 Identifying potential social partners

The initial goal of the Climate and Viticulture project was to identify grape-growing areas in the context of historical and potential future climate variability and change for the relatively young but expanding wine industry in Arizona. One of the first steps in facilitating access to climate data is raising awareness about existing initiatives or projects.

The first attempt to connect with growers came during the 2017 Arizona Grape Growers Symposium, an annual meeting of growers, researchers, Cooperative Extension scientists, and industry representatives where we presented climate information and its implications for cultivating wine grapes in Arizona. After the symposium, the team was able to engage with only a few growers and it became clear that this project was going to take some time and more resources to develop and further engage with grape growers.

3.2.2 Engagement through communication

The following year (2018), the project team led by the Cooperative Extension climate scientist, was again invited to present at the Annual Grape Grower symposium. In addition to the presentation, the interdisciplinary team displayed a poster series of maps depicting different environmental aspects, in addition to climate, of the Sonoita and Wilcox American Viticulture Area (AVAs) in southeastern Arizona³, where most of the wine grape production is located. After the apparent lack of interest in the previous year, the team decided to find more engaging ways to connect with the growers. Using the maps, we conducted an interactive survey in which the growers were asked to locate their vineyards, list grape varieties they grow, and mention any vine phenology-related issues they have experienced, with an emphasis on weather and climate events. The team

³ <https://cals.arizona.edu/research/climategem/content/arizona-avas>

collected the names and contact information of the people who participated in the interactive survey and added them to the existing contact list.

3.2.3 Involvement and knowledge exchange through various participatory activities

This phase of engagement aimed at deepening our understanding of grape growers' needs, perceptions, and concerns through a series of more intensive exchanges where knowledge exchange can occur.

The 2018 symposium became the starting point for a series of introductions and engagement opportunities to meet with growers and other actors in the viticulture industry. At the symposium, the team met the vineyard manager for Yavapai College (YC), located in the Verde Valley AVA⁴ northcentral Arizona. YC offers a viticulture and enology degree program. This meeting led to an invitation to hold a “climate and viticulture exchange” that summer with YC faculty, staff, current and former students, regional producers, and others in the industry. The team used maps similar to those produced for the symposium and a survey of growers' weather, climate, and other industry concerns as a frame to start the open discussion. Attendees brought up many examples of their experiences, information needs, desired products, and climate-related questions such as the effect of diurnal temperature range during the ripening period of grapes.

The interactions between the team and the growers helped structure the 2019 Arizona Wine Grape Growers' Symposium presentation around weather and climate topics that are of concerns to the growers such as their interest in reliable, local weather forecasts, impacts of late frost on vine phenology, and impacts of delayed North American Monsoon.

⁴ <https://cals.arizona.edu/research/climategem/content/verde-valley-ava>

The 2018 symposium and the YC exchange led to invitations to visit vineyards in the state. These one-on-one conversations provided the team with opportunities to learn more about how producers manage their vineyards, which grape varieties they grow, and which weather events are of the greatest concern to them. These interactions not only provided the team with new insights into growers' decision-making, needs and concerns, but it also fostered trust between growers and the team.

One of the main take-away from these symposia and vineyard visits is that growers are keenly aware that climate variability poses a threat to their industry. They are very aware that cooler- or warmer-than-normal spring temperatures essentially set the stage for when most vine growth stages occur throughout the year and that extreme weather events can greatly affect these stages. For example, late spring frost can kill berries and greatly decrease yields. They also observed that in years when late spring frost is combined with above-average August temperatures it can create vineyard traffic jam because all the varieties ripen at the same time and all are ready to be harvested in a shorter harvest season which can become difficult to manage because of lack of seasonal workers to harvest, lack of room to store grapes, and other issues. They also noticed that cool temperatures in the spring delay the timing of growth stages from bud break through harvest and that above-than-average precipitation limits the amount of irrigation needed. On the other hand, a lack of precipitation and above-than-average temperatures increase the need for irrigation which increases ground water stress. Growers' knowledge and experience also help them navigate the cascading effects produced by a wet monsoon season which coincides with the ripening and harvest periods in Arizona including vineyard management and organization of harvest before vine rot settles in the vineyard. Growers have noticed that berry shrivel is becoming common during warmer-than-average summers. With the increasing frequency of hot-and-dry conditions its impact includes increased chances of reduced yields and effects on berry composition.

Discussions about the possibility of a weak-to-moderate El Niño event in late 2018 (and possibly for cooler temperatures and above-average precipitations during the winter and spring in Arizona) presented a new opportunity to engage with wine grape growers. After discussions with the growers on how to provide them with timely and pertinent climate information, a fact sheet⁵ about the El Niño event was produced and sent to the growers with requests for feedback on the utility of such product and their interest receiving one. Based on the positive growers' response, the team launched a monthly climate and viticulture newsletter⁶. The newsletter provides a review of recent temperature and precipitation conditions and an outlook for the coming month and highlights season, special topics, and what they might mean for vineyards in the state. During these events, several discussions between the team and the growers took place about the possibility of developing an annual forum for people in the industry to share experiences from the previous growing season. The first round of *Growing Season in Review* workshops took place in the fall of 2019, after the summer harvest; one is southeastern Arizona and the other one in northcentral Arizona, the two main growing areas of the state. The workshops were designed to be highly interactive by structuring conversation around several topics related to the 2019 growing season and encouraging discussion and comparison among the growers: timing of growth stages, weather events, and occurrences of pests and diseases, and how these events or issues affected vineyards. In addition, discussions were centered around comparing the 2019 and 2018 seasons, and as an example, which varieties had done well or poorly that season. Participants contributed their observations by placing sticky notes on a large prepared growing season timeline poster. This format allowed the participants to connect their timeline entries between activities and compare their experiences to those of others. Combining

⁵<https://cals.arizona.edu/research/climategem/sites/cals.arizona.edu.research.climategem/files/ENwatch20182019overview.pdf>

⁶ <https://cals.arizona.edu/research/climategem/content/climate-viticulture-newsletter>

timeline information from both workshops, we produced a review of the 2019 wine grape growing season in Arizona⁷ that was sent to all the participants and highlighted in the monthly newsletter.

The 2020 and 2021 Arizona Wine Grape Growers' symposia were cancelled because of the Covid-19 global pandemic. In the Fall of 2022, we held two *Growing Season in Review* workshops following the same format.

Although the workshops topics deviated somewhat from the science questions in the original project proposal, they reflected the priorities and concerns of the wine grape growers and provided opportunities to learn more about weather and climate issues of concern to them as well as share key weather and climate information (particularly climate projections for the region). These workshops contributed to the expansion and strengthening of our wine grape-grower network and helped create a relationship based on trust.

In addition, these workshops provided the opportunity for growers to exchange information and experience and build their technical capacities to monitor the effects of extreme weather events. Discussions during the workshops provided insights into how hot-and-dry and wet conditions during the grape ripening and harvest periods affected wine grapes growing in their areas. High temperatures can slow or even shut down vine photosynthesis and slow growth stage progress. Grapes can shrivel under extreme temperatures which can result in yield loss and affect berry composition. Growers noted that in 2020 hot and dry conditions compressed the ripening season and harvest dates occurred earlier. The month of August is when the ripening and harvest periods at many locations in Arizona line up with the North American monsoon season. In 2021, the monsoon hit a near-record- to record-high precipitations and harvest started early and had to be finished

⁷ <https://cals.arizona.edu/research/climategem/sites/cals.arizona.edu.research.climategem/files/growing-season-in-review-2019-workshop-synthesis-final.pdf>

quickly because of early fungus bunch rot affecting the grapes that could lead to crop loss. Growers shared that their experience with these two extreme weather conditions will help them to prepare for future extreme weather events.

Toward the end of the funding available for the Climate and Viticulture project, we reached out to all the growers and other actors in this industry who attended our workshops and received our newsletter for feedback (in the form of a survey) on the project and asked the whole community for input of whether and how they would like to engage with the University of Arizona and Cooperative Extension in the future. Feedback from the participants indicated that the workshops were valuable to the growers because they offered the opportunity to hear from fellow growers. Conversations additionally helped put into broader context not only a challenging season but also different locations of and management approaches to vineyards. Looking ahead to future collaborations, survey respondents were asked to select topics for future research. The most common topics were sustaining and enhancing soil health, conducting additional “growing season review’ workshops, examining current weather impacts on viticulture, and better understanding climate change impacts on the future of viticulture in the region. Respondents also indicated that the newsletters and a website would be helpful modes of engagement but also expressed interest in group workshops and other small meetings around specific topics. Growers expressed particular interest in attending workshops which give them an opportunity to get together and exchange information about their experiences, setbacks, and successes during the growing season.

Although this first phase of the Climate and Viticulture project is ending, the monthly newsletter continues to be produced and Cooperative Extension researchers continue to regularly engage with growers and other actors in the wine industry.

3.2.4 Co-production of knowledge through focused relationships

Through our interactions it became clear that some growers wanted to be more involved in exploring specific climate topics and identifying possible solutions to their particular issues. Bojovic et al. (2021) refers to this type of stakeholders as “champion-users” who seek more in-depth interactions to co-develop tailored and usable climate information. Long-term engagement through regular and diverse types of interactions is essential for true co-production of knowledge to occur (Jagannathan et al., 2020). Ultimately co-production should result in increasing utilization of knowledge in planning, increasing understanding of climate issues, strengthening communities through capacity building and trust, and pushing action for climate adaptation. The Climate and Viticulture project, however, has not yet reached that phase as it will take more time and resources to achieve.

We continue, however, to explore ways to strengthen the viticulture network as well as the connections between the University of Arizona, Cooperative Extension, and the expanding Arizona wine grape-growing industry, both in terms of numbers of connections and quality of partnerships. By continuing to engage with the grape growers’ multiple times and in multiple ways, the research team seeks to help growers clarify and refine their questions, information needs, and interests. This step in the engagement process can be referred as empowerment as it can lead to transformative learning and help develop new capacities such as new means to share information and raising awareness within the collaborators’ networks (Bojovic et al., 2021). Building users’ networks, however, rests on repeated participatory activities over a certain period, which requires additional time and resources than what is usually provided by traditional academic funding structure. The cost of travel and accommodation associated with building relationships in person, cost of organizing workshops and meetings, and cost of producing presentation materials might be difficult to justify to funders. Building and maintaining a network also takes more time. For example, for the Climate and Viticulture project, the first indicators of a solidifying relationship and emergence of a network

started around the 18-month mark when connections between the research team and the growers began to intensify both in their numbers and intensity. The Climate and Viticulture project was funded by two different grants when two research teams merged at the beginning of the project which allowed numerous engagement activities to take place.

Even though the Climate Viticulture project is still in the early stages of engagement, our approach emphasizes the deliberate collaboration between science and stakeholders with different perspectives, knowledge, and expertise to achieve a common goal that follows the four general principles proposed by Norström et al. (2020) that contribute to a high level of co-production: 1) *Context based*: Our process of co-production of climate services is context-specific as it contributes to produce climate information with the wine-grape growers of central and southern Arizona; 2) *Pluralistic*: The climate viticulture project is pluralistic and inclusive as it includes everyone interested in participating in the project and anyone concerned with the effects of climate change in the viticulture industry including grape growers (established or new ones), students, faculty, extension agents, and other actors in this industry; 3) *Goal oriented*: the main goal at the onset of the project was to provide targeted climate information for wine grape growers and as the project progressed the goals were refined to address the growers' needs for particular climate information such as risks of late frost or the role that diurnal temperature range plays during the ripening season; and 4) *Interactive*: The project is interactive with active engagement and frequent interactions among actors through the various presentations at symposia, dedicated workshops, one-on-one vineyard visits, and the monthly newsletter. The ongoing dialogue among the various actors of this project helps build trust and makes the knowledge produced meet the specific needs of the grape growers. In turn, this knowledge is more likely to be incorporated in their decision-making regarding the management of their vineyards in the context of climate change.

3.3 Network building and Sentinel functions

Building an on-the ground network through the co-production of climate services is a promising approach to create a network of stakeholders that can function as sentinels to respond to the threats of climate induced tipping points. Through their engagements with the Climate and Viticulture project, grape growers have demonstrated that they are not only aware that their vineyards are threatened by climate change but that sharing information about their individual experience can help built capacity to monitor such threats.

Grape growers are in essence becoming sentinels of their “territory” to effectively fulfill the characteristics of an early warning system (Figure 2). By their active observations, intuition, knowledge, and varied perspectives and experiences, sentinels can be very effective at identifying and interpreting tipping points (Choo, 2009). In addition, sentinels, through their network, can motivate a range of stakeholders to take action to prevent a potential crisis or adapt to system shifts (Lauerburg et al., 2020; van Ginkel et al., 2022).

Sentinels function within a territory in similar ways to an early warning system (Blanchon et al., 2020; Choo, 2009) which is characterized by four key elements including: 1) knowledge of the threats and vulnerabilities of people and the environment to these threats; 2) technical capacity to monitor threats, forecast threat evolution and communicate warning; 3) communicate and disseminate warnings that can be widely understood; and 4) form a community around a shared sense of place and with a common goal of warning about an eminent threat and take preventive measures to mitigate its harmful effects.

These characteristics started to take shape through the various engagement activities of the Climate and Viticulture project and continue to develop through the ongoing engagements between the grape growers and Cooperative Extension researchers.

1) Knowledge of the threats and vulnerabilities of people and the environment to these threats.

By regularly engaging with growers, their concerns, and observations about temperatures during the growing season, timing of spring frost or onset of monsoon became a starting point to discuss vulnerabilities of their vineyards and consequences such as low yields and poor fruit quality. During our interactions with the growers, it became clear that they have an intimate knowledge of how climate variability and extreme weather events are affecting their grape vines. For example, during the “Growing season in review” workshops, attendees brought up many examples of their experiences and knowledge about the effects of weather events and climate on their vineyards, but they also shared their information needs, and desired products such as effects of diurnal temperature range during the ripening period for grapes, impacts of late frost on vine phenology, and impacts of delayed monsoon.

2) Technical capacity to monitor threats, forecast hazard evolution and communicate warning.

Between the 2020 and 2021 growing seasons, grape growers had to face some uncharted territory compared to previous years. July and August 2020 were near-record to-record hot and dry conditions while in July and August 2021 many locations experienced near record-to-record wet conditions. These extreme weather events led to intensified impacts on the vineyards and posed novel challenges for the growers. They expressed the belief that the experience gained during these two extreme weather conditions will be particularly valuable as they will face a more variable and extreme summer climate that is anticipated for the Southwest region in coming years.

One of the efforts of the Climate and Viticulture project was to provide information to determine which wine grape varieties might be better suited for current and future climate conditions in Arizona. Different wine grape varieties require different amounts of heat accumulation

during the growing season to ripen fruit than do others. Grapes ripen under different conditions which can affect fruit quality.

Increasing the technical capacity of grape growers to monitor and respond to threat through the continued engagement with Cooperative Extension researchers is one of the steps that needs to be further explored in the coming years to strengthen the capabilities of the sentinel' network.

3) Communicate and disseminate warnings that can be widely understood.

One of the characteristics of sentinels is the ability to communicate and disseminate warnings about incoming threats. The highly interactive “Growing season in review” workshops offer the opportunity for grape growers to share their observations on growth-stage timing, weather events, occurrences of pests and diseases, and other issues as well as discussing impacts and responses in vineyards. These workshops also allow growers to compare characteristics and events of the current growing season to the previous one and receive feedback from Cooperative Extension researchers. The workshops fill a need expressed by many grape growers to meet after harvest and discuss conditions and events of the growing season, share what went well and what did not, and share how they dealt with the challenges or took advantage of opportunities. This is a venue for information exchange and feedback and a synthesis of each workshop is then produced and sent to all the growers (participants and non-participants) in the monthly newsletter.

In addition, growers, particularly the champion-users, are in regular communication with Cooperative Extension researchers and can quickly share with them any urgent issues or events occurring in the vineyards. In turn, Cooperative extension researchers can post the information on their website⁸ to quickly disseminate it.

⁸ <https://cals.arizona.edu/research/climategem/content/home>

- 4) A community is formed around a shared sense of place and with a common goal of warning about an imminent threat and taking preventive measures to mitigate its harmful effects.

This nascent community of sentinels started with the participation of growers in the Climate and Viticulture project and continues to develop through the process of co-production of climate services with Cooperative Extension researchers. For the community to fully function as sentinels of their territory, it will take more time and more resources, including more regular and extended periods of engagements with Cooperative Extension researchers as well as more diversify types of engagements (Jagannathan et al., 2020).

Continued collaboration between the grape growers and Cooperative Extension researchers aims at exploring topics such as how temperature and precipitation in the late vine phenology affect fruit quality for a given vintage, and how having early and late varieties in the vineyard can help hedge any negative effects at harvest time.

One of the characteristics of the nascent grape grower community is that through its interactions with the Climate and Viticulture project it has demonstrated greater awareness and understanding of the role of weather and climate for their vineyards and what weather and climate information is available and how that information could be useful. For example, Cooperative Extension researchers received inquiries from growers about how climate change is affecting the North American Monsoon that brings approximately 50% of Arizona's annual precipitation in the summer months, heat stress on vines like the one experienced during the record-breaking heat of summer 2020, and the availability of seasonal forecasts for the region. The process of providing some baseline climate data to the community and then adapting and responding to new questions from the community is helping growers frame what tipping points are and how they can threaten grape growing areas of Arizona.

Building an on-the-ground network of stakeholders that can fulfill sentinel functions is an essential step towards assessing and warning against the threats of SETPs. Even these early stages of engagement have been valuable in developing sentinel functions. Growers have expressed an increasing awareness of weather and climate conditions and their effects on vineyards as well as improved technical capacity to monitor and communicate threats. The ongoing engagement between the growers and researchers is helping build trust and make the climate information produced more specific to the growers' needs and therefore more usable. However, more work is needed to define what tipping points are in this context and the scale of inquiry in order to develop appropriate adaptation strategies to a projected hotter and dryer climate in Arizona.

4. Discussion

Climate-induced SETPs are context specific and most easily identified at the local level as they usually have greater impacts on local communities (van Ginkel et al., 2020). Therefore, stakeholders' perception plays a crucial role in identifying and assessing socio-economic vulnerabilities to tipping points (van Ginkel et al., 2018; Berrouet et al., 2018). Building a network of stakeholders that acts as sentinels or early warning systems is key to identify threats to the socio-economic system and develop actions to mitigate its harmful effects. The viticulture network was built through the process of co-production of climate services because it is one of the most effective ways to connect climate science to decision-makers to generate salient, credible, legitimate, and actionable knowledge (Cash et al., 2003) as it involves the direct and ongoing engagement between researchers and social partners. The inclusion of a variety of stakeholders with different backgrounds, knowledge, and experiences is a key element for assessing the vulnerabilities of socio-ecological systems to tipping points (Lauerburg et al., 2020).

Co-production approaches produce more than just knowledge; they contribute to developing capacity-building, networks building, fostering social capital, and trust, and ultimately help develop actions to address the commonly identified problem (Cvitanovic et al., 2019; Mach et al., 2020; Norström et al., 2020).

Through our case study we describe the steps taken to build such a network and how through these steps a burgeoning community of sentinels started to take shape. Engaged research, however, is not without challenges and barriers in building and maintaining such networks because it is a process that takes additional time, energy, and funds.

4.1 Building networks takes time and resources

Publicly funded research projects that aim at providing salient and usable climate knowledge and services continue to face challenges in moving away from a traditional linear knowledge production and understanding the process of user engagement through participatory research. These projects are often constrained by the requirement to define tasks and activities, including user engagement plans, before the project can be approved. Time and resources available for such engagement are typically limited.

A growing body of literature shows that the amount, timing, and type of interactions influence the quality of co-production outcomes (Dilling and Lemos 2011; Sarkki et al., 2015). Building a network of societal partners requires more time and resources than standard academic research (Brasseur and Gallardo, 2016). This type of research, where intense and repeated engagements are at the core of the research process, requires a lot of resources and support particularly when trying to maintain it past a particular project period (Mach et al., 2020). The process of building and maintaining networks is not compatible with the current funding structure for most academic projects which function on limited time frame. And once a network of social

partners is established and the project reaches its ends, how can such networks be maintained long-term to act as sentinels? The Climate and Viticulture project is able to maintain its engagement with the various actors in this industry because it is part of a larger Cooperative Extension program that works with the grape growers of Arizona; as such, it is not completely limited by a specific funding cycle.

The wine industry is becoming a growing economic force in Arizona; therefore, it is important to have such a functioning network of sentinels that can identify and raise alert when problems arise to prevent climate induced SETPs. Building sentinel networks is only the first step in monitoring tipping points. Maintaining such networks requires support from research and governmental institutions, researchers, the wine industry, and societal partners.

4.2 Need for an interdisciplinary team

Collaborative research demands specific skills to ensure that the research is being conducted with the necessary skills and training needed to undertake such efforts. In addition, the interconnected nature of socio-ecological systems requires an interdisciplinary team that includes social scientists who have the expertise and training in understanding and contextualizing stakeholders' concerns, needs, and specific interests and an understanding of the complexities of engaging and communicating with stakeholders in order to engage in the co-production research process (Mach et al., 2020; Rozance et al., 2020).

At the onset of the co-production process, scientists need to reach out and choose stakeholders whose perspectives are relevant to the research context and need to ensure that there is a balanced representation of all stakeholder groups (Cvitanovic et al., 2020). Once chosen, the scientists need to listen and discuss interests and expectations of all the stakeholders while identifying the research questions together. The ability to understand and navigate power imbalance

between individuals and between types of knowledge is key to prevent “biased” research results and which stakeholder groups are more at risk (Reed et al., 2017).

Social scientists recognize the importance of integrating different kinds of knowledge into the decision-making process. The inclusion of local knowledge is key to engaging appropriately with local stakeholders to develop specific solutions faced by the community (Cvitanovic et al., 2019). Research shows that the ability to integrate different knowledge systems through participatory research helps generate innovation and inclusive solutions as well as building trust in the process (Mauser et al., 2013).

4.3 Next Steps

Building networks of users of climate science is one of the most effective ways to not only help identify threats and potential thresholds indication of SETPs but also investigate their causal mechanisms and find adaptive solutions. The next step for this project is to build on the existing relationship with the grape growers to start defining tipping points and their impacts on the socio-economic system of the wine industry in this region.

For the Climate and Viticulture project, the ongoing interactions, and the close collaboration between the network of grape growers and Cooperative Extension researchers offer an ideal starting point for investigating the SETPs of this small-scale system (i.e., vineyards located in a specific area). The knowledge and experience of grape growers is fundamental to understanding the scale, mechanisms, and abruptness of the changes in the socio-ecological system.

Defining tipping points, however, is not a straightforward task and presents some challenges. We anticipate that different stakeholders, in this case wine grape growers, have different ways of framing and defining what tipping points are, where they occur, and how to identify them. For example, how would individual grape grower define maximum temperature limits to decide to

switch cultivars or how many consecutive unprofitable years would be considered a tipping point to abandon wine grape growing and switch economic activity?

Some stakeholders might oppose the idea of tipping points all together or not see them as an immediate problem. Some might see small scale problems but do not consider them real tipping points that will negatively affect their vineyards. Tipping point is still a vague and subjective concept that is difficult to convey, unless the researchers can show a clear example of what caused it, its mechanisms, and ultimately its consequences.

To agree on what a tipping point is, the research team and the grape growers would need to first define the scale of their inquiry. Are they just going to look at individual vineyards or the whole region? Then they need to discuss the possible mechanisms (climate but also social, institutional, political that enhance or erodes the resilience of a system) causing the tipping points, including cascading effects (increasing heat leads to poor yield and grape quality, which leads to poor quality wine, and eventually a year of extremely low quantity and low quality of wine produced). Another important factor to consider is the abruptness (sudden or gradual) of the events that caused the tipping point such as a gradual lack of groundwater availability for irrigation, or a sudden pest infestation. It is also important to consider questions such as: If the change is too abrupt, will there be time to adapt? Increasing temperatures is a gradual process occurring over many years, which gives time to adapt by planting grape varieties adapted to hot conditions or adopting different canopy management techniques to better shade the grapes. The last point to consider is whether the tipping point is serious enough to cause harm to the business and livelihoods of the growers.

The concept of tipping points combined with the existence of a network of agricultural stakeholders would give a new avenue of research to help find better management strategies to adapt to a shifting socio-ecological system.

5. Conclusion

Direct and ongoing engagement between researchers and societal partners is critical to help identify SETPs and generate actionable knowledge through the process of co-production. The co-production of climate services is one of the most effective ways to foster partnerships between producers and users of climate information to develop tailored information that can be used to reduce climate-related losses. Building connections and networks based on trust is necessary to ensure that the research is context-specific and responsive to the needs and interests of the societal partners (Mach et al., 2020; Norström et al., 2020). With the Climate and Viticulture project we described the early stages of partnership with the wine-grape growers of Arizona to build and maintain a stakeholder network. Intentionally building an on-the ground stakeholder network through the process of co-production of climate services helped create the conditions for the stakeholders to take on the functions of sentinels to monitor and respond to the threats of climate-induced tipping points.

The incremental nature of building, maintaining, and deepening the engagement between the scientific team and stakeholders to develop a sentinel network takes time and resources, which is often overlooked in project planning and funding. Standard academic research with its linear models of knowledge transfer and its funding structure is not well adapted for engaged modes of research needed to build networks of societal partners and connecting climate science to decision-making. Despite the barriers and challenges of engaged research more of this kind of work is needed if we want robust responses to tipping points through early warnings.

As the Climate Viticulture project illustrates, the need for establishing a sentinel network that can act as an early warning system is high. As temperatures continue to trend higher, wine grape growers in warm-climate viticultural regions like Arizona will increasingly be challenged by the many

effects that temperature has on fruit composition and subsequent wine quality, threatening this industry until it reaches a tipping point.

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FIGURES

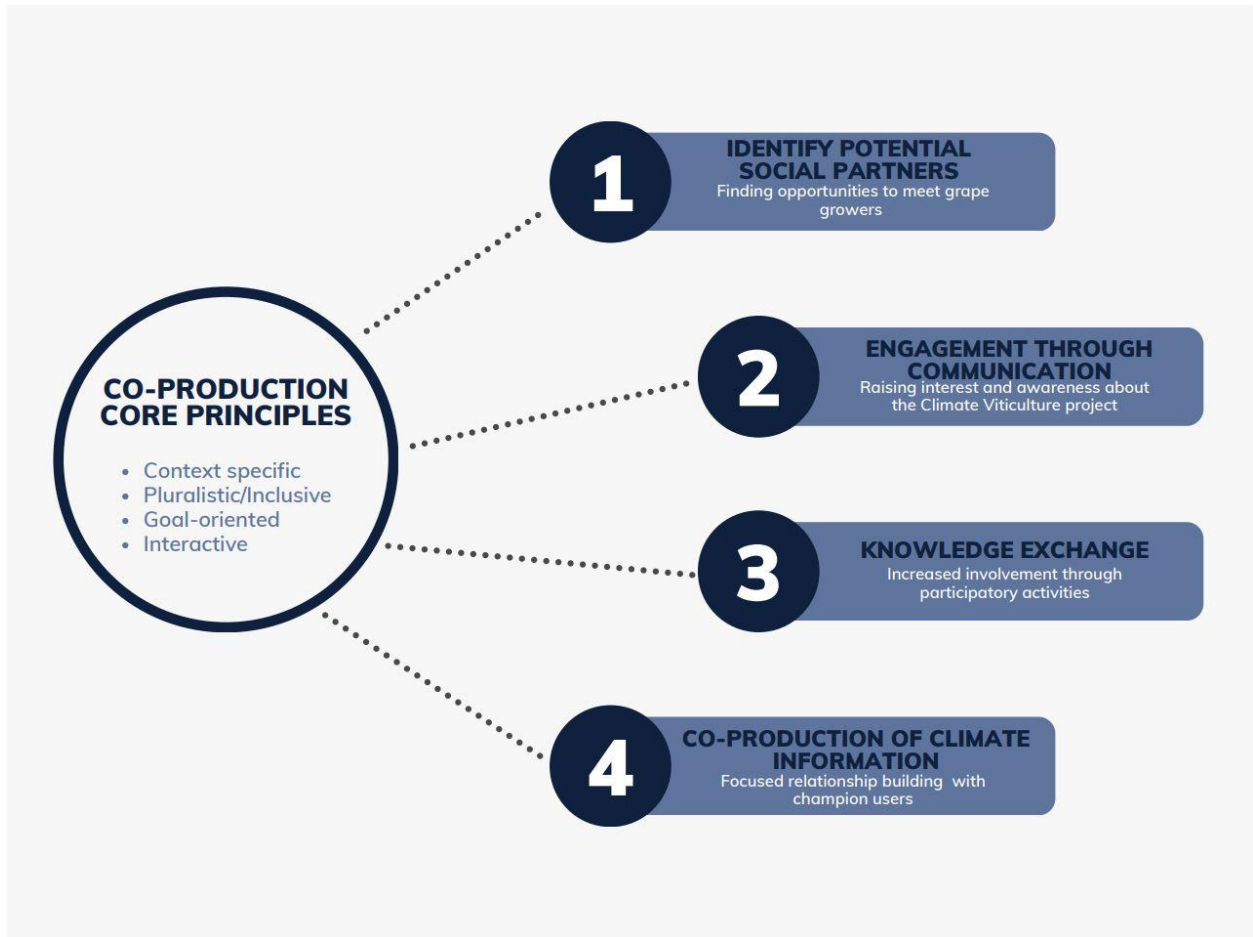


Figure 11. Stages of partnership building for the Climate and Viticulture project. This approach rests on the four principles of knowledge co-production proposed by Norström et al. (2020) and builds on the co-production framework for climate services presented in Bojovic et al. (2021: Figure 1).

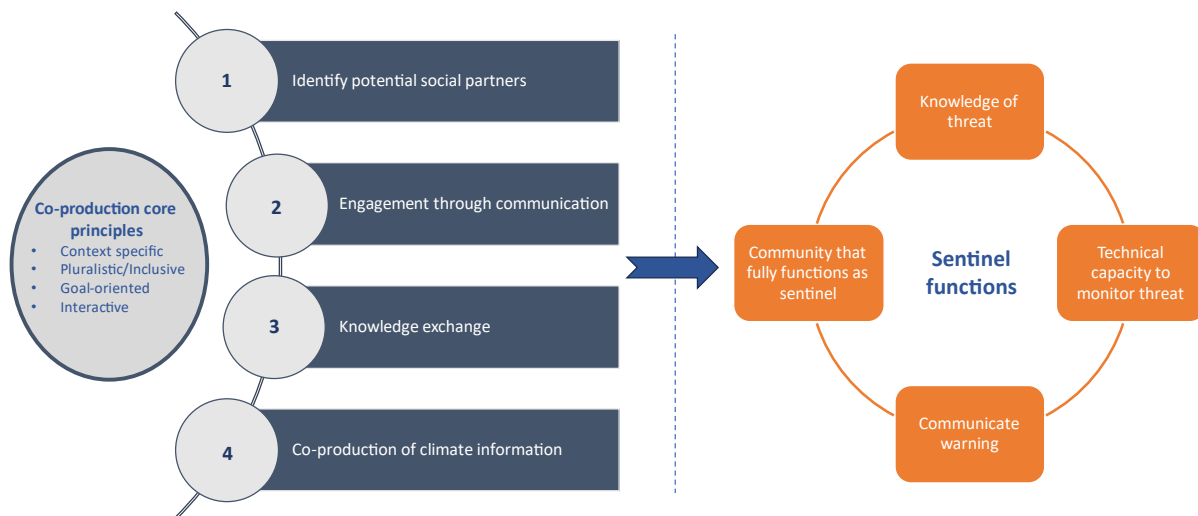


Figure 12. Sentinel functions developed through the process of co-production of climate services of the Climate and Viticulture project.