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Carbon farming in Africa: Opportunities and challenges for engaging smallholder farmers

Friederike Schilling, Heike Baumüller, Julius Ecuru, Joachim von Braun

Abstract

The Intergovernmental Panel on Climate Change (IPCC) highlights the importance of reaching net-zero CO_2 emissions globally by 2050. Unlocking the potential of natural climate solutions in the strive for net-zero emissions is increasingly gaining attention. A large potential may arise from the adoption of agricultural practices that increase carbon sequestration in soils and plants and reduce or avoid greenhouse gas (GHG) emissions in agricultural production, referred to as carbon farming. In practice, existing markets fail to internalize environmental externalities, creating a mismatch between individual costs and societal benefits of carbon farming. One solution to bridge this gap are payments linked to the implementation of carbon farming practices. To support the development of well-functioning agricultural carbon markets, supporting research is crucial. We assessed the opportunities and challenges for involving smallholder farmers in emerging agricultural carbon markets. We placed a specific emphasis on summarizing the state of knowledge in four areas: i) agricultural markets as a funding institution for carbon farming, ii) the role of payments for carbon sequestration in incentivizing the adoption of carbon farming practices, iii) the scaling of smallholder farmers' opportunities in carbon farming by capitalizing on farming groups, and iv) the cost-effective monitoring, reporting and verification of changes in carbon stocks. Further research that supports the accurate and cost-effective monitoring of carbon sequestration, reduction and avoidance of GHG emissions as well as implementation research that focuses on the institutional arrangements required to tap potentials for carbon credits to promote sustainable production methods in Africa will be needed.

Keywords: carbon farming, carbon sequestration, carbon markets, payment for ecosystem services, sustainable agriculture

JEL codes: H23, O13, Q10, Q20, Q56, Q57

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) highlights the importance of reaching net-zero CO_2 emissions globally by 2050. Unlocking the potential of natural climate solutions that increase carbon storage or avoid and reduce greenhouse gas (GHG) emissions - like the protection, improved management, and restoration of forests, wetlands, and agriculture and grassland - in the strive for net-zero emissions is increasingly gaining attention (Griscom et al., 2017; Seddon et al., 2020, 2021). It is estimated that natural climate solutions can cost-effectively provide 37% of CO_2 mitigation required for a chance of holding warming to below 2°C through 2030 (Griscom et al., 2017).

The mitigation potential of agriculture and grassland pathways deserves special attention due to the nexus between climate change and food systems. The global food system is not only vulnerable to climate change because of its dependence on climatic conditions (IPCC, 2019), but also contributes significantly to it. Global food systems are responsible for approximately one-third of anthropogenic GHG emissions (Crippa et al., 2021). At the same time, grassland and agriculture pathways may comprise one-fifth of the climate mitigation potential from natural climate solutions (Griscom et al., 2017). The estimates are derived from existing studies and extrapolated to a global scale. While this exercise may be useful in identifying priority pathways and practices, the effect sizes are subject to considerable uncertainty as demonstrated by large confidence intervals. Further, adding estimates from independent studies may bear the risk of overestimating the total mitigation potential due to neglect of potential market interactions (Griscom et al., 2017; Ohrel, 2019).

While the topic is comparatively new on international climate agendas, the importance of soil organic carbon (SOC) as a key indicator of soil quality and, consequently, food security has been long recognized (Lal, 2004; Reeves, 1997). SOC improves soil fertility resulting in increased productivity and yields (FAO, 2019). Restoring the productivity of degraded agricultural land through agricultural practices that increase SOC is, hence, an important political objective for both climate change mitigation and food security (Ewing et al., 2021), supporting the productivity and long-term sustainability of agricultural production. Carbon farming concepts can draw on the developed concepts of climate-smart agriculture (CSA) and payment for environmental services (PES), as we elaborate on in section 2.

As there is no one-size-fits-all approach to the restoration of SOC, Lal et al. (2018) recommend the adoption of context-specific best agricultural management practices. Emphasized are system-based conservation agriculture approaches, such as agroforestry. Other practices include cover crops, improved crop rotations, reduced tillage, retaining of crop residues, the addition of biochar, and manure management (Lamanna et al., 2020). These practices that improve the rate at which CO_2 is removed from the atmosphere and transformed into plant material and/ or soil organic matter are in recent debates referred to as carbon farming practices (Mcdonald et al., 2021).

Beyond the generally acknowledged productivity benefits associated with increases in SOC, co-benefits of carbon farming relate to improved resilience to water shortages through water and soil conservation, reduction of economic risks through input saving, and resilience to extreme temperatures through agroforestry (Wollenberg et al., 2021). Further, farmers may benefit from new products, such as building materials or fruits from agroforestry, and increased resilience to climate change, resulting, e.g., from shelter from trees or diversification (Engel & Muller, 2016). In addition to the direct benefits, farmers across the globe can, through the adoption of carbon farming practices, play an important role in mitigating and adapting to climate change and contributing to more sustainable, resilient, and productive food systems. However, smallholder farmers oftentimes lack the financial means to invest in carbon farming practices and thereby capitalize on related opportunities and existing markets fail to internalize environmental externalities (Adhikari & Boag, 2013; Bellver-Domingo et al., 2016; Engel et al., 2008; Hendriks et al., 2023), creating a mismatch between individual costs and societal benefits of carbon farming. Smallholder farmers in Africa are often faced with limited resources, a lack of access to markets, and inadequate support from local and national governments

(Streck et al., 2012). These challenges further limit their ability to adopt and benefit from carbon farming practices, leading to a missed opportunity for them to contribute to climate change mitigation and to improve their livelihoods.

To encourage investment and reduce financial barriers to adoption, schemes that pay farmers for carbon sequestration and reductions and avoidance of GHG emissions provide an important opportunity for scaling climate action (Jackson Hammond et al., 2021; Lal, 2013; Lal et al., 2018; von Braun et al., 2021). With limited public funding, emerging agricultural carbon markets could be a possible tool to leverage private capital for transforming the agricultural system towards more adaptive trajectories (Benessaiah, 2012; PwC, 2011). Carbon markets offer a framework that facilitates trading between buyers and sellers of GHG reductions, avoidance, or carbon sequestration in the form of certificates or credits. Carbon market platforms could provide farmers with opportunities to generate and sell carbon credits based on the amount of carbon sequestered or on the level of reduced or avoided GHG emissions. These credits can then be purchased by companies, governments, and other entities to offset their GHG emissions. The level and stability of carbon prices are critical for this to work.

Despite the opportunities related to carbon farming practices and agricultural carbon markets in the transformation of global food systems, their development is at an early stage. Concerns exist about the non-permanence, i.e., the release of previously sequestered carbon negating some of the benefits, and additionality, i.e., determining whether the benefit would have arisen anyway (Smith et al., 2014). For agricultural carbon markets to work, rigorous methodologies and the accurate measurement and monitoring of changes in carbon stocks, including reduced and avoided GHG emissions, are key (Conant et al., 2011). The trading of low-quality credits may result in questioning of the market reliability, undermining the trust in the integrity of the market and potentially leading to a collapse of the incentive structure (Jackson Hammond et al., 2021; Oldfield et al., 2022). The recent debate on the systematic overvaluation of carbon credits issued for avoided deforestation has shown the need for sound, scientifically based methodologies (Fischer & Knuth, 2023).

For the development of well-functioning agricultural carbon markets, context-specific supporting implementation research is crucial. With this paper, we aim to direct the attention of researchers, policymakers, development organizations, and other stakeholders who are interested in exploring opportunities of carbon farming in Africa's smallholder communities. We conducted a literature review and summarized the state of knowledge in four areas: agricultural markets as a funding institution for carbon farming, the role of payments for carbon sequestration, avoidance or reductions of GHG emissions in incentivizing the adoption of carbon farming practices, the aggregation of smallholder farmers into carbon farming groups, and the cost-effective monitoring, reporting, and verification of changes in carbon stocks. The findings highlight important directions for further research. First, the institutional arrangements that are required to tap the potential for carbon credits to promote sustainable production methods in Africa. Second, the technologies and approaches for accurate and cost-effective monitoring of carbon sequestration rates and levels of GHG reductions or avoidance.

The remainder of this paper is structured as follows. Section 2 provides the conceptual framework. Section 3 present the current state of agricultural carbon markets. Section 4 examines smallholder farmers' willingness, ability, and competitiveness to participate in carbon farming. Section 5 explores the role of intermediary institutions in aggregating farmers and achieving scale. Section 5 deals with the monitoring, reporting, and verification of carbon stocks. Section 7 provides concluding remarks.

2 Conceptual Framework

2.1 Concepts and definitions

This section aims at defining the term carbon farming and placing it within the better-known concepts of climate-smart agriculture (CSA) and payment for environmental services (PES).

Climate-smart agriculture (CSA) is a broad framework that *"capture[s] the concept that agricultural systems can be developed and implemented to simultaneously improve food security and rural livelihoods, facilitate climate change adaptation and provide mitigation benefits"* (Scherr et al., 2012). The implementation of CSA practices is understood to benefit farmers via increased productivity, profits, and reduced vulnerability to climate change (Engel & Muller, 2016). These benefits to farmers, however, often occur only in the medium to long term (Engel & Muller, 2016).

Payment for environmental services (PES) is an instrument addressing externalities by translating societal benefits from a change in land-use practices into profits for land users (Engel et al., 2008; Wunder, 2013). Engel (2016) defines PES "*as a positive economic incentive where environmental service (ES) providers can voluntarily apply for a payment that is conditional either on ES provision or on an activity clearly linked to ES provision*." As the adoption of CSA practices provides external benefits to people worldwide, PES can be an appropriate tool to translate these external societal benefits into increased benefits for farmers. Prominent CSA practices are activities that contribute to increased carbon sequestration (Engel & Muller, 2016).

Carbon farming is a term that has gained prominence in the growing recognition of nature-based solutions for climate change mitigation. Despite the increased usage of the term, no unified definition exists. To establish our working definition, we conducted a review of carbon farming definitions used in journal articles. By comparing differences and similarities across all definitions, we identified two groups of carbon farming definitions. Firstly, those definitions with a focus on the ES provision, i.e., carbon sequestration in vegetation and soils. Secondly, those definitions that emphasize the business model of receiving economic benefits for carbon sequestration.

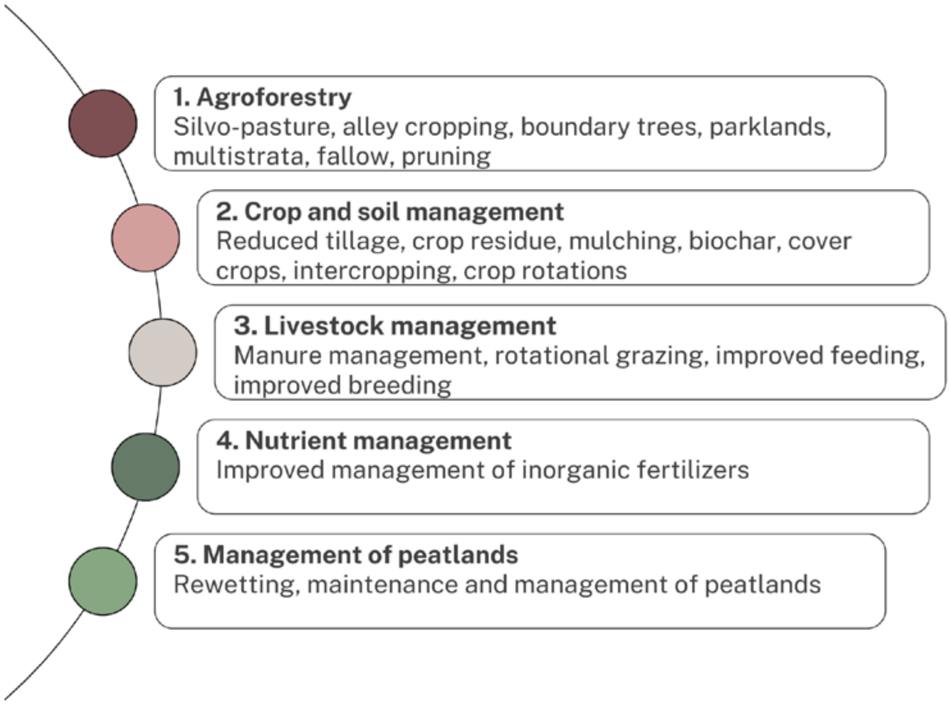
Most definitions focus on the ES provision and refer to carbon farming as agricultural practices that improve the rate at which CO_2 is removed from the atmosphere and converted to plant material or soil organic matter. Differences exist in the coverage, i.e., whether the definition includes beyond the sequestration of carbon also the reduction and/ or avoidance of GHG emissions. Whether this is an intended distinction remains unmentioned. Further, some definitions are limited to carbon sequestration in soils, while others include in addition carbon sequestration in biomass. Definitions related to the business model of carbon sequestration stress the financial component for incentivizing carbon sequestration. Table 1 in the annex provides an overview of the definitions identified in the literature.

To reflect the two categories of carbon farming definitions in our terminology, we distinguish the terms carbon farming and carbon farming practices. We follow Kragt et al. (2016) and define **carbon farming practices** as agricultural management practices that either avoid or reduce the release of greenhouse gas emissions or promote active sequestration of carbon in vegetation and soils. As such, carbon farming is one aspect of the wider approach embodied in CSA. To avoid using the term payments or rewards for the adoption of carbon farming practices, we define **carbon farming** as the business model of remunerating farmers for the implementation of carbon farming practices. Hence, carbon farming may be classified as one type of payment for ecosystem services (PES), with the service being climate change mitigation through carbon sequestration.

2.2 Carbon farming practices

To facilitate the overview of carbon farming practices, we group practices into five categories: agroforestry, crop and soil management, livestock management, nutrient management, and the management of peatlands. In many agricultural production systems, these practices are interrelated, which suggests taking a systems approach for carbon farming. The classification follows largely Mcdonald et al. (2021). An overview is presented in Figure 1.

Figure 1. Carbon farming practices



First, the creation, restoration, and management of agroforestry systems. In an agroforestry system, woody vegetation, such as trees or shrubs, is integrated with crops and/ or animals (Mcdonald et al., 2021). Practices include silvo-pasture, alley cropping, and boundary planting (Lamanna et al., 2020).

Second, improved crop and soil management. Crop management practices include cover crops, intercropping, improved crop rotations, and improved varieties. Soil management practices include reduced tillage, crop residues, mulching, and the addition of biochar (Lamanna et al., 2020).

Third, livestock and manure management refer to technologies aimed at reducing enteric methane, and increasing herd and feed efficiency (Mcdonald et al., 2021). We further include grassland management in this category. Practices include manure management (from the collection, through storage and treatment up to application), improved feeding, improved breeding as well as rotational grazing (Lamanna et al., 2020).

Fourth, nutrient management on croplands and grasslands includes improved nutrient planning, timing, and application of fertilizers as well as reductions in fertilizers (Mcdonald et al., 2021). To avoid overlaps with other categories, this category focuses only on inorganic fertilizers and leaves out organic fertilizers, which are included under crop and soil management practices as well as livestock management.

Fifth is the management of peatlands, which includes peatland rewetting, maintenance, and management (Mcdonald et al., 2021).

2.3 Carbon farming and the bioeconomy

Carbon farming is further interrelated to other important policy efforts, such as the development and expansion of the bioeconomy. The bioeconomy concept is centred around scientific research, knowledge, and innovation to support the *"sustainable production and use of biological resources to create innovative products, processes, and services for all economic sectors"* (Malabo Montpellier Panel, 2022). It aims to *"build value around local bioresources, maximising and using all parts of primary produce and their products"* (EASTECO, 2020). The bioeconomy concept espouses an economic growth model where actors from different sectors combine efforts to co-create sustainable biologically based solutions that reduce carbon emissions and conserve biodiversity. This cross-sectoral nature of the bioeconomy has been put forward as a means to enhance coordinated action against climate change, providing a unique pathway to sustainable and regenerative development (Ecuru et al., 2022; El-Chichakli et al., 2016). Therefore, the expansion of the African bioeconomy arguably provides new opportunities to address climate change, including carbon farming (Malabo Montpellier Panel, 2022). Specifically, the value-adding features of the bioeconomy and the links it creates to national and regional markets through innovation may be seen as opportunities for diversifying rural and urban economies in ways that create new job prospects for the youth, and one of the ways of increasing household incomes.

The bioeconomy concept may be one of the ways of preventing loss of soil carbon, which is attributed, in parts, to extractive practices where biomass is exploited in an unsustainable way and insufficient bio-inputs are returned into the system. The bioeconomic model would promote nutrient recycling, i.e, returning nutrients back to the land, which is oftentimes a missing link in conventional farming. Recycling of biowaste through composting, a key tenet of the sustainable bioeconomy, can be a contribution to climate mitigation as well as objectives of a circular economy (European Environmental Bureau, 2021).

Further, carbon farming is concerned with the build-up of biomass, which is an input for bio-based products, and a key tenet of the bioeconomy. Carbon farming promotes, among others, agroforestry systems which are an important source of raw materials for bio-based by-products. Bio-based materials can be transformed to durable products for long-term carbon storage, potentially creating new or expanding existing value chains (European Commission, 2022). Besides, carbon farming in the the context of the bioeconomy might be designed in such ways to possibly enhance biodiversity conservation, and ecosystem services, both of which are crucial for sustaining life and livelihoods on the planet. These positive externalities could also be considered in pricing carbon farming if they indeed are measurable co-benefits.

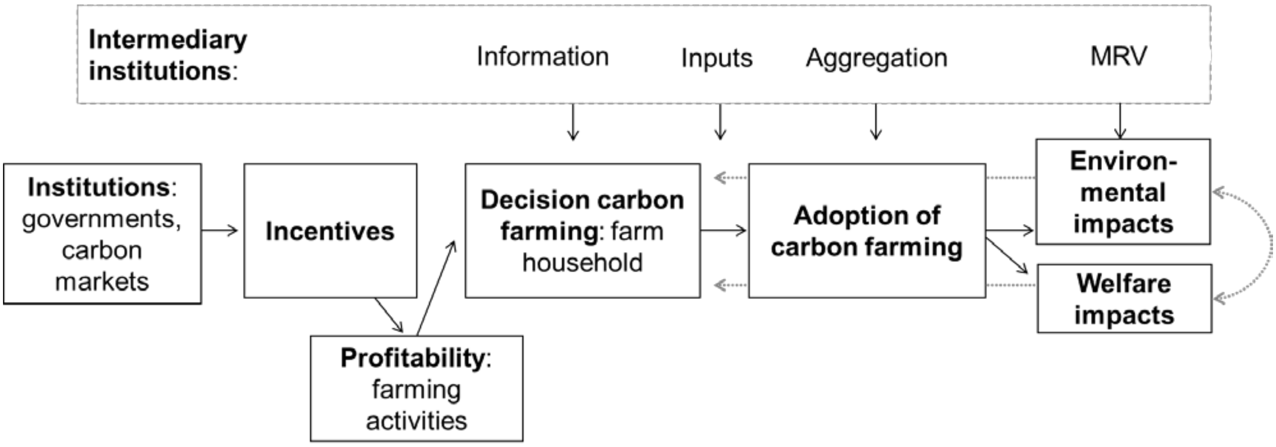
2.4 A framework for smallholder engagement in carbon farming

The conceptual framework in Figure 2 presents the theoretical foundation for engaging smallholder farmers in carbon farming through the introduction of financial incentives. It builds on the broader payment for environmental services (PES) literature, linking ecosystem services and decision-making processes (Daily et al., 2009; Guerry et al., 2015), and was adapted to the context of carbon farming.

African food production systems are dominated by small farms. The farm household is the place where decisions on land use are made (Singh et al., 1986) and, therefore, constitutes the core of our framework. Financial incentives for the adoption of carbon farming practices may be based on agricultural carbon markets or government financed. These incentives alter the profitability of an available set of farming activities. In response to the incentives, farm households define the extent to which they engage in carbon farming. The resulting impacts include environmental impacts, such as increased carbon sequestration, reduction or avoidance of GHG emissions resulting in climate change mitigation, or welfare impacts, such as changes in income or risk reduction for improved resilience to climate change, or all of these in combinations.

Individual farmers are unlikely to interact directly with agricultural carbon markets given different temporal and spatial scales of operation (Lee et al., 2016). Therefore, we include intermediary institutions in our framework. These intermediaries engage with smallholder farmers at different stages of the process. They provide information or inputs and serve as a means for aggregating farmers into carbon farming projects. Further, the intermediaries take on roles in the monitoring, reporting, and verification (MRV) of carbon sequestration levels and reductions and avoidance of GHG emissions, a prerequisite for both activity- and results-based incentive schemes. We did not add time subscripts or feedback loops to the stylized framework, but it shall be noted that in the long run, there may be positive feed backs when impacts become more visible to stakeholders (indicated by dotted lines in Figure 2).

Figure 2. Conceptual framework



Source: Author's own elaboration

**MRV = monitoring, reporting, and verification*

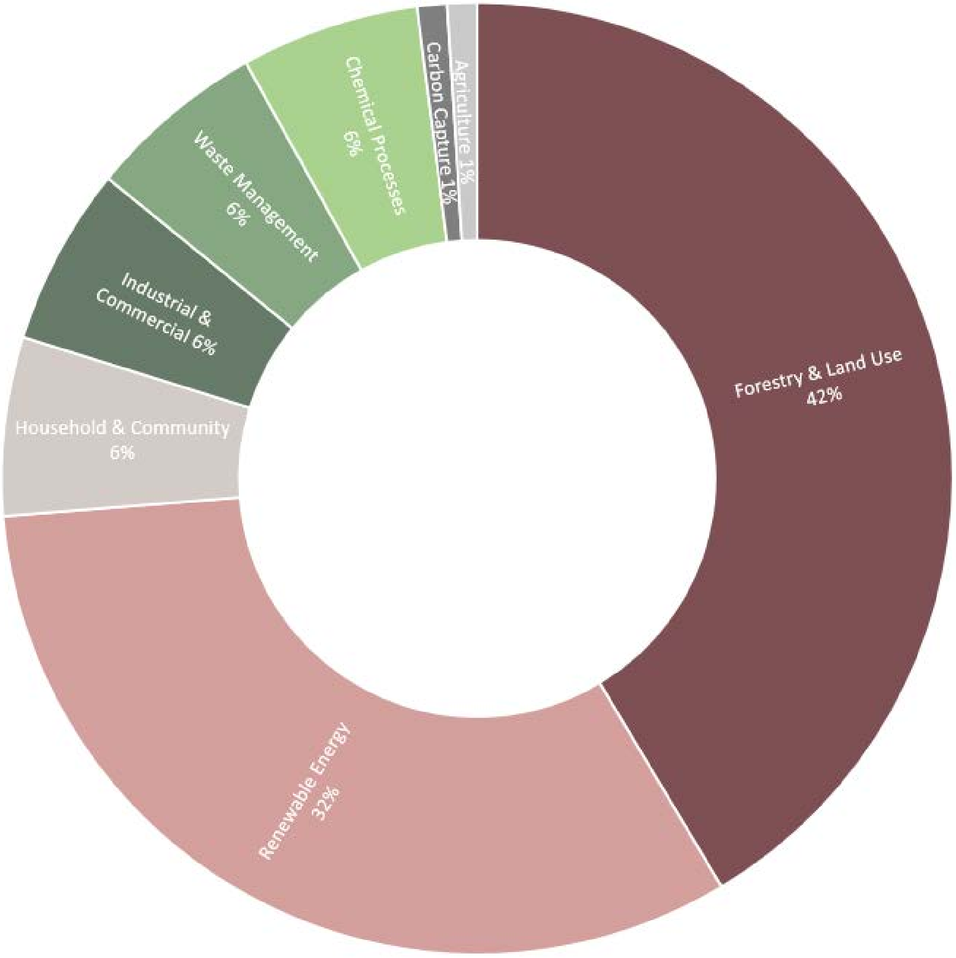
The conceptual framework provides the structure for this paper. Section 3 explores the role of agricultural carbon markets as a funding source for carbon farming. Section 4 explores the connection between incentives and the implementation of carbon farming practices. We evaluate the significance of financial incentives in changing the profitability of farming activities and the role of co-benefits as an indirect motivator for carbon farming adoption. The willingness of farmers to adopt carbon farming is crucial, however, it may not be enough to drive adoption. Hence, we proceed by looking at the ability and eligibility of smallholder farmers to participate in carbon farming. The importance of intermediary institutions is addressed in sections 5 and 6. Section 5 covers the aggregation of smallholder farmers into carbon farming projects, while section 6 discusses the monitoring, reporting, and verification of carbon changes. Section 7 concludes the paper. The findings are based on a comprehensive literature review, which included peer-reviewed articles and relevant technical reports, and working papers from the growing field of carbon farming.

3 Funding institutions: the role of agricultural carbon markets

3.1 The current state of agricultural carbon markets

The payment for environmental services (PES) concept is project- and program-based, and primarily government-funded (Engel, 2016; Lipper & Neves, 2011). Public funding alone, however, cannot achieve the scale for the required structural changes in the agricultural sector (Lee et al., 2016; PwC, 2011). The idea of carbon farming evolves around land use and soil management as part of a strategy for farming to actively enter and engage in the emerging carbon market. Agricultural carbon markets may be a powerful tool to leverage private capital for transforming the agricultural system towards more adaptive trajectories, including the adaptation of carbon farming practices (Benessaiah, 2012; PwC, 2011). In practice, however, funding of agricultural activities under the voluntary and compliance carbon markets is still at low levels (Engel & Muller, 2016; Forest Trends' Ecosystem Marketplace, 2021; So et al., 2023).

Figure 3. Share of carbon credits issued by the voluntary carbon market in 2022

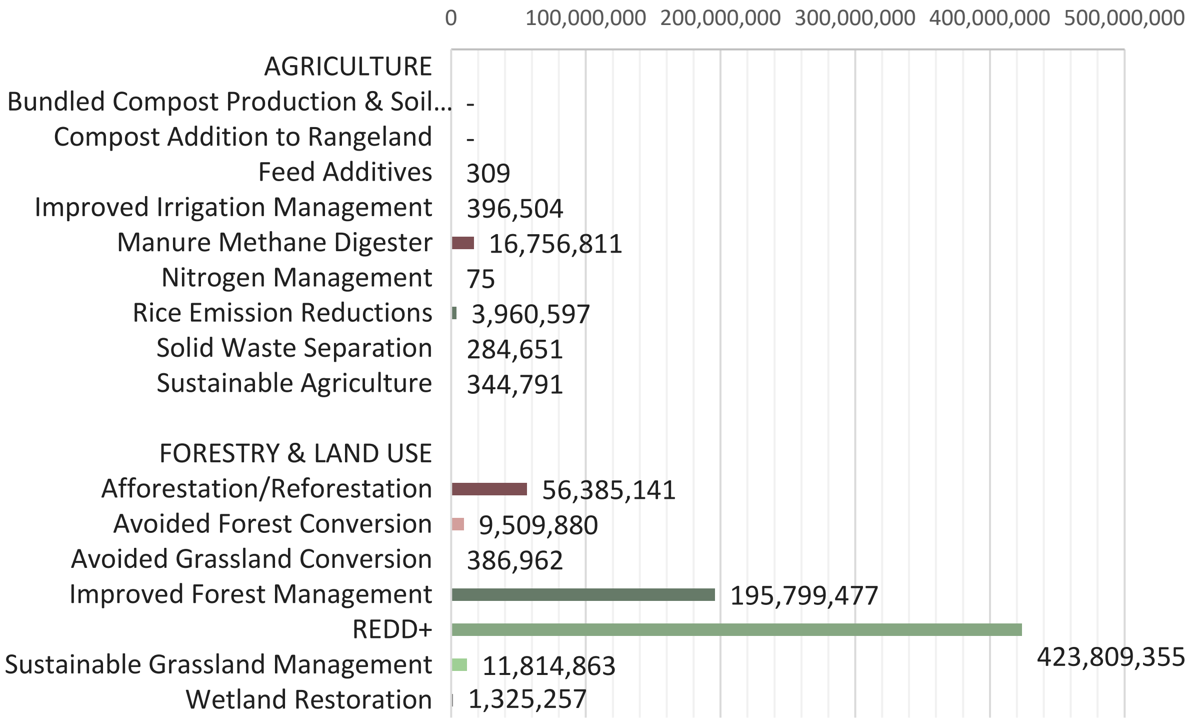


Source: So et al. (2023)

Carbon sequestration and the reduction or avoidance of GHG emissions from agriculture is only to a limited degree eligible in compliance markets. Compliance markets are governed by national, regional, or international greenhouse gas emission limits. The most prominent example is the Clean Development Mechanism (CDM) of the Kyoto Protocol. The CDM allows the trading of carbon credits between developing and industrialized countries (UNFCCC, n.d.). Despite having methodologies applicable to the agricultural sector, projects under the CDM cannot claim GHG removals through soil carbon sequestration. Carbon sequestration in biomass is eligible and covered under afforestation and reforestation methodologies (UNFCCC, 2021). The CDM will transition into a new system under Article 6.4 of the Paris Agreement, which is currently under development (Crook, 2022). The potential impact on the eligibility of carbon credits from agricultural activities remains to be seen.

Voluntary markets target organizations that seek to offset their greenhouse gas emissions outside of regulatory requirements. The greater flexibility regarding the types of eligible projects and methodologies results in land-based carbon projects being better featured in the voluntary carbon market (Benessaiah, 2012). The four main actors are American Carbon Registry, Climate Action Reserve, Gold Standard, and Verra (So et al., 2023). So et al. (2023) compiled a database of carbon credit projects of these four project registries accounting for almost the entire voluntary carbon market. Agriculture, Forestry and Other Land Use (AFOLU) projects accounted for 42% of all credits issued under the voluntary carbon market in 2022 (Figure 3). This is, however, mainly driven by projects under the REDD+ initiative which accounted for 25% of all voluntary carbon credits (Figure 4). The agriculture sector accounted for only 1.3% of all carbon credits (So et al., 2023). Some market growth is visible, with agricultural accounting for less than 1% of carbon credits issued in 2021 (Forest Trends' Ecosystem Marketplace, 2021).

Figure 4: AFOLU carbon credits issued by the voluntary carbon market in 2022



Source: So et al. (2023)

The potential opportunities of carbon farming are challenged by a lack of a well-developed agricultural carbon market. First, until recently, changing only with the UNFCC's COP27 in 2022, there was a lack of recognition of carbon farming practices in international climate change discussions and negotiations (FAO, 2022; UNFCCC, 2022). The ineligibility of carbon sequestration projects in compliance markets, and the limited availability of carbon methodologies were important barriers to the development of agricultural carbon markets (PwC, 2011). Second, low carbon prices in the voluntary market make it difficult for carbon project developers to establish and run carbon projects (Lee et al., 2016; PwC, 2011). Estimates from two carbon finance projects in East Africa indicate that revenues may cover as little as 5 to 25% of project costs (Lee et al., 2016). Third, predicting outcomes and monitoring compliance with contract terms over large and heterogeneous geographical areas and long periods is a key challenge for carbon farming projects (Cacho et al., 2013). The presence of ex-ante costs to develop baselines for emission pathways and predict outcomes of alternative land uses and high fixed costs as well as annual costs of certification prevent farmers from participating directly in carbon markets (Cacho et al., 2013). In addition to the above-mentioned challenges for establishing projects, investors may also shy away from agricultural carbon markets due to concerns related to the environmental integrity of the market, unless reliable certification systems are implemented. Overcoming any of these challenges entails transaction costs, that need consideration in research.

3.2 Concerns related to the environmental integrity of agricultural carbon markets

Risks related to the environmental integrity of agricultural carbon markets can be captured along four pillars: permanence, leakage, additional, and double counting.

First, carbon farming schemes may face the risk of low- or no additionality. To reduce the risk of “paying for nothing”, realistic baseline estimates are required. A pure focus on additionality, however, may penalize those that exerted pro-environmental behavior before the introduction of a scheme and may be perceived as “rewarding the bad guys” (Engel, 2016). Further, payment schemes may create perverse incentives, e.g., inducing an expansion of environmentally destructive activities to obtain higher subsidies at a later stage, some hypothesize (Engel et al., 2008).

Second, carbon farming may lead to leakage, i.e., the displacement of activities damaging environmental service provision to areas outside the project intervention zone (Engel, 2016; Engel et al., 2008). The adoption of carbon farming may lead to changes in output composition, which can induce leakage (Engel & Muller, 2016). If schemes are implemented on a large scale, they might affect food production and consumers may be affected by changes in food prices (Engel & Muller, 2016; Pagiola et al., 2005). Quintero et al. (2009) estimate that switching from a burning maize-pastures cycle to shade-grown coffee in Peru would more than double farmers’ incomes. As long as local food markets operate effectively, these types of switches to cash crops have generally shown not to be a concern regarding local food security (von Braun & Kennedy, 1994).

Third, soil and biomass carbon projects face the risk that carbon sequestered may subsequently be released if management practices or land uses change. Unlike the widely implemented PES projects avoiding deforestation and forest degradation, which are often implying activity reduction and decreasing income, PES in agriculture usually refer to activity changes that by definition of CSA yield benefits for the implementing farmers. Therefore, carbon farming projects may face fewer concerns of permanence (Engel & Muller, 2016). However, there are non-permanence risks related to climate variability, climate change, or unforeseen events such as fire, flood, or drought (Oldfield et al., 2022; Stockmann et al., 2013).

Fourth, double counting, i.e., two entities claiming the same carbon removal or emission reduction, may undermine the integrity of carbon markets. Corresponding adjustments are a framework established under Article 6.2 of the Paris Agreement (Schneider et al., 2019). For credits traded in the voluntary carbon market, it is crucial to avoid the same emission reduction being sold as a voluntary offset and counted towards a country's target under the Paris Agreement. Otherwise, the growth in voluntary carbon markets may disincentivize governments from increasing their climate mitigation efforts (Fearnehough et al., 2020).

To overcome the concerns of investors, it will be important to develop sound methodologies for agricultural carbon projects and, where required, improve on existing ones.

4 Smallholder carbon farming: from willingness to ability and competitiveness

4.1 Willingness: the profitability of carbon farming

Carbon payments may constitute an income source for smallholders and farming communities (PwC, 2011) and can serve as a direct incentive for farmers to adopt more sustainable production practices.

Barriers to adoption usually relate to high short-run costs. A lack of capital or access to credit implies high discount rates and decreases the likelihood of adopting carbon farming practices (Engel & Muller, 2016). In the case of shifting to a system of no- or low-tillage, where improved land productivity is expected in the long run, compensation for carbon sequestration, reduction or avoidance of GHG emissions can help especially poor farmers to overcome capital or credit constraints that prevent them from adopting the practices (Cavatassi & Lipper, 2002). Even if the adoption of carbon farming practices leads to long-term benefits, farmers may be reluctant to shift practices due to delayed returns on investment. The usually prevailing high discount rates make farmers value short-term costs more than long-term benefits. Further, some authors hypothesize that the possibility of higher yield risk in the transition phase after changing practices may reduce the willingness of risk-averse farmers to consider carbon farming (Engel & Muller, 2016; Graff-Zivin & Lipper, 2008; Lipper et al., 2010). As a result, upfront financial payments may be an important means for increasing farmers' willingness to adopt carbon farming practices.

Depending on the timing and certainty, carbon payments could present an important opportunity for the poor to increase security. A steady flow of payments from carbon farming could be an important means to reduce income risk (Lipper et al., 2010). The poor could potentially be lower-cost providers of sequestration services if payments are structured in a way that they provide some form of consumption insurance (Cavatassi & Lipper, 2002).

Many authors, however, argue that carbon payments are so far too low and that it is the presence of agricultural and non-agricultural co-benefits that could induce farmers to adopt new practices and supply carbon (Graff-Zivin & Lipper, 2008; Lee et al., 2016; Lipper et al., 2010; Tamba et al., 2021). Graff-Zivin and Lipper (2008) base their argument on the per hectare carbon sequestration potential in agriculture (0.15-0.8 t C), prevailing market prices per CO_2 equivalent ($3.7 in the Chicago Climate Exchange in 2007) and estimates on the monitoring costs of carbon sequestration per hectare ($5-8 based on US projects) to demonstrate the profitability challenge. Lee et al. (2016) provide examples of payments for carbon sequestration to farmers in East Africa. For example, the International Small Group Tree Planting program (TIST) paid farmers $0.018 per tree planted. Further, they claim that farmers will receive 70% of net carbon revenues once the project is self-funding (TIST, 2013). Trees for Global Benefits (TGB) Uganda and Emiti Nibwo Bulora (ENB) in Tanzania agreed to pay farmers 30% of the anticipated carbon revenue (Lee et al., 2016). Some projects do not make payments to farmers and revenues are fully utilized to cover the project-related costs (Tamba et al., 2021). This demonstrates that alongside increasing carbon prices, there is a need to reduce transaction costs to allow and/or increase payments to participating farmers.

Wide consensus exists on the presence of agricultural productivity benefits associated with increases in SOC, which generally increase agricultural output (Graff-Zivin & Lipper, 2008; Lee et al., 2016; PwC, 2011). Common adaptation benefits are improved resilience to water shortages through water and soil conservation, reduction of economic risks through input saving, and resilience to extreme temperatures through agroforestry (Wollenberg et al., 2021). Additional benefits include new products, such as building materials or fruits from agroforestry, and increased resilience to climate change, resulting, e.g., from shelter from trees or diversification (Engel & Muller, 2016), and using drought-tolerant crop varieties. Further, novel approaches such as the push-pull technology that involves intercropping cereals, an attractant trap plant (e.g., Napier grass), and a repellent plant (e.g., desmodium), lead to improvements in the control of cereal pests (Ndayisaba et al., 2022). Carbon payments also yield opportunities for increasing the economic and ecological returns to rangelands and pasturelands in developing countries (Lipper et al., 2010). Little is known so far about the potential land market or land value effects resulting from the introduction of carbon payment schemes. If carbon farming increases the value of land and the expected returns to farming, a risk of 'land-grabbing' may emerge.

Further, there could be non-income effects such as social or cultural impacts contributing to building social capital, and increased human capital linked to training or community organization. Evidence from forestry projects suggests consolidation of land tenure and improved community organization (Corbera & Brown, 2008; Grieg-Gran et al., 2005).

At currently low carbon prices, co-benefits for agricultural production and beyond are required to induce the participation of smallholder farmers in carbon projects (Graff-Zivin & Lipper, 2008; Lipper et al., 2010; Wollenberg et al., 2021). Some projects in East Africa try to shift the focus to co-benefits and manage expectations by referring to carbon payments as a "token thank you" or "carbon bonus" (Lee et al., 2016). A package approach that provides inputs or training may increase both incentives for participation as well as success rates (Lee et al., 2016).

To date, little evidence exists about the effect sizes as well as the distributional effects of the benefits of carbon farming. This is especially true for effects that are not related to the carbon sequestration level and are, hence, outside the monitoring scheme of carbon farming projects. More research will be needed to support the understanding of the co-benefits of carbon farming, which constitute an important factor in the adoption decision, as well as hypothetical concerns mentioned in the previous section.

Box 1. Example of a carbon farming project in Kenya

The Kenya Agricultural Carbon Project (KACP) is the first soil and agricultural carbon finance project in Africa. Since its validation in 2012, the project has been implemented by the Swedish NGO Vi Agroforestry in Western Kenya. The project has reached more than 60,000 smallholder farmers on more than 45,000 ha of land. The main objective of the project is to increase the productivity of smallholder farmers and to enhance their resilience to climate change through extension services, while carbon sequestration is considered a marketable co-benefit. The project promotes the adoption of sustainable land management practices such as residue management, composting, cover crops, and agroforestry. To support the implementation, local field advisors provide capacity-building and advisory services to farmer groups. One of the buyers of the verified credits for carbon sequestration and avoidance or reduction of GHG emissions is the World Bank's BioCarbon Fund.

The methodology VM0017 'Adoption of Sustainable Agricultural Land Management (SALM) practices' was developed by the BioCarbon Fund of the World Bank, Vi Agroforestry, and UNIQUE forestry and land use based on this project and was successfully verified by Verra in 2011. The methodology is based on an activity baseline and monitoring survey and estimations of soil carbon stock changes using the RothC carbon model. In addition, tree biomass is accounted for by applying a CDM methodology for afforestation and reforestation.

Source: Tennigkeit et al. (2013)

4.2 Ability and competitiveness: practical constraints to the adoption of carbon farming

The potential of smallholders to benefit from agricultural carbon payments depends, apart from their willingness, also on their ability, and their competitiveness in the provision of carbon farming, i.e., opportunity costs and productivity (Cavatassi & Lipper, 2002). Evidence shows that, due to ability and eligibility constraints, an interest in the adoption of carbon farming alone may be insufficient for shifting practices.

Important barriers identified for poor farmers in PES schemes include participation rules that discriminate against mixed, small-scale production systems (Grieg-Gran et al., 2005), a lack of secure land tenure (Lee et al., 2016; Pagiola et al., 2005; Wunder, 2013), higher transaction costs when working with many small farmers compared to working with fewer large firms (Adhikari & Agrawal, 2013; Pagiola et al., 2005), lack of resources to cover required investment costs (Pagiola et al., 2005), and lack of education or access to technical assistance if adoption requires substantial technical capacity (Pagiola et al., 2005).

While a lack of tenure security may discourage farmers from investing in new practices, tenure security also affects the ability of farmers to participate in carbon payment schemes (Tamba et al., 2021; Wollenberg et al., 2021). Tenure clarity and security are important pre-conditions (Abdulai et al., 2011), and a lack thereof may make farmers ineligible for participation (Wunder, 2013). Additional factors for the ability to participate in carbon farming relate to the ability to adopt the required practices. This ability depends on the household's resource endowment. With upfront investment costs, capital and investment constraints prohibit farmers to adopt practices that qualify for carbon payments (Lipper et al., 2010; PwC, 2011; Wollenberg et al., 2021). Additional barriers to adoption are a lack of knowledge of practices, information gaps, and technical or capacity constraints (PwC, 2011; Wollenberg et al., 2021).

While opportunity costs of labor of smallholders are typically lower than those of large-scale farmers, this does generally not apply to opportunity costs of land in the same contexts. Grieg-Gran et al. (2005) argue that services provided by large-scale farmers will be more efficient and with carbon markets eventually becoming competitive, the more efficient suppliers will secure larger market shares. Yet, this is an empirical question as the land productivity of smallholders has often been shown to be higher than that of large farms (Binswanger & McIntire, 1987; Ricciardi et al., 2021). The mitigation potential of carbon farming at the individual smallholder level is relatively low. To realize significant emissions reductions, aggregation is required. The transaction costs associated with working with a large number of smallholder farmers are, however, a major issue (Lipper et al., 2010; PwC, 2011). This challenge will be further addressed in the next section.

5 Intermediary institutions: aggregating farmers into carbon farming groups

Transaction costs are a major barrier to the development of cost-effective carbon farming projects. This is especially true if projects aim to involve smallholder farmers. The carbon sequestration potential per hectare is low, but the aggregate potential is high. At the same time, there are high amounts of fixed and variable transaction costs. Examples include ex-ante costs for developing baselines for emission pathways, predicting outcomes and monitoring compliance with contract terms over large and heterogeneous geographical areas and long periods, annual costs of certification, and administering payments. These costs prevent farmers from participating directly in carbon markets (Cacho et al., 2013; Lee et al., 2016; Lipper et al., 2010; Wollenberg et al., 2021). As a result, intermediaries or carbon credit project developers emerged that take an intermediary role between buyers and sellers of environmental services.

Low carbon prices in the voluntary market coupled with high transaction costs make it difficult for carbon project developers to establish and run carbon projects (Lee et al., 2016; PwC, 2011). The costs associated with identifying, negotiating, contracting, and enforcing carbon sequestration projects are significantly higher when dealing with smallholder farmers, which are geographically scattered (Benessaiah, 2012; Cavatassi & Lipper, 2002; Lipper et al., 2010). Consequently, project developers have favored the participation of larger farms, posing a risk of elite capture of carbon benefits (Benessaiah, 2012). Reducing the transaction costs associated with carbon farming projects is key for ensuring that smallholder farmers can be competitive providers of carbon credits and, hence, get the opportunity to benefit from carbon credit projects (Cavatassi & Lipper, 2002). For smallholder farmers to participate effectively in carbon markets, coordination and consolidation of sequestration supply will be necessary (Cavatassi & Lipper, 2002). We refer to institutions that facilitate the creation of economies of scale in carbon sequestration as aggregators.

Aside from reducing transaction costs for project developers, scaling serves as a risk management mechanism (Lipper & Neves, 2011). Through scaling, projects can set aside carbon credits as a non-permanence buffer to spread risk and support flexibility among participants, allowing them for example to drop out of the projects (Cacho et al., 2013; Lipper & Neves, 2011).

The presence of aggregators who are willing to invest and work with smallholders is essential for enabling further growth of the engagement of smallholder farmers in carbon markets (Cacho et al., 2013). Institutional arrangements that utilize existing structures may offer important opportunities (Cacho et al., 2013; Streck et al., 2012). By using local offices, IT infrastructure, databases, and payment administration of existing public or private entities, transaction costs can be greatly reduced (Cacho et al., 2013). Aside from the existing infrastructure, local institutions also have management capacity (Cacho et al., 2013) and networks in place, which newly established institutions would have to develop. Potential institutions to build on as aggregators are government agencies, NGOs, community groups, farmer organizations, or extension service organizations (Cacho et al., 2013; Lipper et al., 2010; Nyawira et al., 2021).

Local institutions can play a significant role in reducing transaction costs and, hence, making the involvement of smallholder farmers in carbon farming projects a feasible opportunity. Due to their close involvement with individual farmers, farmer organizations and extension service organizations may be promising candidates to operate as aggregators in carbon farming projects. Community governance structures are important for creating an enabling environment, ensuring that projects meet smallholder needs, and supporting effective communication between project developers and smallholder participants (PwC, 2011; Wollenberg et al., 2021). Institutions that provide effective coordination, monitoring, and enforcement are required for both changing practices and for engaging in carbon finance (Lee et al., 2016; Lipper et al., 2010; Wollenberg et al., 2021). Responsibilities of farmer groups may involve the contracting of farmers, by identifying farmers and ensuring that all participants are aware of the obligations and benefits of the carbon farming project (Tamba et al., 2021). Further, they can be the anchor for implementing peer-monitoring schemes that can significantly reduce the costs associated with the monitoring, reporting, and verification of activity- or result-based carbon credit schemes (Cacho et al., 2013). Additionally, farmer groups can serve as both receivers and distributors of carbon payments (Shames et al., 2012; Tamba et al., 2021). Benefits may either be held and reinvested at the group-level or benefit-sharing mechanisms that distribute payments to individuals may be implemented (Tamba et al., 2021). They can provide the platform to facilitate extension services and promote participatory learning techniques (PwC, 2011). Finally, they can provide support for project administration and communication (Tamba et al., 2021). For allowing farmer organizations to take on these roles and responsibilities, improving their institutional capacity is key (Lipper et al., 2010).

In practice, we see many examples of already established groups taking on the above-mentioned roles in smallholder carbon projects. According to Huang and Upadhyaya (2007), many PES programs in Asia have been established around pre-existing community-based natural resource management groups, and payments are often made to community-level organizations (Lipper et al., 2010). In Kenya, the Kenya Agricultural Carbon Project (KACP) recruits farmer groups and provides training and advisory services for sustainable agricultural land management practices. Similarly, the International Small Group and Tree Planting Program (TIST) project also works with farmer groups typically ranging from 15-30 people in size, which ease project administration and communication, while still maintaining individual participation through individual agreements. Further, payments are made to farmer groups as soon as the implementation of practices can be verified, streamlining the process (Lee et al., 2015; Tamba et al., 2021). These practical examples demonstrate the important role that farmer groups can play in carbon credit projects, particularly in terms of contract administration and payment distribution. We note, however, that composition and structure of pre-existing farmer groups will have impacts on the distributional outcomes of the carbon farming adopting group. This may for instance relate to the inclusion or not of women, or finance management capabilities which may be established by micro-credit groups.

6 Monitoring, reporting, and verifying carbon stock changes

6.1 The importance of accurate, cost-effective measurement approaches

To encourage investment and reduce financial barriers to adoption, schemes that pay farmers for carbon capture may provide an important opportunity (Jackson Hammond et al., 2021; Lal, 2013; Lal et al., 2018; von Braun et al., 2021). For agricultural carbon markets to work, the accurate measurement and monitoring of changes in carbon stocks, both in soils and biomass, is key (Conant et al., 2011). Differences in monitoring, reporting, and verification (MRV) protocols are a risk, as they may lead to non-equivalent carbon credit creation. This can undermine trust in the integrity of the market (Oldfield et al., 2022). Further, the trading of low-quality credits may result in a questioning of the market, potentially leading to a collapse of the incentive structure (Jackson Hammond et al., 2021).

From a farmer's perspective, the shift towards carbon farming practices requires trust in their economic advantage, for example through higher and more stable yields (Ewing et al., 2021) and investment in equipment or inputs (Jackson Hammond et al., 2021). Trust depends on information (Ewing et al., 2021). Detailed knowledge of the soil's C content as well as the effectiveness of different agricultural practices on it are, therefore, crucial for decision-making processes at the farm level (Ewing et al., 2021). To provide this information, new tools such as low-cost hand-held digital devices for measuring soil carbon levels are needed (Ewing et al., 2021; von Braun et al., 2021).

Resulting from the above-mentioned data needs, accurate and cost-effective approaches for measuring and monitoring carbon sequestration rates at the farm level, with the possibility for upscaling to larger project areas, are urgently needed. In the following, we present the current state of the art regarding the measurement of carbon sequestration in soils and biomass. We focus in this section on carbon sequestration in soils and biomass and exclude approaches for quantifying the reduction or avoidance of GHG emissions.

6.2 Measuring soil carbon sequestration

6.2.1 The challenges of carbon measurement

The measurement of changes to soil C resulting from changes in agricultural management practices is complex. Smith et al. (2020) list three major challenges. First, short-term changes in SOC are difficult to detect compared to extremely large background stocks (Lal, 2013). The challenge is further amplified by the large spatial variability of soil C (Chatterjee et al., 2009; Freibauer et al., 2004). In addition, soil C gains are slow, and may take several years to occur (Lal, 2013). Second, there is an incomplete understanding of how environmental and anthropogenic factors influence SOC change (Stockmann et al., 2013). Third, the non-permanence of carbon sequestration raises questions about the time frames needed to monitor soil C changes (Rumpel et al., 2020; Smith et al., 2020). Non-permanence risks arise from changes in agricultural practices, climate variability, climate change, or unforeseen events such as fire, flood, or drought (Oldfield et al., 2022; Stockmann et al., 2013).

6.2.2 Best practices and emerging approaches for soil carbon measurement

There are different approaches to the quantification of SOC. Following Acharya et al. (2022), we categorize approaches into laboratory methods, in-situ measurement, and remote sensing.

1. **Laboratory methods**

Wet oxidation and dry combustion are the two techniques applied in ex-situ or laboratory analyses of soil C levels (Chatterjee et al., 2009; Nelson & Sommers, 1996; Saiz & Albrecht, 2016).

Wet combustion involves the oxidization of SOC by an acid solution. Various methodologies are available that differ in the type and concentration of the acids used and the use of external heat. The most popular technique is the Walkley-Black method. Dry combustion methods usually refer to the loss-on-ignition method and the automated analyzer method. The loss-on-ignition method involves strongly heating a soil sample in a furnace and measuring the resulting weight loss. In the automated analyzer method, the soil sample is combusted at high temperatures and converted to CO_2. The CO_2 is then separated from other gases and the detection of the CO_2 concentration is done by a thermal conductivity detector or infrared (Chatterjee et al., 2009).

While wet oxidation has long been the standard for the analysis of SOC, dry combustion using automated analyzers is nowadays considered the gold standard for carbon measurement (Acharya et al., 2022; Chatterjee et al., 2009). It comes with the highest precision, and is rapid, but involves high expenses related to the equipment (Chatterjee et al., 2009). Other disadvantages common across all laboratory methods are the need to collect soil samples and the resulting labor intensity and logistical challenges, as well as the destructive nature of laboratory approaches (Chatterjee et al., 2009). The SOC estimates obtained from laboratory measures are point measurements, both in terms of space and time. Considerable uncertainty is involved when extrapolating estimates, providing limited potential for expansive coverage or longer timescale interpretation (Yakubova et al., 2014).

Given the limitations of current laboratory-based approaches, the development of new, easy, and affordable devices is a priority (Acharya et al., 2022; Ewing et al., 2021). To date, alternative carbon measurement approaches require, due to their accuracy, comparison with dry combustion estimates to establish credibility (Cremers et al., 2001; Ewing et al., 2021; Wielopolski et al., 2011).

2. In-situ measurement

The most recent advances in in-situ carbon measurement build on laser-induced breakdown spectroscopy (LIBS), inelastic neutron scattering (INS), and infrared reflectance spectroscopy (Acharya et al., 2022; Chatterjee et al., 2009; Wielopolski et al., 2010).

Laser-induced breakdown spectroscopy (LIBS) is based on atomic emission spectroscopy, a method that uses the intensity of light emitted at a certain wavelength to determine the quantity of an element in a sample (Chatterjee et al., 2009; Wright & Stuczynski, 1996). In LIBS, a laser is focused on a soil sample. Through the heat that develops on the soil's surface, the chemical bonds are breaking and vaporize, resulting in a high-temperature plasma. The plasma emits light, which is characteristic of the elemental composition of the soil sample. With the help of a spectrometer the emission spectrum can be analyzed, and the soil C content can be quantified via the unique spectral signature of C. Calibration curves or models are required for each sample set (Chatterjee et al., 2009; Cremers et al., 2001; England & Viscarra Rossel, 2018). Strengths of LIBS include the possibility to detect multiple soil characteristics, the rapidity of soil C determination, and the portability of LIBS systems. Drawbacks relate to each measurement analyzing only very small soil volumes and the influence of soil properties on LIBS analyses, requiring sample-specific calibration curves (Chatterjee et al., 2009).

Inelastic neutron scattering (INS) was first proposed by Wielopolski et al. (2000). It is based on gamma ray spectroscopy. The INS method builds on the *"inelastic scattering of 14 MeV neutrons from C nuclei present in the soil and measurement of the resulting 4.44 MeV gamma ray emission".* The neutrons are produced by a neutron generator, while the gamma ray emissions are detected by NaI detectors (Gehl & Rice, 2007). The resulting spectrum of gamma rays is then analyzed in terms of C peak intensities, which are proportional to the soil C concentration. As in LIBS, calibration is required for different soil types and conditions (Gehl & Rice, 2007; Wielopolski et al., 2008). The technology can be used in static and scanning modes, with the latter allowing to get a mean value for the scanned area (Wielopolski et al., 2011). Results are available within one hour (Wielopolski et al., 2000). The main advantage of INS over LIBS and spectroscopic methods are its non-destructiveness, the much larger soil volume analyzed, and the sampling depth of up to 30cm (Wielopolski et al., 2010, 2011).

Disadvantages relate to the expensive and complex equipment (Acharya et al., 2022). Further, its large size and weight pose logistical challenges for in-situ measurements (Yakubova et al., 2017).

Spectroscopic methods can be used to characterize soil organic C based on absorptions at specific wavelengths (England & Viscarra Rossel, 2018). Fundamental features related to different components of soil organic matter generally occur in the mid-infrared (MIR) and near-infrared ranges (NIR) (Shepherd & Walsh, 2002). Hence both, MIR and NIR, are being used for quantifying soil C (Gehl & Rice, 2007). To predict the soil C content, calibration models are required to translate the unique spectral signatures into soil C estimations (England & Viscarra Rossel, 2018). The required datasets are referred to as spectral libraries (England & Viscarra Rossel, 2018; Shepherd & Walsh, 2002). The employment of machine learning has enabled rapid progress in NIR/MIR (Chen et al., 2020). After initial deployments in laboratories, spectroscopic methods can nowadays be used as portable handheld devices (Acharya et al., 2022).

The advantages of in-situ methods for SOC measurement are the real-time availability of results at the field level, the cost-effectiveness, and minimal training needs and soil disturbances (Ewing et al., 2021; Gehl & Rice, 2007). The resulting potential of in-situ measurements lies in the possibility to evaluate spatial and temporal variations of soil carbon at scale, which is unfeasible with laboratory methods (Gehl & Rice, 2007). Despite its potential, concerns relate to the possible trade-off between costs and accuracy (Ewing et al., 2021). No consensus exists on the most promising in-situ measurement technology. Acharya et al. (2022) see the largest potential for soil C measurements at the farm level in hand-held devices based on infrared reflectance spectroscopy. This is also the technology used in commercially available portable measurement devices such as the *Our Sci Reflectometer* and *Yard Stick* (Acharya et al., 2022; Ewing et al., 2021). Researchers from the Brazilian Agricultural Research Corporation (EMBRAPA) and the International Potato Center have jointly developed a portable device based on LIBS[1]. Further research is needed to improve existing portable devices together with in-field testing and benchmarking against SOC estimates obtained from dry combustion.

3. Remote sensing

We follow Angelopoulou et al. (2019) and distinguish three sources of remote sensing imagery: spaceborne, airborne, and unmanned aerial vehicles (UAVs). These so-called platforms differ in their spatial, spectral, and temporal resolution and, hence, their accuracy (Angelopoulou et al., 2019).

Spaceborne remote sensing refers to imagery retrieved from satellites (Angelopoulou et al., 2019). They provide the opportunity to map large areas. The spread of free and open-access satellite-based imagery has led to an increased interest in exploring the possibility of accurate SOC measurement (Angelopoulou et al., 2019). Through their fixed temporal resolution, satellites can be a useful source of time series data. However, prevailing weather conditions when passing the area of interest may lead to distorted images or missing data (Angelopoulou et al., 2019). Further, the resolution of digital mapping by satellites is limited by the resolution of remotely sensed data, which in much of the world does not match the sub-hectare scale of management (Ewing et al., 2021). **Airborne remote sensing** refers to remote data collected by sensors mounted on airplanes (Angelopoulou et al., 2019). As compared to satellite data, data collected by airplanes is more flexible as the measurement window can be adjusted to optimal flight conditions for SOC measurement (Angelopoulou et al., 2019; Usha & Singh, 2013). Due to their capacity to carry a great payload, they allow for wide spectral range hyperspectral sensors to be mounted on them (Angelopoulou et al., 2019). **Unmanned aerial vehicles**, also known as drones, fly at lower altitudes than satellites or aircraft, providing imagery with a high spatial resolution (Angelopoulou et al., 2019). Drones are, however, more limited in terms of flight duration and payload capacity (Angelopoulou et al., 2019).

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[1] Portable tool to measure carbon levels in soil | Water, Land and Ecosystems (cgiar.org) [last accessed. 11.01.2023]

The core advantages of all remote sensing approaches are their non-destructive nature, the coverage if large and potentially inaccessible areas, and the possibility to collect other soil features and auxiliary data (Angelopoulou et al., 2019). The main disadvantage is that the estimates are limited to the first few centimeters of the topsoil (Angelopoulou et al., 2019). With carbon farming encouraging the covering of bare soils, the potential for direct measurement of soil C by remote sensing is limited (Gehl & Rice, 2007). Further, the prediction accuracy of soil C from remote sensing is low (Acharya et al., 2022). As a result, a more important role of remote sensing is seen in the collection of auxiliary data such as soil cover and tillage, which can be used for model-based estimation of C sequestration (Gehl & Rice, 2007).

6.3 Approaches for measuring carbon sequestration in biomass

6.3.1 Determining above-ground biomass

Above-ground tree biomass is most directly and accurately quantified by harvesting, drying, and weighing all trees in a given area (Gibbs et al., 2007). This is, however, impractical at scale as it is destructive and time-consuming (Gibbs et al., 2007; Henry et al., 2011; Ketterings et al., 2001).

Alternative approaches rely on the estimation of above-ground biomass based on the extrapolation of data points from destructively harvested trees (Gibbs et al., 2007). Two methods are well-established and generally applied (Brown, 2002; IPCC, 2003). Firstly, biomass expansion factors (BEFs) allow to expand the merchantable volume of a tree to total aboveground biomass volumes that also include the non-merchantable volume. The above-ground biomass is in this approach calculated as the commercial tree volume multiplied by the wood density and the BEF (IPCC, 2003). Secondly, using allometric equations, above-ground biomass can be estimated based on measurable dimensions such as diameter or height (Drexler et al., 2021). This approach involves four steps; determining the functional form of the equation, selecting values for adjustable parameters in the equation, conducting field measurements of the input variables, calculating above-ground biomass for individual trees using the allometric equation, and performing summation to get area estimates (Ketterings et al., 2001).

Some authors argue that allometric equations can yield estimates as accurate as destructive sampling techniques, however, only if site- and species-specific coefficients are used (Dittmann et al., 2017; Drexler et al., 2021). Continuous updates of tree databases, expansion of tree coverage, and free access can be important means of further improving the accuracy (Brown, 2002).

Above-ground biomass mapping has traditionally been based on field sampling and forest inventories (Goetz et al., 2009). Remote sensing complements these approaches by allowing greater coverage and reducing the burden of traditional mapping (Mitchell et al., 2017). Despite major advances in the spatial estimation of above-ground biomass from satellite-based observations, field measurements will remain important for both the calibration as well as the validation of remote sensing models and approaches (Goetz & Dubayah, 2011).

6.3.2 Quantification of below-ground biomass

While methods for above-ground biomass measurement are well established, the below-ground biomass of trees is more difficult to measure (Brown, 2002). Direct quantification approaches include the excavation of roots and the soil core or pits method (Brown, 2002). For coarse roots, partial or complete excavation of roots is usually conducted (Brown, 2002). The collected roots are separated from soil, oven-dried, and weighted (IPCC, 2003). For fine and medium roots, the soil core or pits method is mostly applied (Brown, 2002). Soil samples are collected and the roots are then separated from the soil either through a root washing machine or by sieving through a fine mesh. As with coarse roots, the biomass is then oven-dried and weighted (IPCC, 2003). The methods to quantify below-ground biomass are destructive, time-consuming, and lack standardization (Brown, 2002).

For indirect approaches, researchers rely on the link between above-ground and below-ground biomass, i.e., root-to-shoot ratios (Brown, 2002; Martin & Thomas, 2011). Cairns et al. (1997) report root-to-shoot ratios ranging between 0.2 and 0.30, with the average being 0.26. IPCC (2006) provides reference root-to-shoot ratios for different domains and ecological zones derived from the literature, ranging on average from 0.2 to 0.56. Applying root-to-shoot ratios is practical and cost-effective (Brown, 2002). To ensure accurate estimations, a focus should be placed on existing databases and implementing standardized rigorous experimental designs (Brown, 2002).

In grassland ecosystems, a large proportion of biomass is below-ground. Conceptually, the methods used for estimating below-ground biomass in grasslands are not different from the above-mentioned (Gill et al., 2002; IPCC, 2003; Liu et al., 2021; López-Mársico et al., 2015). Nevertheless, the quantification of biomass in grasslands faces some unique challenges, notably through the exposure to frequent vegetation fires influencing biomass regrowth and root-to-shoot ratios as well as the influence of management activities, such as grazing, on biomass stocks (IPCC, 2003).

6.3.3 Converting above- and below-ground biomass to carbon

After estimating the total tree biomass, the estimate is usually converted to carbon by assuming a carbon fraction of 50% (Martin & Thomas, 2011). This estimate is based on average data from chemical analyses of woody tissues (Thomas & Martin, 2012). However, some authors argue that the carbon content of wood varies and suggest applying adjusted conversion factors (Lamlom & Savidge, 2003; Martin & Thomas, 2011). As a result, some protocols such as IPCC Good Practice Guidance for LULUCF (2003) allow the use of different C fraction values depending for example on the species, components of a tree or a stand, and age of the stand. This has been shown to significantly reduce biases (~2%) in forest C stock when compared to a 50% C fraction assumption (Martin & Thomas, 2011).

6.4 MRV approaches of carbon farming projects in Africa

6.4.1 Quantifying soil organic carbon changes in carbon credit projects

Methodologies for measuring and verifying carbon sequestration and the avoidance or reduction of GHG emissions in carbon credit projects are based on frameworks provided by verification bodies (Tamba et al., 2021). In the context of carbon farming projects, these are in particular Verra, Gold Standard, and Plan Vivo. In the following, we present selected monitoring, reporting and verification (MRV) approaches applied in carbon farming projects in Africa.

The earliest methodology for smallholder carbon farming projects is the Verra methodology VM0017 *'Adoption of Sustainable Agricultural Land Management'*, which has been developed within the scope of the pioneer Kenya Agricultural Carbon Project (KACP) in 2011 (see Box 1). As of 2023, seven projects in Africa are either registered or are applying for registration under this methodology (Verra, 2023b). This makes it one of the most applied carbon farming methodologies for smallholder farmers in Africa. Different from the approaches presented in section 6.2, the methodology does not involve soil sampling. Instead, changes in different carbon pools are estimated by combining activity data (e.g., changes in the area under mulching) with relative stock change factors (e.g., from scientific publications), which allows quantifying the net carbon removals for each activity. To collect the activity data, representative baseline and monitoring surveys are conducted in the project area (Tennigkeit et al., 2013). Verra will inactivate the methodology end of March 2023 to align it with best practices and scientific consensus in soil organic carbon (SOC) and agricultural greenhouse gas (GHG) accounting (Verra, 2023a). A potential replacement may be the VM0042 *'Methodology for Improved Agricultural Land Management'*, which was approved in 2020. Currently, six projects in Africa are being developed using this methodology. Though, none has been certified yet (Verra, 2023b). The methodology moves away from purely model-based estimations to a hybrid approach that combines modelling and soil sampling (Oldfield et al., 2021).

Verra with the AR-AMS007 methodology for ‘*Afforestation and reforestation project activities implemented on lands other than wetlands’* of the CDM (UNFCCC, 2013) and the Plan Vivo *‘Smallholder Agriculture Mitigation Benefit Assessment (SHAMBA)’* methodology (Plan Vivo, 2015) offer frameworks that allow projects to issue credits for both, changes in soil organic carbon levels as well as for changes in above- and below-ground woody biomass. As with Verra’s VM0017 methodology, changes in soil organic carbon levels are quantified based on models, using either relative stock change factors or the RothC carbon model. Though Gold Standard has recently developed a soil organic carbon methodology, the *‘Soil Organic Carbon Framework Methodology v 1.0’* that relies either purely on soil sampling or on a combination of soil sampling and modelling (Oldfield et al., 2021), it is not applied in registered projects (Gold Standard, 2023).

Overall, soil sampling and the best practices for measuring and monitoring changes in soil organic carbon levels as described in section 6.2 of this paper play a negligible role in existing smallholder carbon farming projects in Africa. However, the inactivation of Verra’s VM0017 methodology may indicate a shift in the market towards increased integration of soil sampling into smallholder carbon projects. This might reflect a demand for more rigorous methodologies for carbon credit projects.

6.4.2 Quantifying changes in above-and below-ground carbon in carbon credit projects

As described in section 6.3 of this paper, approaches for estimating above- and below-ground biomass based on biomass expansion factors and root-to-shoot ratios are well established. The commonly applied methodologies are the Gold Standard *‘Afforestation/Reforestation GHG Emissions Reduction & Sequestration Methodology’*, which is applied by nine out of ten Gold Standard carbon farming projects in Africa (Gold Standard, 2017, 2023). Most of Verra’s agroforestry projects in Africa (five) apply the AR-AMS007 methodology for *‘Afforestation and reforestation project activities implemented on lands other than wetlands’* of the CDM (UNFCCC, 2013; Verra, 2023b). The methodologies are in line with the IPCC Guidelines for National GHG Inventories and approaches described in section 6.3 of this paper.

7 Conclusion

In the debate on climate change and the potential of carbon farming, two aspects are stressed. First, the importance of reaching net-zero CO_2 emissions globally by 2050. Second, the need to transform food systems to address persistently high levels of food insecurity in some global regions, including Africa. Carbon farming has the potential to contribute to both objectives by promoting agricultural practices that increase carbon sequestration in soils and plants and contribute to the reduction or avoidance of GHG emissions while also increasing the productivity and long-term sustainability of agricultural production. However, smallholder farmers lack the financial means to invest in carbon farming practices and thereby capitalize on related opportunities. One solution to bridge this gap are payments linked to the implementation of carbon farming practices, thereby compensating farmers for the societal benefits that they generate. Based on a literature review, we assessed the opportunities and challenges for involving smallholder farmers in emerging agricultural carbon markets.

Applying a conceptual framework to analyse the engagement of smallholder farmers through financial incentives in emerging agricultural carbon markets, we placed a specific emphasis on four areas: agricultural markets as a funding institution for carbon farming, the role of payments for carbon sequestration, reduction or avoidance of GHG emissions in incentivizing the adoption of carbon farming practices, the aggregation of smallholder farmers into carbon farming groups, and the cost-effective monitoring, reporting, and verification of changes in carbon stocks.

Moreover, carbon farming fits the wider cross-sectoral sustainable bioeconomy opportunities in Africa. Positioning carbon farming in the strategic bioeconomy context provides a unified approach to emissions reduction, climate change mitigation, as well as the conservation of biodiversity and green innovations.

We started by assessing the current state of agricultural carbon markets and identifying the challenges hindering their growth. The lack of recognition of carbon farming practices in international climate change discussions and negotiations, the ineligibility of carbon sequestration projects in compliance markets, and the limited availability of carbon measurement methodologies are some of the challenges that need to be addressed. Furthermore, low carbon prices in the voluntary market and high ex-ante and transaction costs related to predicting outcomes and monitoring compliance with contract terms present significant barriers for carbon farming projects. Investors may also be wary of participating due to concerns about the environmental integrity of the market. This underpins the need to develop sound methodologies that address the potential concerns of investors.

The profitability of carbon farming practices is a crucial factor affecting farmers' willingness to adopt carbon farming. However, at currently low carbon prices, additional co-benefits such as improvements in agricultural production and productivity are required to induce farmer participation in carbon projects. As carbon prices are bound to increase, investment in carbon farming can be expected to rise, but without supportive policies and investments, smallholder farmers may not be the ones to benefit from resulting opportunities. Their adoption of carbon farming may face important financial and non-financial barriers such as participation rules that discriminate against mixed, small-scale production systems, lack of secure land tenure, high transaction costs, lack of resources to cover investment costs, and lack of education or technical assistance. To support the development of agricultural carbon markets, it is important to implement support measures such as capacity-building programs or promoting access to credit and insurance, securing land rights, and creating enabling regulatory and institutional frameworks. This could help address the identified barriers and enable farmers to participate effectively in carbon farming projects.

Transaction costs, such as ex-ante costs for developing baselines, certification, and administration are a significant barrier to the development of cost-effective carbon farming projects, especially for smallholder farmers. Low carbon prices in the voluntary market and high transaction costs make it difficult for carbon project developers to establish and run carbon projects, leading to the involvement of larger farms rather than smallholder farmers. Reducing transaction costs is essential for smallholder farmers to participate in carbon markets and benefit from carbon credit projects. Farmers and other community groups may serve as the anchor for implementation, receivers, and distributors of carbon payments, and provide support for project administration and communication. Improving the institutional capacity of farmer organizations is key to allowing them to take on these roles.

We further reviewed the importance of monitoring, reporting, and verification of changes in carbon sequestration, or reduction and avoidance of GHG emissions. For agricultural carbon markets to work, the accurate measurement and monitoring of changes in carbon stocks, both in soils and biomass, is key. To date, the most accurate approaches for measuring and verifying changes in soil carbon sequestration rely on laboratory methods. Due to high costs and logistical challenges, they are impractical for the monitoring of changes in SOC levels, especially in the context of smallholder carbon projects. More research will be needed to improve newly developed portable devices for in-situ carbon measurements at the field level.

Our review summarized the state of knowledge on the challenges and opportunities of engaging smallholder farmers in carbon farming and identifying priority areas for research supporting the development of well-functioning agricultural carbon markets. A shortcoming inherent to this approach is the focus on existing challenges rather than the presentation of potential solutions. We recommend future research on the accurate and cost-effective monitoring of changes in carbon sequestration. Further, implementation research that focuses on the institutional arrangements required to tap the potential for carbon credits to promote sustainable production methods in Africa will be need

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Annex

Table 1. Overview of carbon farming definitions used in the literature.[2]

Definition of carbon farming		Source
1. Environmental service provision		
(1)	“[…] land-use practices aimed at sequestering carbon in vegetation and soils.”	(Baumber et al., 2022)
(2)	“[…] farming practices that increase the carbon content in soils, mostly via photosynthesis.”	(Ollikainen et al., 2020)
(3)	“Carbon farming aims to improve the rate at which CO_2 is removed from the atmosphere and converted to plant material and soil organic matter.”	(Jansson et al., 2021)
(4)	“[…] management practices that accelerates the rate of removal of atmospheric carbon dioxide and locking them up into the plant material and/or soil organic matter.” / “[…] practices that are known to improve the rate at which CO_2 is removed from the atmosphere and converted to plant material and/or soil organic matter.”	(Debnath et al., 2022; Nath et al., 2015) based on (IPCC, 2007; Smith et al., 2014)
(5)	“Carbon farming practices aim to increase C sequestration and reduce GHG emissions.”	(Almaraz et al., 2021)
(6)	“[…] agricultural activities that can sequester carbon and/or reduce GHG emissions.”	(Tang et al., 2016)
(7)	“[…] a range of land management activities designed to either increase carbon sequestered in vegetation and soils or reduce greenhouse gas emissions from vegetation, soils and livestock.”	(Baumber et al., 2020)
(8)	“[…] involves practices that sequester or avoid the release of greenhouse gas (GHG) emissions in vegetation and soils, typically in agricultural landscapes.”	(Jassim et al., 2022) based on (Evans, 2018; Kragt et al., 2017; Lin et al., 2013)
(9)	“‘[…] range of land use and land management practices designed to reduce emissions from farming activities, or sequester carbon in natural sinks such as soil and vegetation.”	(Dumbrell et al., 2016) based on (Smith et al., 2008)
(10)	“[…] land-based management practices that either avoid or reduce the release of greenhouse gas emissions […] or promote active sequestration of carbon in vegetation and soils.”	(Kragt et al., 2016)
2. Economic business model		
(1)	“[…] refer to any land use in which landowners capture economic benefit linked to the amount of carbon sequestration.”	(Funk et al., 2014)
(2)	“[…] policy innovation to incentivise the management of native vegetation and soils to sequester carbon […]”	(Baumber et al., 2019)
(3)	“[…] a green business model that rewards land managers for taking up improved land management practices, resulting in the increase of carbon sequestration.”	(Holzleitner & Gawlik, 2022)
(4)	“[…] allows farmers to financially value their tree plantations as carbon storage (i.e., carbon farming).”	(Vannier et al., 2022)
(5)	“Farmers can register […] their fields with commercial providers who certify SOC increases […]. This provides additional income to farmers (“carbon farming”) […]“	(Paul et al., 2023)

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[2] We used the platform www.lens.org to conduct a review of existing definitions of carbon farming. Using the search term “carbon farming” and restricting the results to journal articles. After a preliminary review, we excluded those only including the term “carbon farming initiative”. The final review of definitions was then based on 212 journal articles.

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