International Journal of Environmental Monitoring and Analysis
2024, Vol. 12, No. 6, pp. 149-156
https://doi.org/10.11648/j.ijema.20241206.12

Review Article

Carbon Farming, Climate Smart Agriculture Practice and Current Climate Change Mitigation Strategy- In the Case of Ethiopia

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Abstract

Ethiopia is among the countries vulnerable to the impact of climate change due to its mostly resilient on rain-fed agriculture, but currently started crop production by irrigation even if it is not done in large, and largely rural population. Carbon farming is an emerging agricultural practice focused at mitigating climate change by increasing the carbon sequestration potential of farmlands. Both climate-smart agriculture and carbon farming encloses different approaches such as agroforestry, cover cropping, and application of bio-char and no-till farming, all of which promotes soil carbon sequestration and improves soil health; which help capture carbon dioxide from the atmosphere and store it in soil and vegetation. This system not only mitigates greenhouse gas emission but also fortifies ecosystem resilience through enhancement of soil fertility, water retention and biodiversity. By incorporating carbon farming into worldwide climate action frameworks, agricultural landscapes can evolve from being major sources of greenhouse gases to functioning as net carbon sinks. As scalable strategies to address climate change, carbon farming presents a dual advantage fulfilling the pressing requirements to reduce atmospheric CO_2 levels while promoting sustainable agricultural practice and enhancing rural economies. Climate-smart agriculture has emerged as a paradigm shifting approach aimed at improving agricultural productivity, adapting to evolving climatic conditions, and mitigating to the emission of greenhouse gas emissions. This review accentuates the significance of climate-smart agriculture and carbon farming as a crucial strategy for Ethiopia to fulfill its national determined contributions under the Paris agreement, while simultaneously bolstering the resilience of its agricultural system. By scaling up both approaches, Ethiopia can attain a harmonious equilibrium between food security and climate change mitigation; ensuring sustainable development for the rapidly expanding population.

Keywords

Carbon Farming, Sequestration, Greenhouse Gas, Mitigation, Sustainable Agriculture

1. Introduction

Agriculture is a fundamental component of Ethiopia's economy significantly influencing food security and socio-economic development. Different scholars [1, 2] reveled, 85% of the population relies on agriculture, which contributes to 46% of the GDP and 90% of export revenues. Various challenges such as soil fertility decline, limited access to

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Received: 28 November 2024; **Accepted:** 9 December 2024; **Published:** 25 December 2024

technology; like seed which significantly influenced the advancement of agriculture, since the initial documentation of crops by humans for the past 11,000 years [3], and weak linkage between different stakeholders and farmers hindered the agricultural productivity not to be as expected [4].

Climate smart agriculture practice trend is growing even if its acceptance is not as expected by smallholder farmers, but it is getting recognition of the need to adapt to climate change while enhancing agricultural productivity in Ethiopia. Despite the government's effort to promote climate smart agricultural practices, adoption rate among farmers remain low, influenced by different socio-economic factors. Carbon sequestration is connected to the process of extraction carbon dioxide from the atmosphere and sequestering it in an enduring carbon reservoir, ensuring its storage is conducted efficiently and devoid of leakage links [5].

Carbon farming has recently been advocated as a significant strategy for the mitigation of climate change through the enhancement of carbon sequestration or the reduction of carbon emission. Carbon is a very important element serving as an indispensable role in existence of life on the earth; constituting fundamental component of human deoxyribonucleic acid, DNA and it is ubiquitous in our dietary sources [6].

2. Climate-Smart Agriculture Practice Trend in Ethiopia

The increase in average temperatures, irregularities in precipitations trends, and heightened intensity and frequency of droughts, and floods, coupled with erratic rainy seasons, hurricanes, and variation in the concentration of atmospheric CO_2, represents conspicuous indicators of climate change that have significantly influenced and will persists in affecting the agricultural sector and productivity [7]. The phenomenon of climate depreciates the capacity of natural resources to deliver their services and poised to exert more effects on agricultural sector. Climate change encompasses a broad spectrum of detrimental repercussions on agricultural practices [8, 9]. In similar way [10, 11], stated that, climate change impose an influence on agricultural productivity within African continent, with a particular emphasis on Ethiopia, and [12] agricultural practices in Ethiopia are primarily reliant on rainfall rendering them susceptible to changes in precipitation patterns.

Abegaz A., et al. findings depicted, widely adopted climate smart agriculture practice (CSAP), includes, soil and water conservation (61.5%), integrated soil fertility management (56.5%), and agroforestry (48%) which gives a huge hope to adopt this technology to mitigate the current pressing climate issue [13]. In other dimension, practices like improved fodder and manure management have varying adoption rates, with improved fodder at 60.1% in some regions of the country [14]. In order to facilitate the establishment of climate-resilient agriculture and various production systems, nations needs to implement strategies to both adapt to and alleviate the repercussions of climate change. Enclosed by global, regional, and specifically African frameworks, Ethiopia serves as an exemplary case study from which significant insights can be derived.

3. Carbon Farming Strategies

Carbon farming strategies comprise a diverse array of practices designed to prove soil carbon sequestration while alleviating the adverse effect of climate change within the agricultural sector. These methodologies are progressively acknowledged for their capacity to enhance soil integrity, promote biodiversity, and yield economic advantage for agricultural stakeholders. In relation to mitigation strategies in the agricultural sector, the world wide technical mitigation capacity is projected to be in the range of ~ 5500-6000 $MtCO_2$-eq/yr, with the expected contribution from soil carbon sequestration accounting for 89% [15].

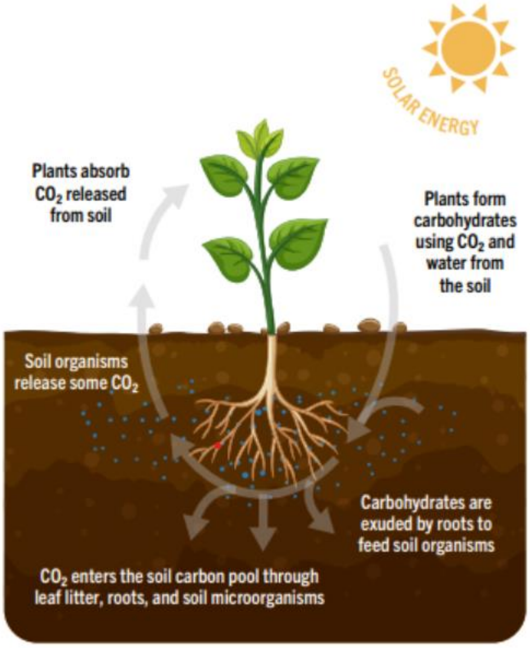

Figure 1. *Plants role in carbon sequestration.*

Source (https://www.stopwaste.org/at-home/home-and-community-gardening/carbon-farming) achieved on 01/11/2024

4. Carbon Farming Reflection through Different Practices

4.1. Cover Cropping

Utilizing cover crops constitutes a sustainable agricultural practice which significantly improves soil vitality, enhance agricultural productivity, facilitates effective weed control, and improves soil moisture content. This practice entails the cultivation of particular crops to envelop the soil, resulted in plethora of ecological advantages such as enhancement of soil microbial communities and optimization of nutrient cycling. Cover crops markedly improve the multi-functionality of soil, in the context of diminished precipitation, through modification in microbial community composition and the intricacy of network interactions [16]. The decomposition process of cover crop residue has the capacity to affect the level of oxygen in the soil, which resulted in heightened emissions of N_2O, especially when such residues are combined with nitrogen based fertilizers [17]. Leguminous cover crops exemplified by crimson, clover have been demonstrated to enhance nitrogen bio-availability facilitating superior corn yields in comparison to non-leguminous alternatives such as cereal type rye [18]. A comprehensive global synthesis revealed that the implementation of cover cropping typically culminates in a moderate yield improvement of 2.6%, with leguminous crops exhibiting a potential yield increase of up to 21.8% in the absence of fertilization [19]. Cover crops possess the capacity to inhibit weed proliferation via competitive interactions, physical obstructions, and allelophatic mechanisms, with specific species demonstrating in a reduced biomass requirement for effective weed suppression [20]. Although the implementation of cover cropping presents a multitude of advantages, there exist persistent challenges concerning the management of nitrogen availability and potential emission of greenhouse gases, thereby necessitating a meticulous selection and management of cover crop species to enhance overall agricultural outcomes.

4.2. Reduced Tillage

Reduced tillage implementation methodologies encompassing conservation tillage, has garnered significant scholarly interest due to their prospective advantages in agricultural systems, specifically in relation to soil integrity, crop productivity, and ecological sustainability. Nonetheless, the ramifications of reduced tillage are intricate and can fluctuate depending on particular circumstances and methodologies employed. Reduced tillage has the potential to enhance the soil moisture retention and diminish soil erosion, consequently resulting in enhanced agricultural productivity, as evidenced by maize research conducted in Ethiopia [21]. It is important to note that reduced tillage does not invariably lead to an increase in arbuscular mycorrhizal (AM) fungal diversity with certain investigations indicating a decline in AM fungal richness when reduced tillage in comparison to traditional agricultural practices [22].

4.3. Crop Rotation

Crop rotation strategies are instrumental in carbon farming initiatives, as they contribute to augmentation of soil organic carbon (SOC) concentrations and the enhancement of comprehensive soil vitality. Empirical studies suggested that varied crop rotations; that integrate cover crops and organic amendments, can facilitate heightened SOC sequestration and bolster resilience in climatic changes. Multi-crop rotations have demonstrated favorable soil organic carbon (SOC) balance, exhibiting considerable enhancement in SOC in comparison to monoculture rotations, as integrated with organic amendment such as farmyard manure [23]. The incorporation of cover crops within rotational system has been associated with 6-8% improvement in SOC alteration rates, thereby promoting soil health and mitigating nitrogen leaching phenomena [24]. Specific crop rotations, exemplified by the wheat-soybean system, facilitates increased microbial diversity enhanced carbon cycling mechanisms, resulting in elevated SOC concentrations attributable to optimized decomposition process [25]. Crop rotation practice, particularly in the semiarid regions, enhances water retention and reduces evapotranspiration, which is imperative in sustaining soil organic carbon levels during periods of drought [26]. Agricultural systems that combine crop and livestock production, incorporating leys and cover crops, can realize substantial increase in SOC, thereby supporting the initiative that aids and seeks to mitigate carbon emissions [27]. Although crop rotations confer advantage for carbon sequestration, it is of paramount importance to account for site specific conditions and management strategies to maximize their efficacy. Numerous studies indicated that in the absence of meticulous management, particular crop rotation can fail to deliver the anticipated soil organic carbon advantages, underscoring the necessity for customized methodologies in carbon farming.

4.4. Organic Inputs

Organic inputs are integral to concepts of carbon farming, facilitating the process of soil carbon sequestration while simultaneously promoting agricultural sustainability. Multitudes of research endeavors underscored the efficacy of organic methodologies, including the application of bio-fertilizers, compost, and cover crops, in enhancing soil quality and reducing greenhouse gas emissions. Numerical researches suggested that biofilm bio-fertilizers (BFBF) can sequester as much as 15 tons of stable carbon per hectare per season; surpassing the efficacy of traditional chemical fertilizers in the preservations of soil carbon reserves [28].

Table 1. *Soil labile carbon (SLC) as percentage of soil organic carbon (SOC) in two practices during three seasons.*

Season	Practice	SOC ($*10^4$ mg kg^{-1})	SLC ($*10^3$ mg kg^{-1})	SLC as a percentage of SOC
Dry	BFBF	1.60	1.97	12.3
2018	CF	1.35	1.48	11.0
Wet	BFBF	1.93	2.03	10.5
2018/19	CF	1.91	1.91	10.0
Dry	BFBF	2.31	2.89	12.5
2019	CF	1.77	2.64	15.0

Source: [28]

The incorporation of compost and organic fertilizers significantly improved soil structure and enhanced soil microbial activity, which in turn leads to heightened soil fertility and increased carbon sequestration; however, their initial application resulted in elevated greenhouse gas emissions [29]. Researchers indicated that organic farming practices have enhanced microbial populations and enzymatic activities, both of which were essential for maintaining soil health [30]. The adoption of carbon farming approaches, including cover cropping and reduced tillage, fosters biodiversity and augments ecosystem services, contributing to a more robust agricultural system [31]. Despite the advantages associated with organic inputs in carbon farming, challenges persisted concerning their implementation and the necessity for additional research to optimize these practices across varied agricultural contexts.

5. Soil Microbe's Role in Carbon Sequestration

Soil microorganisms exert huge influence on carbon sequestration by modulating the dynamics of soil organic carbon (SOC) and microbial-derive carbon (MDC). Their biochemical activities promote carbon retention through diverse mechanisms, such as the transformation of plant-derived carbon into stable compounds and the synthesis of microbial necromass. [32] revealed that, soil microbes played a pivotal role, in mediating the conversion of surface plant carbon into particulate organic carbon (POC), which has significant implications for the stability of soil organic carbon. As stated by [33], carbon-fixing microorganisms facilitates the assimilation of carbon via various metabolic pathways, with oxygenic phototrophs being the predominant group in specific soil environments. Microbial-derived carbon and soil health accounts nearly 40% of the global soil carbon reservoir, thus underscoring its critical role in carbon sequestration and the mitigation of climate change [34-36] found that an increase in microbial carbon use efficiency (CUE) within organic-rich soils enhances the potential for carbon sequestration, as active microbial assemblages preferentially allocate greater proportion of carbon towards biomass synthesis. The contribution of microbial necromass carbon (MNC) to soil organic carbon (SOC) is heterogeneous across different forest ecosystems, with boreal and temperate forests displaying elevated levels of microbial necromass carbon [36]. The incorporation of soil amendments such as bio-char and organic composts significantly enhanced microbial diversity and activity, thereby facilitating an increase in carbon sequestration [37]. Scholars depicted that these amendments establish conducive environments for microbial communities; improved soil microorganism's capacity to stabilize carbon within soil aggregates [38]. Even though soil microbe's role in carbon sequestration has been extensively documented, fundamental challenges persist regarding the precise quantification of their contribution and elucidation of intricate interactions within diverse ecosystems. This complexity accentuates the necessity for further investigations to refine microbial functionalities for improved carbon storage.

6. Policy and Economic Considerations in Carbon Farming

Carbon farming entails substantial economic and policy implications, especially regarding the mitigation of climate change. This practice encompasses strategies that improve carbon sequestration within agricultural and natural ecosystems; however, its execution encounters numerous obstacles, including market intricacies and regulatory structures. The operational landscape of carbon farming is situated both in regulated and voluntary carbon markets, which frequently exhibit a lack of standardization; complicating the engagement of producers [39]. The financial outlays associated with the implementation of carbon farming approaches can be substantial, but, the prospective income generated from carbon credits can serve to mitigate these expenditures over time [40]. Carbon farming in Ethiopia offers a complex array of prospects for both economic advancement and ecological sustainability. The amalgamation of agroforestry with carbon management methodologies has the potential to improve the economic conditions of smallholder farmers and simultaneously aiding in the mitigation of climate change. The revenue generated from carbon credits has enhanced economic potential and financial resources of farmers engaged in multi-strata agroforestry, with prospective earnings ranging from US$40 to US$100 per ton of CO_2 sequestered [41]. Initiatives aimed at participatory forest governance have resulted in a remarkable 143% increase in the average income of households within forest-dependent communities; fostering sustainable practices and minimizing dependence on agricultural expansion [42]. The adaptation of climate-smart agricultural practices not only serves to mitigate greenhouse gas emissions but also contributed to the stabilization of crop yields; enhancing food security [43]. The prevailing policies in Ethiopia predominantly emphasize economic growth, frequently overlooking the environmental ramifications associated with agricultural practices. More comprehensive and integrated strategies are imperative to harmonize economic and environmental objectives [44]. The complicated nature of carbon farming market, characterized by fluctuating standards and associated transaction costs, presents significant obstacles for farmers aspiring to engage in carbon farming [39]. The incorporation of carbon farming into pre-existing climate policy frameworks had multifaceted challenges, enclosed issues related to the monitoring, reporting and verification standards [45, 46]. Carbon farming constitutes essential elements of climate agenda, which aspires to achieve net-zero emissions by 2050; necessitating comprehensive policy frameworks to facilitate its advancement [47, 48]. Although carbon farming confers considerable economic and environmental advantages, the success of this initiative is dependent of the establishment of coherent policies that effectively bridge economic development with sustainability. Addressing the complexities inherent in the market and improving the integration of policies will be essential for optimizing the potential of carbon farming within the Ethiopian context.

7. Challenges of Climate-Smart Agriculture

Climate-smart agriculture (CSA) represents a compelling strategy pointed at bolstering agricultural dependence and improving productivity while simultaneously confronting the challenges posed by climate change. The realization of its potential encounters various impediments that necessitate remediation for its successful integration. The lack of unequivocal consensus regarding the definition and parameters of CSA complicates its application across diverse agricultural settings [49]. The inadequacy of financial incentives coupled with the absence of robust institutional frameworks obstructs the widespread implementation of CSA systems [50]. The incorporation of cutting-edge technologies including precision agriculture and data analytics remain limited; impending the operational efficiency of CSA initiatives [51, 52]. Different scholars, [53, 54] indicated that There exists a pressing need for further investigation to access the long term outcome of CSA on productivity and sustainability, particularly within varied agro-ecological regions.

8. Opportunities of Carbon Farming and Climate Smart Agriculture

Climate-smart agriculture (CSA) and carbon farming constitute essential methodologies in the endeavor to alleviate climate change while simultaneously bolstering agricultural sustainability. These strategies are designed to minimize GHG emissions, enhance soil vitality and secure food availability amidst the impending challenges posed by climate change [55]. Other scholars found, carbon farming was centered on the augmentation of soil organic carbon through different dimensions such as cover cropping, crop rotations, which have the capacity to reduce carbon emissions by as much as 60% in specific geographical areas [56]. By fostering diverse cropping systems, carbon farming contributes to the enhancement of biodiversity which is critical factor for the resilience of ecosystem. Climate-smart agricultural practices, including nutrient efficient and water-efficient techniques, can bolster resource utilization by as much as 30% and improve soil health by 20% [57, 58]. Households that implemented CSA exhibit an average annual farm income that is 20.3% greater than that of non-adopters, thereby underscoring the economic feasibility of these practices and contributing to enhance food security, as evidenced by a significant proportion of households attaining acceptable food consumption scores [59]. Other scholars also implied [50, 60] that, CSA encompasses the implementation of climate-resilient crop varieties and precision agriculture methods, both of which are essential for sustaining productivity amidst evolving climatic conditions.

Although producers implement a range of community supported agriculture approaches such as the diversification of crops, application of irrigation techniques, and the management of soil fertility through integrated practices; which are essential for effective response to the challenges posed by climate change. In the context of Ethiopia, although CSA presents substantial benefits, the necessity for precisely formulated policies and enabling frameworks is critical to mitigate prevailing obstacles and to foster enhanced adoption rates among agricultural practioners.

9. Conclusions

Climate change threatens agriculture globally, especially in vulnerable regions like Ethiopia. CSA practice such as soil and water conservation, agroforestry, integrated soil fertility management, and improved fodder build resilience. Carbon farming, which sequesters carbon while enhancing soil health and biodiversity, is crucial, with soil carbon sequestration accounting for 89% of agriculture's mitigation potential. Key strategies include cover crops, which improve soil health, productivity, and weed control, and leguminous crops, which boost nitrogen and yield but require careful management to minimize emissions. Reduced tillage enhances soil health, while crop rotation and organic amendments increase soil organic carbon and resilience, improving microbial diversity and carbon cycling. Combining crops with livestock also bolsters SOC and reduces emissions but requires tailored approaches. Organic inputs like bio-fertilizers, compost, and bio-char improve soil structure, microbial activity, and carbon sequestration. Biofilm bio-fertilizer can sequester up to 15 tons of carbon per hectare annually. Soil microorganisms are critical, converting plant carbon into stable SOC, with microbial necromass contributing significantly to carbon reservoirs. Despite its potential, carbon farming faces challenges such as high initial costs, regulatory barriers, and market complexities, though carbon credits offer financial incentives. In Ethiopia, practices like agroforestry enhance livelihood and mitigate climate change, but policies focused on economic growth over environmental concerns hinder progress. Integrated strategies and supportive policies are essential to achieve net-zero emissions by 2050.

10. The Way Forward

The future direction on carbon farming, CSA practices, and current climate change mitigation strategies involves a comprehensive, multifaceted approach that combines sustainable agricultural practices with innovative technologies. This transition is not only critical for combating climate change but also for ensuring long-term food security, improving livelihoods, and maintaining ecosystem health. Precision agriculture tools, remote sensing, and data analytics can optimize resource use, monitor carbon sequestration rates, and assess the impacts of various interventions. Developing drought resistant and climate resilient crop varieties through biotechnology and traditional breeding methods can further strengthen agricultural systems. Policy frameworks and financial mechanisms must also evolve to support these transitions. Government and international bodies should implement clear policies that incentivize carbon farming through subsidies, grants and carbon credit schemes. Establishing robust monitoring, reporting and verification systems can ensure accountability and transparency in carbon farming projects.

Capacity building and knowledge-sharing are equally important; providing training for farmers, particularly in vulnerable regions like Ethiopia, will empower communities to adopt climate-smart practices effectively. Collaborative research initiatives which refine these practices, tailoring them to diverse agro-ecological contexts and addressing specific challenges, such as reducing greenhouse gas emissions and enhancing microbial carbon efficiency. Finally, achieving these goals requires a holistic perspective that prioritizes environmental sustainability alongside economic growth. Coordinated efforts between governments, private sectors, NGOs, and local communities can align short-term developmental priorities with long-term climate mitigation goals, paving the way for a resilient and sustainable agricultural future.

Abbreviations

CSA	Climate Smart Agriculture
SOC	Soil Organic Carbon
MNC	Microbial Necromass Carbon
CUE	Carbon Use Efficiency
CSAP	Climate Smart Agriculture Practice

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] T. Wato, "Improvements of Crop Production through Integrated Soil Fertility Management in Ethiopia," *Asian J. Environ. Ecol.*, vol. 11, no. 1, pp. 1–11, 2019, https://doi.org/10.9734/ajee/2019/v11i130130

[2] H. Hailu and S. Feyissa, "Role of Integrated Nutrient Management on Soil Fertility Improvement and Selected Crop Production in Ethiopia: Review Study," *Int. J. Appl. Agric. Sci.*, vol. 9, no. 5, pp. 149–158, 2023, https://doi.org/10.11648/j.ijaas.20230905.14

[3] G. Abebe and A. Alemu, "Role of Improved Seeds Towards Improving Livelihood and Food Security At Ethiopia," *Int. J. Res. -GRANTHAALAYAH*, vol. 5, no. 2, pp. 338–356, 2017, https://doi.org/10.29121/granthaalayah.v5.i2.2017.1746

[4] L. D. Chibsa, Y. J. Hola, A. Extension, N. Resource, A. Extension, and N. Resource, "The Role of Researchers and Farmers Linkage in Agricultural Innovation System: Challenges and Intervention Options in Ethiopia," *Res. J. Financ. Account.*, vol. 13, no. 9, pp. 1–11, 2022, https://doi.org/10.7176/rjfa/13-9-01

[5] R. Lal, "Soil carbon sequestration to mitigate climate change," *Geoderma*, vol. 123, no. 1–2, pp. 1–22, 2004.

[6] R. Noble and D. Noble, *Understanding living systems*. Cambridge University Press, 2023.

[7] G. S. Malhi, M. Kaur, and P. Kaushik, "Impact of climate change on agriculture and its mitigation strategies: A review," *Sustainability*, vol. 13, no. 3, p. 1318, 2021.

[8] G. C. Nelson *et al.*, *Climate change: Impact on agriculture and costs of adaptation*, vol. 21. Intl Food Policy Res Inst, 2009.

[9] N. K. Arora, "Impact of climate change on agriculture production and its sustainable solutions," *Environ. Sustain.*, vol. 2, no. 2, pp. 95–96, 2019.

[10] A. Mekonnen, A. Tessema, Z. Ganewo, and A. Haile, “Climate change impacts on household food security and adaptation strategies in southern Ethiopia,” *Food Energy Secur.*, vol. 10, no. 1, p. e266, 2021.

[11] R. Solomon, B. Simane, and B. F. Zaitchik, “The impact of climate change on agriculture production in Ethiopia: application of a dynamic computable general equilibrium model,” *Am. J. Clim. Chang.*, vol. 10, no. 1, pp. 32–50, 2021.

[12] D. Conway and E. L. F. Schipper, “Adaptation to climate change in Africa: Challenges and opportunities identified from Ethiopia,” *Glob. Environ. Chang.*, vol. 21, no. 1, pp. 227–237, 2011.

[13] A. Abegaz, W. Abera, S. Jaquet, and L. Tamene, “Adoption of climate-smart agricultural practices (CSAPs) in Ethiopia,” *Clim. Risk Manag.*, vol. 45, no. March, p. 100628, 2024, https://doi.org/10.1016/j.crm.2024.100628

[14] E. Balcha, H. T. Menghistu, A. Zenebe, T. Teferi, and B. Hadush, “Climate-smart agricultural practices: a case of dairy cooperative farmers in Agula and Maychew, Northern Ethiopia,” *Carbon Manag.*, vol. 14, no. 1, p., 2023, https://doi.org/10.1080/17583004.2023.2271880

[15] P. Smith, “Land use change and soil organic carbon dynamics,” *Nutr. Cycl. Agroecosystems*, vol. 81, no. 2, pp. 169–178, 2008, https://doi.org/10.1007/s10705-007-9138-y

[16] Y. Guo *et al.*, “Microbial communities mediate the effect of cover cropping on soil ecosystem functions under precipitation reduction in an agroecosystem,” *Sci. Total Environ.*, vol. 947, p. 174572, 2024.

[17] F. Lussich, J. K. Dhaliwal, A. M. Faiia, S. Jagadamma, S. M. Schaeffer, and D. Saha, “Cover crop residue decomposition triggered soil oxygen depletion and promoted nitrous oxide emissions,” *Sci. Rep.*, vol. 14, no. 1, pp. 1–14, 2024, https://doi.org/10.1038/s41598-024-58942-7

[18] R. KC and S. Snapp, “Cover crop quality and quantity influences organic corn performance more than soil context,” *Nutr. Cycl. Agroecosystems*, vol. 129, no. 2, pp. 185–201, 2024, https://doi.org/10.1007/s10705-024-10368-3

[19] Y. Peng, L. Wang, P. A. Jacinthe, and W. Ren, “Global synthesis of cover crop impacts on main crop yield,” *F. Crop. Res.*, vol. 310, no. 2024, pp. 1–32, 2024, https://doi.org/10.1016/j.fcr.2024.109343

[20] R. Gerhards, M. Schumacher, M. Merkle, W. A. Malik, and H. P. Piepho, “A new approach for modelling weed suppression of cover crops,” *Weed Res.*, vol. 64, no. 3, pp. 219–226, 2024, https://doi.org/10.1111/wre.12627

[21] M. A. Handiso, A. H. Hemacho, B. L. Bongido, and M. M. Anjulo, “Effect of conservation tillage on soil and water conservation, yield and yield components of Maize (Zea mays L.) in South Ari District, Southern Ethiopia,” *Discov. Agric.*, vol. 1, no. 1, 2023, https://doi.org/10.1007/s44279-023-00008-9

[22] T. Vahter *et al.*, “Reduced tillage intensity does not increase arbuscular mycorrhizal fungal diversity in European long-term experiments,” *Eur. J. Soil Sci.*, vol. 75, no. 4, pp. 1–12, 2024, https://doi.org/10.1111/ejss.13546

[23] T. Šimon, M. Madaras, M. Mayerová, and E. Kunzová, “Soil Organic Carbon Dynamics in the Long-Term Field Experiments with Contrasting Crop Rotations,” *Agric.*, vol. 14, no. 6, 2024, https://doi.org/10.3390/agriculture14060818

[24] A. Attia, C. Marohn, A. R. Shawon, A. de Kock, J. Strassemeyer, and T. Feike, “Do rotations with cover crops increase yield and soil organic carbon?—A modeling study in southwest Germany,” *Agric. Ecosyst. Environ.*, vol. 375, no. November 2023, 2024, https://doi.org/10.1016/j.agee.2024.109167

[25] Y. Zhang *et al.*, “Metagenomic insights into microbial variation and carbon cycling function in crop rotation systems,” *Sci. Total Environ.*, vol. 947, p. 174529, 2024.

[26] X. Zhang *et al.*, “Crop rotation with plastic mulching increased soil organic carbon and water sustainability: A field trial on the Loess Plateau,” *Soil Use Manag.*, vol. 39, no. 2, pp. 717–728, 2023.

[27] J. D. L. Rios, A. Poyda, T. Reinsch, C. Kluß, F. Taube, and R. Loges, “Integrating Crop-Livestock System Practices in Forage and Grain-Based Rotations in Northern Germany: Potentials for Soil Carbon Sequestration,” *Agronomy*, vol. 12, no. 2, 2022, https://doi.org/10.3390/agronomy12020338

[28] A. Jayasekara, S. Ekanayake, M. Premarathna, D. Warnakulasooriya, C. Abeysinghe, and G. Seneviratne, “Organic material inputs are not essential for paddy soil carbon sequestration,” *Environ. Challenges*, vol. 8, no. February, p. 100551, 2022, https://doi.org/10.1016/j.envc.2022.100551

[29] G. Badagliacca, G. Testa, S. G. La Malfa, V. Cafaro, E. Lo Presti, and M. Monti, “Organic Fertilizers and Bio-Waste for Sustainable Soil Management to Support Crops and Control Greenhouse Gas Emissions in Mediterranean Agroecosystems: A Review,” *Horticulturae*, vol. 10, no. 5, 2024, https://doi.org/10.3390/horticulturae10050427

[30] L. Jamar, H. Magein, M. Lateur, M. Aubinet, and M. Culot, “Effect of organic farming practices on five orchard soil bioindicators,” *Acta Hortic.*, vol. 873, no. 1, pp. 129–136, 2010, https://doi.org/10.17660/ActaHortic.2010.873.13

[31] D. I. Avasiloaiei, M. Calara, P. M. Brezeanu, N. S. Gruda, and C. Brezeanu, “The Evaluation of Carbon Farming Strategies in Organic Vegetable Cultivation,” *Agronomy*, vol. 13, no. 9, p. 2406, 2023.

[32] M. Chen *et al.*, “Effects of Soil Microorganisms on Carbon Sequestration under Different Mixed Modification Models in Pinus massoniana L. Plantation,” *Forests*, vol. 15, no. 6, pp. 1–13, 2024, https://doi.org/10.3390/f15061053

[33] M. Le Geay, K. Mayers, M. Küttim, B. Lauga, and V. E. J. Jassey, “Development of a digital droplet PCR approach for the quantification of soil micro-organisms involved in atmospheric CO2 fixation,” *Environ. Microbiol.*, vol. 26, no. 6, pp. 1–20, 2024, https://doi.org/10.1111/1462-2920.16666

[34] H. J. Jiang, T. C. Underwood, J. G. Bell, S. Ranjan, D. Sasselov, and G. M. Whitesides, "Mimicking Lighting-Induced Electrochemistry on the Early Earth," *Proc. Natl. Acad. Sci.*, vol. 120, p. 2017, 2017, https://doi.org/10.1073/pnas

[35] H. Hu *et al.*, "Reducing the uncertainty in estimating soil microbial-derived carbon storage," *Proc. Natl. Acad. Sci.*, vol. 121, no. 35, p. e2401916121, 2024.

[36] Q. Xu *et al.*, "Active microbial population dynamics and life strategies drive the enhanced carbon use efficiency in high-organic matter soils," vol. 15, no. 3, 2024.

[37] D. V. R. T. Amulothu *et al.*, "Microbial Responses to Carbon Sequestration Soil Amendment and Productivity," *Int. J. Environ. Clim. Chang.*, vol. 13, no. 10, pp. 3587–3597, 2023, https://doi.org/10.9734/ijecc/2023/v13i103029

[38] M. K. Shahid, A. Kashif, P. R. Rout, and Y. Choi, "An overview of soil bacteria for CO2 sequestration," *Adv. Agric. Ind. Microbiol. Vol. 1 Microb. Divers. Appl. Agroindustry*, pp. 91–103, 2022.

[39] S. Mooney and K. Janoski, "Economic considerations for the development of a carbon farming scheme.," 2022.

[40] C. Holzleitner, " Carbon farming in the EU," *Food Sci. Technol.*, vol. 36, no. 1, pp. 36–39, 2022, https://doi.org/10.1002/fsat.3601_10.x

[41] P. Waldén, M. Eronen, J. Kaseva, M. Negash, and H. Kahiluoto, "Determinants of the economy in multistrata agroforestry in Ethiopia," *Land use policy*, vol. 141, no. April, 2024, https://doi.org/10.1016/j.landusepol.2024.107162

[42] D. Collison, "Carbon Management through Participatory Forest Governance in the Bale Eco-region, Oromia, Ethiopia," in *EGU General Assembly Conference Abstracts*, 2023, p. EGU-3161.

[43] D. Feliciano, J. Recha, G. Ambaw, K. MacSween, D. Solomon, and E. Wollenberg, "Assessment of agricultural emissions, climate change mitigation and adaptation practices in Ethiopia," *Clim. Policy*, vol. 22, no. 4, pp. 427–444, 2022, https://doi.org/10.1080/14693062.2022.2028597

[44] T. Dejenie and T. Kakiso, "Development and environmental policies of Ethiopia: Policy review from view point of development-environment sustainability linkage," *Heliyon*, vol. 9, no. 6, p. e16608, 2023, https://doi.org/10.1016/j.heliyon.2023.e16608

[45] S. Hönle and C. Heidecke, "Status and current considerations on carbon farming in selected European countries," in *EGU General Assembly Conference Abstracts*, 2023, p. EGU-17445.

[46] P. Günther, B. Garske, K. Heyl, and F. Ekardt, "Carbon farming, overestimated negative emissions and the limits to emissions trading in land-use governance: the EU carbon removal certification proposal," *Environ. Sci. Eur.*, vol. 36, no. 1, 2024, https://doi.org/10.1186/s12302-024-00892-y

[47] G. Kyriakarakos, T. Petropoulos, V. Marinoudi, R. Berruto, and D. Bochtis, "Carbon Farming: Bridging Technology Development with Policy Goals," *Sustain.*, vol. 16, no. 5, 2024, https://doi.org/10.3390/su16051903

[48] F. Schilling, H. Baumüller, J. Ecuru, and J. von Braun, "Carbon farming in Africa: Opportunities and challenges for engaging smallholder farmers," 2023.

[49] Y. Lou *et al.*, "Climate-smart agriculture: Insights and challenges," *Clim. Smart Agric.*, vol. 1, no. 1, p. 100003, 2024, https://doi.org/10.1016/j.csag.2024.100003

[50] M. Safdar *et al.*, "Climate smart agriculture and resilience," *Emerg. Technol. Mark. Strateg. Sustain. Agric.*, pp. 28–52, 2024, https://doi.org/10.4018/979-8-3693-4864-2.ch002

[51] A. Kumari *et al.*, "Climate smart agriculture: A roadmap to sustainable agriculture," *Conserv. Halting Reinstating Degrad. Nat. Resour. Dur. UN Decad. Ecosyst. Restor.*, vol. 14, no. 7, pp. 187–204, 2023.

[52] J. Mehraj *et al.*, "Climate Smart Agriculture: A Roadmap to Sustainable Food Security," *Int. J. Environ. Clim. Chang.*, vol. 14, no. 7, pp. 234–253, 2024.

[53] M. M. Ahmed *et al.*, "Climate-smart agriculture for resilience and profitability," *Sustain. Pract. Agric. Mark. Converg.*, pp. 27–50, 2024, https://doi.org/10.4018/979-8-3693-2011-2.ch002

[54] A. Chandra, K. E. McNamara, and P. Dargusch, "Climate-smart agriculture: perspectives and framings," *Clim. Policy*, vol. 18, no. 4, pp. 526–541, 2018.

[55] A. A. Berhanu, Z. B. Ayele, and D. C. Dagnew, "Impact of climate-smart agricultural practices on smallholder farmers' resilience in Ethiopia," *J. Agric. Food Res.*, vol. 16, p. 101147, 2024.

[56] S. Spotorno, A. Gobin, F. Vanongeval, A. Del Borghi, and M. Gallo, "Carbon Farming practices assessment: Modelling spatial changes of Soil Organic Carbon in Flanders, Belgium," *Sci. Total Environ.*, vol. 922, p. 171267, 2024.

[57] B. Bhattarai, L. Gurung, J. S. Rawal, and G. R. Joshi, "Integrating climate - smart agriculture for sustainable agriculture : Opportunities, challenges and future directions," vol. 9, no. 3, pp. 449–458, 2024.

[58] N. K. Arora and I. Mishra, "Sustainable development goal 13: recent progress and challenges to climate action," *Environ. Sustain.*, vol. 6, no. 3, pp. 297–301, 2023.

[59] A. Belay *et al.*, "Does climate-smart agriculture improve household income and food security? Evidence from Southern Ethiopia," *Environ. Dev. Sustain.*, vol. 26, no. 7, pp. 16711–16738, 2024, https://doi.org/10.1007/s10668-023-03307-9

[60] K. T. Erekalo and T. A. Yadda, "Climate-smart agriculture in Ethiopia: adoption of multiple crop production practices as a sustainable adaptation and mitigation strategies," *World Dev. Sustain.*, vol. 3, p. 100099, 2023.