Carbon Farming: A Holistic Review of Efforts to Maximize Carbon Sequestration in Agriculture

Aria Sanya

Abstract

Agriculture is ripe with opportunities for carbon capture and sequestration. Carbon farming refers to the management of agricultural land in order to maximize the storage of carbon in soil. Not only does carbon farming have the potential to offset its own sectoral emissions, but it can potentially compensate for emissions in other sectors. This paper synthesizes previous studies on carbon farming to measure its efficacy as a method to sequester carbon. It finds that carbon farming is largely beneficial but requires the implementation of broader incentives and education in order to make it successful in the United States. The paper will discuss additional benefits of carbon farming besides sequestration, including increased biodiversity, the cultural connections that carbon farming techniques encourage, and profits through the carbon market. Obstacles to the mass adoption of carbon farming include accessibility, cost, and education. Additionally, the paper will outline future suggestions towards increasing the implementation of carbon farming–including an increase in government-funded incentives and information surrounding how to participate in the carbon market.

Introduction

Methods to actively remove carbon from the atmosphere through carbon sequestration must be utilized to offset anthropogenic emissions and slow the harmful effects of climate change and global warming (Scheid et al., 2023). This review is necessary to provide a holistic understanding of carbon farming, especially in the face of the impending climate emergency. This is especially relevant to the carbon impact of the United States, as the country accounts for around 25% of historic global emissions (Ritchie, 2019).

Overall, soil is the largest terrestrial carbon sink on Earth, so it is imperative to understand the most effective ways to utilize it (Sharma et al., 2021). Estimates suggest that US agricultural lands could sequester up to 250 million metric tons of carbon dioxide equivalent (mtCO2e)–around 4% of US emissions–annually through conservation practices (National Academies, 2019). Carbon farming is the process of managing farmland to maximize the rate of carbon sequestration, such that agriculture has net negative carbon emissions. Carbon farming practices are designed to remove carbon from the atmosphere and store it in plant material (Winfield & Ostoja, 2020), where it will then be known as soil organic matter (SOM) and will stay for as long as these practices are maintained.

SOM includes soil microbes, decaying organic material, and humus. SOM also aids soil's water retention, structure, and fertility, enhancing plant productivity and suggesting higher yields. Higher yields allow farmers to accumulate more profit. Additionally, it reduces erosion–a factor that can negatively impact aquatic ecosystems–and improves surface water quality by filtering out contaminants, further reducing the negative impacts soil can have on its surroundings (Ontl & Schulte, 2012).

Soil organic carbon (SOC) is the measurement of carbon in SOM and can be used to determine the productivity of soil carbon sequestration. Human activities to convert the natural ecosystem to agricultural land–through factors such as soil tillage, erosion, and reduced plant biomass–have led to the depletion of SOC levels over time (Ontl & Schulte, 2012); thus, there exists a need to find sustainable ways to manage farmland.

However, alongside the pressure for farmers to adopt carbon farming methods, questions arise relating to the profitability, education, and policy/incentives related to these practices in the United States (Sharma et al., 2021). This essay aims to weigh the benefits and drawbacks of carbon farming to measure its effectiveness.

Techniques

Carbon farming techniques prioritize minimal soil disturbance and encourage regenerative and strengthening soil practices. Techniques include low or no-till farming (Lal et al., 2015) and the utilization of cover crops (Jansson et al., 2021). Both minimize carbon release by keeping it “locked” in the soil, additionally preventing erosion.

The diversification of cover crops, crop residue mulch, and integrated nutrient management (INM)–manure, biosolids, compost–and genetically altering crops help promote biodiversity, strengthen the fertility of the soil, increase SOM, and therefore help sequester carbon in the soil.

Alley cropping, agroforestry (Sharma et al., 2021), and afforestation (Wiltshire & Beckage, 2022) are all techniques that can be beneficial, as well. Alley cropping is the method of planting trees in rows to create “alleys” where crops can be grown, while agroforestry is the integration of trees and shrubs into crop/animal farming systems. Finally, afforestation is the establishment of forests on land not previously forested. The roots of the trees help keep soil down, preventing erosion. The increased shrubbery promotes biodiversity and can sequester carbon itself, while also enriching soil which can boost crop yields.

Moreover, afforestation can allow land to store the largest amount of SOC compared to other practices (Wiltshire & Beckage, 2022). Jansson et al. (2021) also suggest genetically modifying or breeding crops to increase root biomass/depth, allowing carbon to be stored deeper in the soil and for a longer period of time. However, it is important to understand that these methods can have trade-offs–such as high costs (Lal et al., 2015).

Co-benefits

Besides the long-term storage of carbon in soil, carbon farming also has many other benefits called co-benefits. These can not only benefit farmers, but also, indirectly, the surrounding community.

Environmental

There is substantial evidence that farmer participation in adopting carbon farming methods is driven by potential environmental co-benefits, rather than by financial returns (Barbato & Strong, 2024). A high level of SOC in soil indicates soil fertility and health, as it can store nutrients more effectively, thereby minimizing the need for nitrogen/fertilizer inputs and reducing costs. Enhancing soil quality can also improve farm productivity and allow for increased water movement and capacity in the soil. Both above and below-ground biodiversity can be better sustained in soil, depending on the carbon farming techniques used (Scheid, 2023). Carbon techniques to prevent erosion also prevent algal blooms and dead spots in nearby water bodies.

Social/Cultural

Many agricultural efforts to store carbon in an ecosystem are based on indigenous land management practices, meaning that carbon farming can help contribute to community development and education. Intercropping, or planting more than one crop together, as well as cover cropping, crop rotation, and polyculture derive from native practices (Weiss, 2022). Indigenous Americans also pioneered agroforestry and early methods of irrigation (Heim, 2020).

Increasing SOC in soil increases crop yield as SOC is necessary to hold water and nutrients, improving soil structure and biotic activity. Research found that an increase of 1 ton of SOC can increase wheat grain yield by 27 kg/ha in North Dakota (Lal, 2004). Therefore, soil carbon sequestration can potentially contribute to poverty relief and food security since it can result in higher yields–though it is important to keep in mind that increases will vary depending on the climate of an area. Higher yields also benefit the farmer directly, since the farm will be able to sell more crops and therefore, gather a higher income. This shows the importance of carbon farming not only for business, but also for community development.

Profitability

Biodiversity and Higher Yields

As noted above, carbon farming can help conserve biodiversity, which has been shown to increase plant resistance to climate events (Isbell et al., 2015). Additionally, it can help plants sustainably and naturally protect from pests and both wildlife and human diseases (Civitello et al., 2015). These points portray the effectiveness of conserved biodiversity as an aspect of carbon farming because it can result in higher yields which can increase profit. Additionally, it can result in higher quality produce, which can then be sold at a premium price.

Carbon Market

Farmers apprehensive about adopting carbon farming are mostly concerned about a potential decrease in their profits. The rising prevalence of the carbon market and the utilization of carbon credits have created a new avenue for the monetary success of carbon farming. A carbon credit is a permit that allows a company to produce a certain amount of carbon emissions. Groups can sell offset credits by *removing* a certain amount of carbon from the atmosphere. Excess credits a company has bought can be sold/traded between corporations and investors to reduce their footprint, through the carbon market.

Research shows optimistic results that carbon farming–through cover crops and no-till farming–can be profitable for US farmers through voluntary carbon market initiatives (Plastina et al., 2024). Different payment regimes can influence farmers' preferences due to varying carbon sequestration. For example, companies charging per outcome vs. per practice can attract different groups of farmers, based on the farmers' primary techniques (Plastina et al., 2024).

As Barbato & Strong (2023) found, many carbon farmers view carbon market benefits as a "bonus" on top of the profits they will anyway make; many agree that the economic benefits come second to the ecological and environmental benefits.

Government-issued Financial Incentives

Financial incentives exist in the USA to encourage farmer participation in carbon farming. In 2023, the Biden Administration began allocating $3.1 billion to encourage farmers, ranchers, and forest owners to transition to climate-smart practices, including carbon farming. The program emphasizes supporting disadvantaged and underserved agricultural operations to progress towards increased carbon sequestration and reduced emissions in their work. The USDA estimates that more than 60 million metric tons of carbon dioxide will be sequestered through this program (*Partnerships for Climate-Smart commodities,* n.d.). This is the equivalent of removing more than 12 million gas-powered vehicles from the road in one year (*Partnerships for Climate-Smart commodities,* n.d.). It has outlined 141 projects and involvement with nearly 100 universities (*Partnerships for Climate-Smart commodities,* n.d.), showing a large reach and institutional influence.

The USDA has more programs such as the Environmental Quality Incentives Program (EQIP), the Conservation Reserve Program (CRP), and the Agricultural Conservation Easement Program (ACEP) to help support farmers' conservation and soil carbon sequestration efforts too (United States Department of Agriculture, n.d.). These programs provide financial and technical aid.

Additionally, many local and state governments provide aid to support conservation efforts. Grants from non-profit organizations and private entities can also serve to aid farmers financially.

Obstacles

Despite financial incentives, studies have portrayed certain barriers to farmers adopting carbon farming strategies, including concerns about struggles to access market-related information and the costs of changing techniques.

Carbon Market Education and Dissemination of Information

Overall, lack of consistent, clear, and readily available information about carbon farming has hindered its adoption. Plastina et al. (2024) simulated the profitability of no-till farming and cover cropping, comparing limited vs. full information availability for farmers participating in the carbon market. They found that farmers with full information about the transaction and the amount of carbon their land/practices can sequester will generate more carbon credits than those with less. One of the most consistent complaints by farmers is the lack of clear understanding of carbon credit values and payouts. As Barbado & Strong (2023) outlined, carbon payments may be too low to incentivize farmers to adopt different agricultural strategies. Payments can be hard to predict as they are calculated differently between programs, especially for farmers new to adopting carbon strategies (Barbato & Strong, 2023).

Long-term profitability has also been an enduring worry among farmers. Wiltshire & Beckage (2022) found that SOC buildup in agricultural land is asymptotically limited, meaning that the rate of soil carbon sequestration will decrease over time. Farmers may not be able to receive the additional profit from the carbon market a few decades after the implementation of carbon farming techniques because of this limit.

In addition, farmers have expressed difficulty in digitizing documents and gathering records to input into the carbon market system. It may be challenging for farming businesses that are older, smaller, or do not already practice carbon sequestration strategies to participate in the market because of this technological transition (Barbato & Strong, 2023).

Finally, concerns continue to prevail over the ethics of the carbon market. For example, some farmers worry that it enables corporations to engage in greenwashing–using carbon credits to create an image of sustainability without making substantive changes to reduce fossil fuel usage (Barbato & Strong, 2023).

Methods

Changing techniques can be expensive and require different equipment and information that may not be readily available to farming businesses. Plastina et al. (2024) found that methods such as no-till farming and cover cropping had only been implemented in 26.4% and 3.9% of croplands in the lower 48 states, respectively. The US agricultural sector may only sequester the 250 million mtCO2e estimated by National Academies (2019) if a large transition to implementing soil carbon sequestration techniques occurs.

Discussion

Carbon farming has many co-benefits besides sequestration: environmental, social, and economic. These include strengthening the fertility of soil, increasing water quality, developing connection to indigenous communities, increasing yields, providing food security/poverty relief, encouraging carbon market participation, and advancing profitability.

However, it can be challenging for farmers to predict profitability of carbon farming. In regard to the carbon market, farmers are uncertain about (a) how much carbon their land will sequester and (b) what the value of carbon credits is, given discrepancies between companies, as simulated by Plastina et al. (2024). This demonstrates a lack of accessibility because farmers cannot guarantee that switching to carbon farming practices will have a better or worse impact on previous profitability. This demonstrates the importance of widespread information, education, and accessibility to guide farmers through the benefits and significance of carbon farming and carbon market participation.

Despite this, financial aid in the form of grants and government incentives exist to further support farmers. Increased yields as a product of sequestration efforts as well as the usage of organic farming can drive down equipment costs and increase profitability, too.

In summary, there must be better access to information about carbon farming and the carbon market, along with government-funded financial support to expand the use of carbon farming.

Such models have become administered under the Biden Administration in the United States. This approach creates optimism for the future of carbon farming and works to further the potential of this method of farming, as it invites access to agricultural workers with typically less opportunity. As a country that generates many emissions, the United States can also serve to influence other nations to participate in similar subsidy programs too.

Conclusion

In conclusion, carbon farming effectively reduces atmospheric carbon accumulation. Farmers who choose to implement carbon farming practices can expect to see rewarding effects on the environment, community, and their profits.

Despite the discussed challenges of carbon farming, it can serve as a beneficial practice that contributes to soil health and given the right conditions, provides an additional income stream for farmers. Carbon farming can provide long-term benefits to our food system and to the greater health of the environment.

The American agriculture sector can also influence other sectors to lower their carbon impact and work towards systemically utilizing sustainable forms of energy. America, as an industrial powerhouse, can serve to influence other countries to transition to carbon farming as well. Global agriculture will see long-term environmental benefits itself but can also intensely reduce the amount of carbon concentrated in the atmosphere. Given that there is a threshold for how much sequestration soil can endure, it is important to view carbon farming not as a complete solution that can alleviate climate change entirely, but as a measure to mitigate carbon impacts while larger, systemic changes–such as major policy reforms and converting to renewable energy–are pursued.

References

1. Barbato, C.T., Strong, A.L. Farmer perspectives on carbon markets incentivizing agricultural soil carbon sequestration. *npj Clim. Action* **2**, 26 (2023). https://doi.org/10.1038/s44168-023-00055-4

2. Civitello, D. J., Cohen, J., Fatima, H., Halstead, N. T., Liriano, J., McMahon, T. A., Ortega, C. N., Sauer, E. L., Sehgal, T., Young, S., & Rohr, J. R. (2015). Biodiversity inhibits parasites: Broad evidence for the dilution effect. In Proceedings of the National Academy of Sciences (Vol. 112, Issue 28, pp. 8667–8671). Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1506279112

3. Heim, T. (2020, October 12). The indigenous origins of regenerative agriculture - National Farmers Union. National Farmers Union - United to Grow Family Agriculture. https://nfu.org/2020/10/12/the-indigenous-origins-of-regenerative-agriculture/

4. Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., Bezemer, T. M., Bonin, C., Bruelheide, H., de Luca, E., Ebeling, A., Griffin, J. N., Guo, Q., Hautier, Y., Hector, A., Jentsch, A., Kreyling, J., Lanta, V., Manning, P., … Eisenhauer, N. (2015). Biodiversity increases the resistance of ecosystem productivity to climate extremes. In Nature (Vol. 526, Issue 7574, pp. 574–577). Springer Science and Business Media LLC. https://doi.org/10.1038/nature15374

5. Jansson, C., Faiola, C., Wingler, A., Zhu, X. G., Kravchenko, A., De Graaff, M. A., ... & Beckles, D. M. (2021). Crops for carbon farming. Frontiers in Plant Science, 12, 636709.

6. Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. Current Opinion in Environmental Sustainability, 15, 79–86.doi:10.1016/j.cosust.2015.09.002

7. Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science, 304(5677), 1623–1627.doi:10.1126/science.1097396

8. National Academies of Sciences, Engineering, and Medicine. 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

9. Ontl, T. A., & Schulte, L. A. (2012). Soil carbon storage. Nature Education Knowledge, 3(10).

10. United States Department of Agriculture. (n.d.). Partnerships for Climate-Smart commodities. USDA. https://www.usda.gov/climate-solutions/climate-smart-commodities

11. Plastina, A., Jo, H., & Wongpiyabovorn, O. (2024). The business case for carbon farming in the USA. Carbon Balance and Management, 19(1), 1-17.

12. Ritchie, H. (2019, February 9). *Who has contributed most to Global CO2 emissions?*. Our World in Data. https://ourworldindata.org/contributed-most-global-co2

13. Scheid, Aaron et al. 2023: Carbon farming co-benefits: Approaches to enhance and safeguard biodiversity. Berlin, Brussels: Ecologic Institute, IEEP.

14. Sharma, M., Kaushal, R., Kaushik, P., & Ramakrishna, S. (2021). Carbon farming: Prospects and challenges. Sustainability, 13(19), 11122.

15. United Nations. (n.d.). The Paris Agreement. United Nations. https://www.un.org/en/climatechange/paris-agreement

16. United States Department of Agriculture. (n.d.). *Climate-smart agriculture and forestry resources*. Farmers.gov. https://www.farmers.gov/conservation/climate-smart#:~:text=Environmental%20Quality%20Incentives%20Program,-The%20Environmental%20Quality&text=EQIP%20supports%20climate%2Dsmart%20conservation,building%20resilience%20for%20the%20future

17. Weiss, M. (2022, December 16). *Looking back to move forward: How today's carbon farming is rooted in indigenous growing practices*. Indigo Ag. https://www.indigoag.com/blog/looking-back-to-move-forward-how-todays-carbon-farming-is-rooted-in-indigenous-growing-practices

18. Wiltshire, S., & Beckage, B. (2022). Soil carbon sequestration through regenerative agriculture in the US state of Vermont. PLOS Climate, 1(4), e0000021.

19. Winfield, E., & Ostoja, S., USDA California Climate Hub (2020). Climate-smart agriculture: Soil health and carbon farming [Fact sheet]. DOI:10.32747/2020.7303347.ch