CARBON FARMING SCHEME

LIFE Preparatory Project

Impacts of carbon farming practices on biodiversity, nutrient leaching and climate – summary of the literature

Report from activity A4 of the LIFE CarbonFarmingScheme project

LIFE19 PRE FI001 – SI2.828588
The Life Carbon Farming project has received funding from the LIFE Programme of the European Union

The LIFE Preparatory Project

The LIFE Preparatory Project aims at identifying and accelerating the development and adoption of novel incentives for carbon sequestration and the increase and maintenance of the organic carbon stock in soil and biomass in Europe. With the aim of promoting a well-functioning carbon market, the project will uncover the key factors in supply and demand measures to invite the private sector to accelerate climate action. The project is co-funded by the LIFE Program of the European Union.

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3 May 2022

Integration of carbon farming in productive agriculture for co-benefits

Carbon (C) sequestration in agricultural soils is one of the main approaches in carbon dioxide removal from the atmosphere and storage in terrestrial ecosystems (Paustian et al. 2019). Adopting management practices such as improved crop rotations, cover cropping, cultivation of perennial grasses and legumes, agroforestry, crop residue retention, no or reduced tillage, organic fertilizers, application of biochar and other soil amendments, and improved grazing is key to increasing C content of mineral soils (Paustian et al. 2019, Almaraz et al 2021). When we use the term "carbon farming", we specifically mean practices integrated into regenerative agriculture, the holistic approach to food production that strengthens the ecosystem while producing food and increasing soil carbon stocks (Hagelberg et al. 2020).

Revegetation of agricultural landscapes through tree plantings, such as environmental plantings or agroforestry, is a common carbon sequestration strategy. Well planned land use changes related to carbon farming can result in increased vegetation diversity at the landscape scale, enhanced ecosystem services and increases in biodiversity overall. However, loss of remnant vegetation can degrade ecosystem services. Thus, focusing solely on carbon sequestration, for example through monoculture plantations replacing diverse remnants, can result in poor environmental outcomes (Lin et al. 2013).

Diversity is the key

Use of functionally diverse crop rotations with perennial and cover crops are efficient means to exploit otherwise unproductive niches in time (King and Blesh 2018). Reducing fallow periods and increasing plant diversity are also important for soil fungi (Hannula and Morrien 2022), which is known to have a crucial role in C cycling (Hannula and Morrien 2022, Yang et al. 2022). Diverse plant communities with diverse root architectures enhance aboveground-belowground interactions, which feed both soil biodiversity and the fungal biomass. The natural capacity of diverse soil communities to both sequester carbon as well as restore organic matter content of soils also increases crop yields (Zhang et al. 2021, Hannula and Morrien 2022).

A guiding principle for raising soil C is to increase perennial crop and constant vegetation cover (King and Blesh 2018). However, annual crops are also needed for food production. A potential path to increase soil C stocks is to select and design crop cultivars that deposit more carbon into the soil, either by a greater root biomass or by a greater surface area of roots. Although the root systems play a key role in soil organic carbon (SOC) supply and storage, the impact of greater root systems on long-term C storage is not obvious (Jansson et al. 2021). For example, a nine-year-old field trial in Michigan, USA, comparing different ecosystems demonstrated that a monoculture switchgrass had noticeably lower SOC levels when compared to a native successional community, although the belowground productivity of the switchgrass system was substantially higher (Kravchenko et al. 2019). Thus, it is not clear that breeding crops that produce higher root biomass is the path to more effective SOC storage (Jansson et al. 2021). Rather, a preponderance of deep rooting crops and a mix of crops with varied rooting depths on the same field is recommended (Hannula and Morrien 2022).

A long-term grassland experiment in Jena, Germany, has shown that higher plant species richness increases SOC content via its positive effects on root biomass, microbial growth, and microbial biomass carbon (Prommer et al. 2019). Similarly, a 22-year long experimental grassland restoration trial on abandoned farmland in Minnesota, USA found that higher plant diversity was associated with the greater rate of soil C sequestration (Yang et al. 2019). A meta-analysis by McDaniel et al. (2013) showed the importance of crop diversity on C sequestration: they found that soil C increased by 3.6% when one or more crops were added to a monoculture, and by 8.5% when crop rotation included a cover crop. Clearly, biodiversity can be used as a means for carbon farming.

Benefit to biodiversity depends on crop rotation

Carbon farming and biodiversity: a mutually beneficial relation

Common carbon farming practices can be beneficial to biodiversity. For example, agroforestry systems often successfully integrate food production with biodiversity conservation (Rolo et al. 2020). Numerous studies have shown positive impacts of both arable and pasture system agroforestry on floral, faunal, and/or soil microbial diversity (Tsonkova et al. 2012, Varah et al. 2013, Moreno et al. 2015, Plieninger et al. 2015, Gibbs et al. 2016, Oldén et al. 2016, Torralba et al. 2016, Udawatta et al. 2019). Agroforestry can help biodiversity in several ways, including providing habitats, creating ecological corridors between habitats, and providing an alternative to the agricultural systems involved in the degradation or destruction of natural habitats (Udawatta et al. 2019). Overall, high plant diversity is beneficial to biodiversity. Inclusion of cover crops, especially species rich cover crop mixtures, in crop rotations can promote functional diversity of the agroecosystem (Finney and Kaye 2016).

When it comes to no- or reduced tillage, contradicting results are found. For example, a review of German data showed different responses of soil biodiversity to tillage, as the species diversity of earthworms increased under lower tillage systems, but the diversity of collembolans and mites decreased with reduced tillage (van Capelle et al. 2012). Barré et al (2018) compared the effects of two tillage and weed control farming systems, conservation tillage using a cover crop and conservation tillage using herbicide, on common farmland birds abundance. Conventional tillage was used as a control. They found more birds in conservation tillage with a cover crop than in tilled study fields. The tilled fields had more birds than the conservation tillage using herbicides. Thus, herbicides had a greater negative impact on farmland birds compared to tillage.

Certain carbon farming practice can have the opposite effect on other taxa. For example, Morris (2021) reports that soils under regenerative grazing management (including holistic planned grazing) have increased microbial activity and often richer soil biota, but that different groups of floral and faunal communities respond inconsistently with increased, decreased, or neutral diversity. Thus, regenerative grazing is not universally beneficial to biodiversity but can be adapted to provide more heterogeneous habitat suitable to a wider range of biota. At landscape scale, this can be achieved by ranging from more intensively grazed patches to lightly grazed paddocks. Stocking densities, duration and timing of grazing can all be used to achieve the aim of creating the desired habitat mosaic (Morris 2021).

Every habitat within a farm contributes to the farm biodiversity. Thus, the biodiversity depends also on the coexistence of other habitats, including marginal habitats (Moreno et al. 2015). All field margins provide ecosystem services by providing the habitat for the beneficial insects that contribute to pollination and natural pest regulation (Cole et al 2020). Flower-rich field margins, especially in intensively cultivated cropland, can support threatened bumblebee species in Europe (Marja et al. 2018). Also, hedgerows are proven to be beneficial both for biodiversity (Heath et al. 2017, Vanneste et al. 2020), and for soil carbon accrual (Biffi et al. 2022). Biodiversity-increasing farming practices and small field size can enhance natural enemies without relying on chemical pest and weed control (Redlich et al. 2021).

Several meta-analyses and reviews have shown common carbon farming practices (Table 1) having either positive (Liu et al. 2016, Udawatta et al. 2019, Kim et al. 2020, Puissant et al. 2021, Hannula and Morrien 2022) or neutral (Torralba et al. 2016, Puissant et al. 2021) impact on soil microbial diversity. Except for agroforestry, which has shown to have a strongly positive impact on overall biodiversity (Torralba et al. 2016), the impact of carbon farming practices on above-ground floral and faunal diversity seems less studied.

Table 1. Effects of common carbon farming practices on biodiversity, water quality and N20 emissions, according to the literature. Numbers in each cell correspond to the respective meta-analysis, review article or large-scale modelling study listed below the table.

+ = positive impact

0 = neutral impact

- = negative impact

Practice	Biodiversity			Water quality			N_2O		
No/reduced tillage	+ 3	0 12	- 3	+ 1		- 15			- 8,16,17
Mulching/ residue retention	+ 14			+ 11		- 1			- 7
Cover crops/ green manure	+ 12,13,14,19	0 19		+ 1,8,9, 11,15,19	0 19		+ 17,19		
Agroforestry	+ 4,5,6			+ 6,8			+ 17	0 8,10	
Organic fertilizers/soil amendments	+ 2,12,14			+ 1			+ 8		- 21
Biochar				+ 8			+ 8,17,18		
Perennial leys	+ 19			+ 19		- 19	+ 19		
Regenerative grazing	+ 20	0 20,22	- 20				+ 23		

References:

1. Olin et al. 2015, 2. Hannula and Morriën 2022, 3. van Capelle et al. 2012, 4. Udawatta et al. 2019, 5. Torralba et al. 2016, 6. Tsonkova et al. 2012, 7. Zhao et al. 2020, 8. Almaraz et al. 2021, 9. Valkama et al. 2015,10. Kim et al. 2016, 11. Quemada et al. 2013, 12. Puissant et al. 2021, 13. Kim et al. 2020, 14. Liu et al. 2014, 15. Abdalla et al. 2019, 16. Huang et al. 2018, 17. Guenet et al. 2021, 18. Zhang et al. 2020, 19. Hyvönen et al. 2020, 20. Morris 2021, 21. Zhou et al. 2017, 22. McDonald et al. 2019, 23. Gomez-Casanovas et al. 2021.

Optimal drainage conditions and soil water table management as the foundation for carbon farming

Increasing soil C storage requires efficient growth of plants which, in turn, require favourable moisture conditions for growth. Unsuitably dry or wet conditions both limit plants' ability to grow, which directly affects the magnitude of the carbon input ending up into the soil (Heinonsalo, eds., 2020). Excess soil water limits field trafficability and crop growth in early season, while lack of water limits crop growth in late season. . In mineral agricultural soils, a well-drained soil is a prerequisite for carbon farming. Both intense rainfall and drought are also increasing phenomena, and controlled and shallow drainage systems can contribute to both adaptation to, and mitigation of, climate change (Castellano et al. 2019).

Under the precondition that soil drainage is sufficient, carbon farming practices can positively contribute to soil water management. Vegetation cover either by perennial leys, cover crops (Hyvönen et al. 2020), or agroforestry (Tsonkova et al. 2012, Torralba et al. 2016), promote erosion control and, thus, soil water conservation. An increase in soil organic matter (SOM) content improves soil aggregate stability, which reduces water erosion. However, the effect of SOM on soil water holding capacity is limited by the fact that SOM increases are often primarily concentrated in the surface soils rather than distributed throughout the full soil profile (Murphy 2015).

Water quality benefits depend on ability of soil and plants to retain and use nutrients

Carbon farming can help to reduce nitrogen leaching

The overall impact of carbon farming on water quality is positive. The common carbon farming practices have been shown to reduce nitrogen (N) leaching (Quemada et al. 2013, Olin et al. 2015, Abdalla et al. 2019, Hyvönen et al. 2020, Almaraz et al. 2021) with exceptions of some research showing increasing leaching by crop residue retention (Olin et al. 2015) and no-till (Abdalla et al. 2019).

According to meta-analysis by Almaraz et al. (2021), the net effect of carbon farming practices on N cycling was positive. The impacts are highly variable, depending on e.g., crop type and location. Sufficient available N is necessary to increase soil C storage capacity. Adoption of carbon farming practices can reduce N losses and decrease the need for additional N fertilizers. In some cases, additional N inputs may be needed to maintain soil C gains, and this can result in carbon farming increasing N losses to the environment. Combining different C farming practices (agroforestry, biochar, organic amendments, cover crops, no-till) can potentially decrease N leaching and N emissions while maintaining crop yields (Almaraz et al. 2021).

Most nitrate (NO_3^-) leaching occurs during the fallow season when the field is crop-free. Cover crops grown during the fallow season can take up surplus N and reduce leaching (Almaraz et al. 2021). Particularly, the use of non-legume cover/catch crop seems beneficial, while legume cover crops do not reduce N leaching (Quemada et al. 2013, Valkama et al. 2015). However, because yield gains are more likely to be achieved with the use of legume or mixed catch crops (Valkama et al. 2015), cover crop diversity is a good guideline.

Dissolved phosphorus poses a risk to waterways

Although long-term vegetation cover reduces erosion and particulate phosphorus (P) pollution, it also increases the dissolved P content of waterways. Long-term no-till management and vegetation boost the stratification of phosphorus in the surface soil, which further increases the risk of dissolved P leaching (Hyvönen et al. 2020). Despite the increased dissolved P pollution, Hyvönen et al. (2020) calculated that the fields covered by vegetation posed a significantly smaller overall risk to waterways compared to spring cereal fields ploughed in the preceding autumn. However, more research is needed about the risk of dissolved P in different cultivation systems and crop rotations.

Risk of emissions of other greenhouse gases must be considered

The risk of nitrous oxide emissions depends on the practice

Agricultural soils are an important source of nitrous oxide (N2O), which is a powerful greenhouse gas. The climate change mitigation potential of carbon farming can be overestimated if associated N2O are not taken into account. Some management options, such as addition of biochar to soils, can even reduce N2O emissions (Zhang et al. 2020, Almaraz et al. 2021, Guenet et al. 2021). The risk of induced N2O emissions must be considered, especially in the case of no/reduced tillage (Huang et al. 2018, Almaraz et al. 2021, Guenet et al. 2021), organic fertilizer application (Charles et al. 2017, Zhou et al. 2017), and crop residue retention (Zhao et al. 2020). In their compilation of results from multiple meta-analyses, Guenet et al. (2021) showed that N2O emissions in no-till systems may cancel out the C storage gain when expressed in CO2 equivalents. This finding is contrary to the outcomes of the other carbon farming practices reviewed reviewed by Guenet and colleagues.

Increased moisture and decreased aeration of soils under no-tillage enhance the activity of anaerobic soil microbes, which contributes to higher N2O emissions (Huang et al. 2018). No-till has been shown to increase N2O emissions in poorly aerated soils with restricted drainage, with lower impact in better aerated soils (Rochette 2008). Mei et al. (2018) report that conservation tillage-induced N2O emissions were significantly higher in the tropical and warm temperate climate, while no effect was found in the cool temperate climate.

The use of organic fertilizers may induce N2O emissions. Meta-analysis by Zhou et al. (2017) found that, compared to application of synthetic N fertilizer and as expressed as N2O emission factor, raw manure application significantly increased N2O emissions by 1.83%. However, pretreated manure application did not increase N2O emissions significantly. Whereas meta-analysis by Charles et al. (2017) showed that the emissions were higher when soils received organic fertilizers in combination with synthetic fertilizers, Xia et al. (2020) found no difference in net N2O emissions by manure, crop residue and synthetic fertilizer application. Subsurface manure application, which is strongly recommended practice to reduce ammonia (NH3) volatilization in soils, seems to increase N2O emissions (Zhou et al. 2017). The effects of organic fertilizer application are also site-specific and are dependant on conditions such as soil type and drainage (Charles et al. 2017, Zhou et al. 2017). Effective practices to reduce N2O emissions include applying manure fertilization to meet crop needs, using cover crops and managing grazing intensity (Montes et al. 2013).

Only slight methane fluxes in mineral soils

Methane (CH4) in soils is produced under anaerobic conditions. Wetlands and rice paddies are important sources of CH4 (Dutaur and Verchot 2007). Artificial drainage can reduce CH4 emissions through improved soil aeration (Castellano et al. 2019). A synthesis of a large data set collected across the United Kingdom showed that, compared to organic soils producing much larger emissions, the methane fluxes in mineral soils were only slight (Levy et al. 2012). A Boreal climate study conducted on well-drained mineral soil showed that the perennial grassland system acted as a sink for CH4 (Lind et al. 2020). Adaptive multi-paddock grazing (AMP) has been shown to decrease CH4 emissions from soils (Shrestha et al. 2020, Gomez-Casanovas et al. 2021). However, the enteric ruminant fermentation emissions can be higher under AMP, particularly at higher grazing intensities. It remains unknown whether the decreases in CH4 emissions from soil can partly offset the higher emissions from ruminants (Gomez-Casanovas et al. 2021).

Permanence – long-term effects are localized and largely under-researched

Complicated longevity of soil carbon

The permanence of carbon sequestered in soil is a question often posed in the context of C sequestration offsets (Dynarski et al. 2020). Soil is a complex environment with continuously moving and transforming organic compounds that affect carbon longevity. Although the mechanism by which fungi controls soil carbon stabilization is unknown to date (Hannula and Morrien 2022), it is generally accepted that the microbial – and particularly fungal – necromass favours the most persistent soil organic carbon build-up (Liang et al. 2019, Hannula and Morrien 2022). Deeper soil horizons have the potential to accumulate persistent soil C, yet research on C sequestration in deeper soils is rare (Dynarski et al. 2020).

Carbon sequestration has its limits and drawbacks. After adoption of a sequestering practice, carbon storage increases first, but the increase diminishes over time until it reaches a steady-state equilibrium. Retention of soil C requires that the sequestering practice be continued because otherwise the stored carbon is re-emitted (Thamo and Panell 2016). Because carbon sink saturation is specific to location and practice, it is highly variable and occurs over a period ranging from 10-100 years (Ruseva et al. 2020). Moreover, the addition of organic matter inputs to the soil can, through a process called priming effect, stimulate the decomposition of old and theoretically stable soil carbon (Dynarski et al. 2020, Liu et al. 2020). For example, cover cropping and inclusion of perennial crops in the crop rotation may result in tradeoffs in their contributions to C flow if the additional C supply accelerates microbial decomposition (Dynarski et al. 2020). Climate warming further complicates the soil C dynamics, which may result in negative consequences for soil C storage and atmospheric CO2 concentrations (Chen et al. 2020).

The adoption of carbon farming practices should not lead to carbon leakage. Leakage can be divided into two types: indirect leakage, meaning that emissions elsewhere result from substitutions in response to the sequestration; and direct leakage, meaning that emissions result from the sequestration activity (Thamo and Panell 2016). The risk of climate policy-related carbon leakage in the agricultural sector is under-researched (Arvanitopoulos et al. 2021).

Diversity increases the resilience of agroecosystems

Forests have traditionally been thought of as robust C sinks. However, a study in California, USA, an area known for its dry and fire prone ecosystems, showed that grasslands are more resilient C sinks than forests in response to rising temperatures. In the event of a wildfire, a smaller fraction of the grass biomass is damaged, when compared to trees (Das et al. 2018). Agroforestry systems can reduce wildfire risk compared to conventional forestry (Moreno et al. 2018) and, thus, provide a sustainable land management option in drought prone areas such as European Mediterranean countries (Damianidis et al. 2021). These studies further highlight the role of agricultural lands as C sink, even as forest soils generally store significantly higher amounts of C (Liang et al. 2019).

Agrobiodiversity, a fundamental part of carbon farming as discussed earlier in this paper, can provide farmers with natural insurance against fluctuations in agricultural production caused by environmental and market conditions (Baumgärtner and Guaas 2007, Augeraud-Véron et al. 2019). Generally, higher access to financial insurance results in lower agrobiodiversity (Baumgärtner and Guaas 2007). Safeguarding a greater number of species and restoring the functional biodiversity of the agricultural landscapes ensure improved ecosystem services, such as pollination, flood control, and pest control which, in turn, reduce the volatility of agricultural productivity (Gangatharan and Neri 2012, Augeraud-Véron et al. 2019). Biodiversity can also improve soil fertility resilience by reducing wind and water erosion. Since vegetation cover, irrespective of its diversity, tends to reduce erosion problems, a multi-species culture is more likely to provide better year-round cover (Gangatharan and Neri 2012).

CONCLUSION

It may not be possible to draw a universally valid conclusion of which carbon farming practices are best for all the aspects of environmental sustainability. Carbon farming practices should always be adopted in consideration of the local conditions at the regional, farm, and field scales. The evidence shows that carbon farming based on single measures cannot reliably produce climate change mitigation effects. Rather, in agriculture, it is always a matter of holistic farm and cropping cycle management which affects the aggregated impact in GHG mitigation, biodiversity, and water quality. Carbon sequestration and maintenance of carbon storage require active land stewardship and integration of carbon farming into productive agriculture to be a viable and resilient option for carbon dioxide removal from atmosphere.

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