TRANSNATIONAL CARBON FARMING TRAINING MATERIAL FOR FARMERS

DELIVERABLE D.1.1.1

Version 1

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CONTENT

1. INTRODUCTION AND SCOPE OF THE TASK

In the Carbon Farming CE project, this Deliverable 1.1.1 is linked to Activity 1.1, which includes all preparatory activities for testing carbon farming techniques. It is developed transnationally by the nine participating countries and 11 project partners.

The objective of Deliverable 1.1.1 is to provide training materials on carbon farming for farmers. It contains descriptions of seven carbon farming techniques and 12 best practice examples. It was written for farmers and in collaboration with farmers. Broad feedback from the practical perspective of implementing carbon farming techniques was generated through national co-creation workshops.

In addition to guidance on implementation, this deliverable provides insight to farmers into how each technique improves soil carbon levels, helping to mitigate the effects of climate change by reducing greenhouse gases in the atmosphere. It also promotes awareness of how carbon farming can restore and build resilience in soil health and maintain the safety of food production. It also discusses environmental impacts, economic impacts, and potential barriers and difficulties with practical implementation.

Also included are 12 best practice examples. These examples comprise documented carbon farming experiments that have already been completed, techniques implemented with a positive outcome in terms of C sequestration, and evidence of feasibility from a practical perspective.

As training material for farmers, this document is written in an easy-to-understand language. Nevertheless, correct citations and references are provided to give interested persons the possibility to research the topic further.

Deliverable 1.1.1 is part of the project's communication goal and is intended to generate farmer interest in carbon farming techniques and provide information about their ability to store CO_2 in the soil. In its original version, it is written in English. Nevertheless, each country will translate the document into its local language and disseminate the set of measures locally through agricultural channels to reach farmers and agricultural advisors.

2. DESCRIPTION OF SEVEN CARBON FARMING TECHNIQUES FOR FARMERS, INCLUDING INSTRUCTIONS FOR IMPLEMENTATION, EFFECTS ON CARBON SEQUESTRATION, ENVIRONMENTAL BENEFITS AND ECONOMIC IMPACT

2.1 EXTERNAL ORGANIC FERTILIZERS

Instructions for implementation:

The application of organic fertilizers is one method of introducing carbon (C) into agricultural soils. Agricultural holdings with livestock produce organic fertilizers on-farm. Stockless farms can gain access to organic fertilizers through cooperation with neighbouring farms or biogas plants trading in alfalfa or clover-grass as fodder, straw, or substrate (see 2.2). Organic fertilizers differ in their state of matter (solid or liquid) and, for granulate solid fertilizers, their grain size. Compost and solid manure can be applied with a spreader. Slurry should be applied with trailing shoe applicators or shallow injection systems to ensure quick soil infiltration and therefore prevent gaseous N_2O-losses (Webb et al. 2010). Try to avoid application during hot and dry conditions, especially with band spreading. Aside from losses during application, organic fertilizers are also subject to gaseous C-losses and gaseous and liquid losses of nitrogen in the form of ammonia and nitrous oxides due to metabolic losses during storage. That is why measures for low-loss storage must be taken. Legal limits are defined by EU (EU Nitrate Directive) and national authorities regarding water or air quality. For instance, Austria has set annual limits for nitrogen application for each crop regarding soil nitrate and ammonium (N_{min}) at crop cultivation and yield potential and has also defined a general application ban for the period between 15th November and 15th February to avoid leaching in periods with low soil activity. In general, the application of organic fertilizer should be limited to periods with high activity of microorganisms in soil and therefore high plant activity.

Effects on carbon sequestration:

By forming protecting aggregates, the effective organic matter content is particularly important for the establishment of stable humus (Quist, 2020). Solid organic fertilizers like compost or composted manure have the highest C-content and increase soil organic matter (SOC) (Rath et al., 2021). C-compounds stabilize over time as the period of conversion or composting increases and fugitive C-compounds are primarily used for microbial metabolism and lost as CO_2. Compost has a high organic matter content (Zethner et al., 2000) and compost organic matter is highly humified and its C/N ratio is like that of soil humus (Diez and Krauss, 1997; Smidt and Tintner, 2007). Around 50 % of the compost organic matter is effective for SOC reproduction (BGK, 2005).

Liquid organic fertilizers like slurry, semi-liquid manure or digestate contain much less C than solid organic fertilizers; their C-input and effect on carbon sequestration are small. Liquid fertilizer compounds are more easily decomposable. When relatively large amounts of easily decomposable organic matter are added at once, this can have a negative priming effect on the soil that can lead to additional short-term decomposition of the organic matter (Kolbe, 2010).

Mineral fertilizers do not contain carbon; they do not increase carbon balances.

Environmental benefits:

The use of organic fertilizers assures an input of organic matter (Kolbe, 2010) which is beneficial for geobiontic and surface-dwelling fauna, and microfauna as a food source for detritivores or for prey of predators (Anderson et al., 2017). Negative impacts like the leaching of nitrate and phosphate may lead to water pollution and must be avoided (Benke et al, 2017). Appropriate counter actions are concrete storage units for solid manure and compost or the use of wood chips as a ground layer of field heaps and windrows. Potential gaseous losses of nitrous oxide (N_2O), which has 298 times the global warming potential of CO_2, are most critical with the application of animal slurries, less critical with solid manure and least critical with fertilizing composts or pellets of clovergrass (Charles et al. 2017). Measured in carbon dioxide equivalents (CO_2e), emissions of on-farm produced, or locally traded organic fertilizers are significantly lower in comparison to externally purchased mineral fertilizers containing the same amount of nitrogen, see 2.2 (Bio Forschung Austria, 2022).

Economic impacts:

Different kinds of organic fertilizers call for different spreading techniques, the means for which are not necessarily present on-farm. Rental of off-farm machinery can be expensive. The use of on-farm machinery or at most one single off-farm piece of machinery is recommended to keep costs and working load low. Farms with livestock or compost save costs for external fertilizers that may lead to a total substitution of external fertilizers, see 2.2 (Bio Forschung Austria, 2022).

The main advantage of aerobic composting is the possibility to control the timing of the composting process by increasing or decreasing the rate of turning so that the compost is ready for application at the appropriate time. Still, compost turning is work-intensive and therefore expensive. Anaerobic conversion methods must not be turned (Witte, 2013). That is why the conversion process is less demanding, although windrows must be compressed at the end to create a plain surface and therefore the establishment is more complex. The main disadvantage of anaerobic methods is a lack of control over the process making the turnout of the final product unpredictable as well as limiting possible courses of action against process failures (Bio-Forschung Austria, 2022).

Possible obstacles and difficulties:

Weather conditions: Do not apply during heavy winds to ensure accuracy of application. Humid conditions during application may lead to worse environmental gaseous N_2O losses than anaerobic conditions in soil enhance denitrification and N_2O production (Charles et al., 2017). Aerobic conditions during storage of solid or liquid manure leads to much higher gaseous NH_3-losses, which should be prevented by covering heaps of solid and stocks of liquid manure (Paulsen et al. 2013, Kupper and Häni, 2018).

Farmers see some obstacles in the transport of organic fertilizers, e.g., compost, or animal manure without own animal husbandry, and in case of dusty matrices, how to manage the distribution/spreading. Furthermore, the high quantities needed, the possible presence of pollutants and heavy metals (e.g., in slurry or digestate), the sometimes, limited supply of readily available nutrients for the plants and at the same time possible leaching or emissions of compounds are concerns (outcome co-creation workshops Italy and Poland, pers. comm.). Nevertheless, the method of adding organic fertilizers such as livestock manure, compost or biochar is the one that farmers are most familiar with and consider most effective and important for carbon sequestration (outcome co-creation workshop Slovenia, pers. comm.)

2.2 RELOCATION OF HARVEST RESIDUES

Instructions for implementation:

Clover grass in the crop rotation ensures soil stability and increased soil fertility – benefits that stockless farms like to take advantage of as well. There are several choices for utilizing chopped harvest residues with low C/N such as fresh alfalfa or clover-grass or silage: use as mulch material, use as substrate for composting and using it as a trading good to exchange residues within a cooperation for manure or digestates.

Stockless organic farms, which cultivate alfalfa for natural N fertilization but cannot utilize the alfalfa biomass for fodder, may use the chopped material as mulch in young maize, sunflower, pumpkin, or potato crops. For that purpose, alfalfa is harvested in mid-June by forage harvester, blown onto a compost spreader driving alongside and applied to a young root crop at rates of 70-140 m^3/ha.

One advantage of cooperations is the possibility of using manure and slurry to fertilise other fields as required. With an exchange rate of 1 t of clover grass silage for 1.2 t of manure or 2,35m^3 slurry, promising and fair results regarding nutrients could be achieved (Erhart et al. 2023).

Harvest residues may also be used as input materials for composting or conversion for later use as organic fertilizer (see 2.1.).

Set up harvest residues to heaps or windrows for aerobic composting or covered heaps for anaerobic conversion methods such as microbial carbonisation according to Witte (2013). Obtaining enough moisture and N-rich raw material is crucial for successful conversion methods in dry areas. Ensuring enough air is flowing or obtaining C-rich raw material is crucial in wet areas. In general, a mix of approx. 2/3 C-rich substrates and 1/3 N-rich substrates is desirable for both aerobic and anaerobic conversion methods.

Farms that have given up cattle farming, but still own meadows may utilize the hay as an organic fertilizer for their freshly harvested fields and incorporate it before sowing a cover crop (see 2.3).

Effects on carbon sequestration:

Relocating harvest residues as mulch or organic fertilizer into row crops that usually decrease C_{org} in soil during vegetation period like maize, sunflower, potato, or rape may increase the total farm humus balance (Erhart et al. 2023, Kolbe, 2011). Relocation of C from alfalfa or cover crops can be considered as efficient as C supply in the donating field through sufficient belowground biomass (root mass). The surplus C of above-ground can thus be used for more efficient C-input within those crops limited to C_{org}. Soil organic matter content in cut-and-carry-systems rose compared to the previous dairy farm system (Erhart et al., 2023)

Though the humus effect of mulch must be considered in the long term, mulch reduces evaporation in the short term (Erhart et al., 2018, Erhart et al. 2023). Longer periods of soil moisture support enduring mineral sorption of C which is likely to lead to long-term soil carbon (Védère et al., 2020; Hagedorn et al., 2015).

In a fodder-manure-cooperation, solid manure has a much higher C-content than slurry and is preferred.

Environmental benefits:

Compared to the use of synthetically produced nitrogen fertiliser, a net saving of 200 – 600 kg of carbon dioxide equivalent (CO_2e) per 100 kg of nitrogen applied was achieved with closed-cycle-measures where harvest residues were relocated. Greenhouse gas emissions for production of 1 kg synthetically produced nitrogen fertiliser exceeded those emissions of 1 kg organic fertiliser produced with closed-cycle-measures where harvest residues were relocated by factor 1:1.8 to 1:27 (Bio Forschung Austria, 2022).

Transfer mulch in root crops is an important protection against evaporation, especially on hot days in early summer when the rows are not yet closed. At the same time, the mulch provides important soil protection during heavy rain events, in order not to lose the precious topsoil in root crops (Erhart et al. 2023). To transfer 1,000 kg of carbon to the receiving field by transfer mulch, a total of 98 and 203 kg of CO_2e were created by the machinery and transport processes for relocating harvest residues at two case studies. With increasing transport distance, the share of emissions caused by transport in total emissions rises steeply (Erhart et al. 2023).

Economic impacts:

Organic fertilizers can be created or organized from nearby farms with all their benefits (see 2.1) to substitute off-farm fertilizers which must be offset with the increased workload.

An economic comparison of cycle-based relocation actions with external fertilizers makes only sense with regard of nitrogen as functional unit because nitrogen content is leading motivation for professional use of external fertilizers. Further mineral fertilizers contain no C, that is why an economic comparison on base of C is simply impossible.

In comparison with commercial organic fertilisers suitable for use in organic agriculture, all cycle-based action using translocation of on-farm chopped alfalfa except of slurry cooperation (exchange alfalfa to slurry between farmers) and addition of charcoal for better composting achieved net cost savings in terms of nitrogen supply (Erhart et al., 2023).

In comparison with commercial conventional fertilisers not suitable for use in organic agriculture no method achieved net cost savings in terms of nitrogen supply only. It is important to underline that there is an input of C and many more different nutrients than N in organic fertilizers, but not in mineral fertilizers. Note that potential future prices for greenhouse gas emissions from production and transport are not calculated, which were significantly higher for N mineral fertilizer in all case studies (Erhart et al. 2023).

But relocating harvest residues is time consuming, which must not be underestimated.

Possible obstacles and difficulties:

Often additional off-farm machinery is necessary on one hand to load and transport residues as well as to spread organic fertilizers. Additional space for storage must be created or defined. There are legal restrictions for storage of organic fertilizers in many countries to reduce greenhouse gas emissions or leaching (see 2.2.). Relocating harvest residues is overall time consuming which might be an obstacle for implementation.

However, farmers viewed the technique of shifting postharvest residue as positive, as it can promote crop diversification within the cropping system. At least in the long run, this could increase the overall sustainability of agriculture. However, the impact on soil carbon content will vary depending on soil type, climate factors, and cropping pattern (outcome co-creation workshop Czech Republic, 2023, pers. comm.)

2.3 ADDITIONAL COVER CROPS

Instructions for implementation:

Cover crop cultivation should be executed with the same care as main crops. Therefore, the use of an adequate sowing technique is essential to ensure optimal sowing depths for cover crops. The species in the cover crop mixture must be adapted for sowing time and conditions (e.g., sorghum or sunflower need to be sown early in the hot months of July/Aug., radish or enduring crops prefer later dates of Sept./Oct.). To ensure satisfying field emergence, cover crops with different root systems and different temperature and moisture preferences should be mixed.

Sowing of cover crops during extremely hot and dry periods in summer should be avoided (Bio Forschung Austria, 2020). Several trials show a higher field emergence when cover crop cultivation is conducted later, after an extreme drought period, and once rain or dew has set in again (of course under dry enough soil conditions). Alternatively, cover crops can be undersown in spring to use the main crops' shadowing and cooling effect for successful youth development.

To make use of the benefits of summer and winter cover crops, a winter cover crop might be strewed carefully into a summer cover crop in October or sown after the summer cover crops' early termination.

Effects on carbon sequestration:

The cultivation of cover crops is a well-established on-site method to enhance on-field carbon stocks by prolonging periods of crop production on the field. (Adewole et al., 2020; Bio Forschung Austria, 2020; Blanco-Canqui et al., 2015; De Baets et al., 2011) The prevention of soil erosion is an appropriate countermeasure against C-losses and well-achieved with cover crops. The later the incorporation of cover crops, especially after winter – not before – the higher the benefits for soil protection and C-sequestration. (Blanco-Canqui et al., 2015; De Baets et al., 2011)

Cover crop cultivation increases soil organic carbon in sub soils (Rath et al., 2021). C-inputs in sub soils have often undergone several microbial transformation processes that result in simpler molecular structures (Roth et al., 2019). These simple microbial (C-)products may preferentially associate with mineral surfaces and may therefore be inaccessible and protected from further microbial metabolism to ensure C is persistent in soil (Samson et al, 2020).

Different root systems and rooting depths support the spatial distribution of the rhizosphere, which is the most beneficial environment for carbon sequestration (Schlüter er al. 2022). Symbiosis between mycorrhizal fungi and roots increases the surface of roots and nutrient absorption (Scheller, 1993). Main crops after cover crops tend to use same root channels as cover crops which is an efficient way to establish wide-ranged root systems and rhizosphere (Erhart et al. 2020). Increasing the diversity of aboveground growth that leads to more "layers" in cover crop mixtures and increased leaf surface and therefore photosynthetic production. This leads to an increased input of organic matter from above-ground biomass.

Measures to save soil moisture by prevention of soil evaporation through shadowing are especially valuable for summer cover crops in early autumn when soil microfauna is very active. Sufficient moisture is essential for diffuse C-transport from organic matter (POM) towards mineral sorption sites, where C is physically protected from microbial respiration (Védère et al., 2020; Hagedorn et al., 2015).

Environmental benefits:

Cover crops provide many environmental benefits such as: Protection against erosion and evaporation (by shading ground); weed suppression increasing biodiversity by providing an ecosphere and food sources for microorganisms, detritivores, predators, pollinators, and mammals; improved soil structure and tilth; protection against leaching. The longer the active period of cover crops lasts, the more these benefits take effect. Winter cover crops and underseeds are most beneficial due to their long active field period (Adewole et al., 2020; Bio Forschung Austria, 2020; Blanco-Canqui et al., 2015; De Baets et al, 2011).

Economic impacts:

Cover crops mobilize nutrients such as P and N (through legumes), store nutrients and release them for the main crop in a plant-available form of mineralization (Lavergne et al., 2020). These fertilizing effects may lead to large savings or total substitution of external fertilizers as seen in several best practice examples, e.g., in organic agriculture. Cultivation of cover crops may lead to a reduction in work time and vehicle traversals on the field due to improved trafficability and weed suppression (Blanco-Canqui et al., 2015). In wet areas, winter cover crops increase water retention capacities in loamy soils which leads to prolonged trafficability in spring. In dry areas, winter cover crops with rye and vetch did not show negative effects on soil moisture content in spring before termination, but winter cover crop with rye and winter pea did (Bio Forschung Austria, 2020). Cover crops may lead to increased yields if water is not limited for the subsequent crop (Blanco-Canqui et al., 2015). Increased root biomass leads to more biopores in soil which are generally useful for water retention capacity and yield assurance under increasingly extreme weather conditions. Farms with livestock may use cover crops as an additional source of fodder. All farms may relocate above-ground biomass of cover crops (see 2.2) without decreasing carbon balance on a farm base. The use of an adequate high-quality sowing technique is expensive, especially if the means are not present on-farm, and so are high-quality and certified seeds. Low-effort sowing techniques reduce costs on the one hand but bear a risk of insufficient field emergence and failing to achieve desired effects such as C-sequestration, environmental and economic benefits (Bio Forschung Austria, 2020).

Possible obstacles and difficulties:

Foregoing adequate seed quality or sowing technique is the most dangerous obstacle. Straw and crop residue distribution on the field may lead to more intensive methods for seedbed preparation, possibly with longer waiting periods before cover crop or subsequent main crop can be sown after harvest or incorporation. Make sure there is enough soil moisture at cover crop sowing. If doubtful, wait until rain or dew has set in again before sowing. Another challenge may be where to place the cover crops in the crop rotation in terms of nutrient dynamics, especially nitrogen dynamics. Incorporation of cover crops becomes increasingly complicated with increasing above-ground biomass, especially for winter cover crops with rye in spring. Be aware of phytosanitary gaps in crop rotation. Especially when using legumes and brassicaceae in cover crops this can increase the abundance of pests and diseases in the main crops of the same plant family if used too often within crop rotation (Bio Forschung Austria, 2007). In addition, the soil warms more slowly with cover crops in the spring, which may be suboptimal for the following main crop under certain conditions.

Most organic farmers take advantage of the opportunity to grow cover crops, but economic viability is of paramount importance. In addition, farmers see the difficulty of sowing in the warmest time of the year. To avoid losses, they grow cover crops as undersows in the preceding main crop (sometimes drone-sown), or they sow later to ensure sufficient moisture (as described above), or they grow cover crops with a reduced seed rate or in mixtures with on-farm components such as oats or peas to avoid high economic risks (outcome co-creation workshop Germany, 2023, pers. comm.).

2.4 DIVERSIFICATION IN CROP ROTATION

Instructions for implementation:

The implementation of diversification in crop rotation starts with planning the crop rotation. The crop rotation plan should be based on economic, phytosanitary, and ecological considerations such as proactive weed suppression, nutrient (especially nitrogen) dynamics, assuring operational yield and balancing out work peaks.

In good practice, cultivation of summer and winter crops should alternate, as well as row crops (e.g., maize, potato, soybean, sunflower) and grains. Before the first cultivation of an innovative crop, an analysis of soil N_{min} and the use of high quality and regional seeds is strongly recommended. If there is doubt regarding cultivation methods, try to gain experience from colleagues or experts.

According to the EU Common Agricultural Policy (CAP), there are several crop rotation requirements to qualify for subsidies.

Effects on carbon sequestration:

A broad variety of different root systems within the crop rotation increases rhizosphere and soil pore volume as plants tend to root directly into those channels left by roots of foregoing crops. New non-invasive methods of soil analysis indicate that soil pores containing organic matter, such as pores with plant roots, tend to increase C-sequestration in soil, while empty pores tend to decrease soil C-stocks (Schlüter et al. 2022). Different photosynthesis processes (C3 and C4 plants) from grains support root exudation of different C-compounds into soil (Siavaram et al., 2018; Vranova et al. 2013, Kim et al.

2001). Whereas C4 grains produce a higher quantity of root exudates, C3 grains produce a higher diversity of root exudates (Bledsoe et al., 2020).

More arbuscular mycorrhizal structures are present in the rhizosphere when C4 plants are grown in a soil than when C3 plants are in the same soil (Pirtillä et al., 2021).

A combination of crops with both strategies within the crop rotation seems to be beneficial for C-sequestration. In most cases, that means adding C4-crops like sorghum, panicum, setaria species or maize to the crop rotation. The addition of legumes to the crop rotation is also beneficial because they could react to an increased CO_2 concentration in their environment with increased root exudation (Stöber, 2007). Legumes benefitting C-inputs are solely proposed for perennial growth by Lavergne et al. (2020).

With all these aspects in mind, we conclude that a maximally diverse crop rotation also favours carbon farming.

Environmental benefits:

Employing a sufficiently diverse crop rotation is a well-established preventive plant protection measure as it reduces the potential of pests and diseases, thus diminishing the need for crop protection and the associated CO_2 emissions. It also supports biodiversity and microbial diversity. In fact, the positive effects are often similar to those of cover crops, see 2.3., regarding space and time requirements. However, root exudations are plant-specific and an important mediator of plant interactions with soil microbes (Lyu and Smith, 2022). Their intensity can be increased yet again using different main crops.

Economic impacts:

This method increases income security for farms by providing yield assurance through the diversification of cash crops and therefore reducing the risk of total yield failure, especially by adding drought tolerant C4 species. Trading new and innovative crops is often difficult and should be planned carefully in advance, e.g., by contract farming.

Possible obstacles and difficulties:

Finding and testing the optimal machine settings for cultivation may be difficult and time consuming for new and innovative crops. Sometimes, new, and adapted cultivars still must be bred and provided on the market. Identifying optimal conditions for cultivation regarding soil temperature and moisture or predicting optimal growth stages at certain points in time (e.g., hibernation) to deduce optimal sowing times is more difficult than it is for casual crops. Interviewing experts or conducting your own low-level trials in advance may provide the information necessary.

Crop rotation diversification, including intercropping and mulching, could be challenging, as farmers need to plan and select the right crop species, while also considering profitability. Possible additional investments to implement the technique could be a drawback, but the expected long-term effect of soil conservation should offset these concerns (outcome co-creation workshop Poland, Czech Republic, and Croatia, 2023, pers. comm.).

2.5 AGROFORESTRY

Instructions for implementation:

Agroforests or hedges can take diverse forms: orchards, windbreak hedges, fuelwood strips, multi-use hedges or individual landscape elements on agricultural land (Brown et al., 2018; Bio Forschung Austria, 2020). Agroforestry systems may be combined with silvo-pastoral systems and livestock grazing. Because this technique is applied over a long-term period, agroforestry systems are very effective for carbon sequestration. It is therefore advisable to contact the regional authority before planting the first trees. The planning process, planting and even maintenance of agroforestry systems is often financed or financially supported and/or even carried out by the responsible authorities (Bio Forschung Austria, 2020).

Effects on carbon sequestration:

Agroforestry is beneficial for carbon sequestration on multiple levels such as above-ground C-input, below-ground C-input, decomposition, and nutrient cycling (Brown et al., 2018; Jose and Bardhan, 2012). Perennial plants develop a much larger root system than one- to two-year-old arable crops. Roots reach much deeper soil layers where their residues tend to remain (Kutschera, 2013). That is why humus contents are significantly higher in meadows and forests than those on arable land. Forty % of assimilated carbon is transferred into the ground by plants as root biomass or root exudates, with 27 % of this process or 11 % of total photosynthetic C being excreted as rhizodepositions (Jones et al., 2009). A significant increase of root biomass causes a quantitative increase in the soil processes responsible for carbon sequestration, such as mineral sorption of carbon compounds. The bonding of C_{org} into mineral-associated aggregates in root exudates occurs 2-13 times more efficiently than in organic matter from above- or below-ground biomass (Sokol et al, 2019). An enlarged rhizosphere also promotes the establishment of microfauna populations, whose metabolic products tend to last longer in the soil than raw organic matter (Soares and Rousk, 2019).

Environmental benefits:

Agroforests reduce wind speed, and thus wind erosion, up to a distance of 25 times the hedge height on the downwind side and up to 5 times on the upwind side. Due to the reduced air movement, they have a positive effect on the microclimate and the local water balance (Wildermuth, 1978). Agroforestry systems provide food sources, hiding places and nesting opportunities for insects, birds, and mammals, thereby promoting beneficial animals (Kühne and Freier, 2013).

Economic impacts:

The sum of positive influences raises the yield on adjacent agricultural areas by up to 10% within a distance of up to 10 times the hedge's height (Kromp and Hartl, 1991; Freyer et al., 2009). There may be a decrease in yield directly next to the hedge due to shade, but in the end, hedges have a positive effect on total yield. In multi-use hedges, tree species are chosen that provide additional benefits for the farm such as edible and non-food goods (e.g., wild fruit, nuts, mushrooms, oil), fuelwood or high-grade crafting wood to compensate for a loss of income from the unused agricultural area of the hedge (Bio Forschung Austria, 2020).

Possible obstacles and difficulties:

Movement of heavy machinery becomes more difficult due to an increased number of obstacles. fewer straight-line paths might be possible, particularly in case of orchards or singular structural elements on the field. All agroforestry techniques cause arable fields to become smaller in size. There is additional workload required for planting and maintaining agroforestry structures, particularly within the first five years (Bio-Forschung, 2020b).

2.6 REDUCING TILLAGE

Instructions for implementation:

This method aims to reduce the usual intensity of soil cultivation according to type, depth, and frequency with the goal of slowing down mineralization of organic matter in the soil and therefore limiting CO_2 release from the soil and increasing persistence of C_{org}. The least intense form of this method is direct sowing, in which the crop is sown directly into the soil that has not been ploughed since the previous crop was harvested or the cover crop was sown using a special seed drill while no further tillage is being done. A smoother transition to reduced tillage systems can be achieved by significantly reducing the use of ploughs and heavy cultivators in favour of shallower tillage (Gollner et al., 2019). Increasing soil rest times by foregoing soil-specific cultivation measures is also effective, e.g., two-time soil cultivation with depth of 10 and 15 cm instead of three-time cultivation to a depth of 30 or 40 cm (Reithofer, 2023, pers. comm.).

Effects on carbon sequestration:

Reduced tillage leads to several positive interactions. Organic matter remains close to the surface. This promotes C-input into the soil and meets the natural feeding habits of decomposers, especially that of the earthworm, which significantly promotes the vertical C-distribution within soil through clay-humus complexes and pore stabilisation (Satchell, 1983). Synergies of other forms of C-input arise by increasing potential rooting space in earthworm-made biopores, which has a positive effect on root growth in quantity and distribution (Schlüter et al., 2022).

Environmental benefits:

The abundance of earthworms and beneficial predators is higher under reduced tillage systems than with conventional tillage (Berner et al. 2008; Rowen et al., 2020). Leaving plant residues on the surface for as long as possible provides protection from erosion and heat for soil inhabitants and microbes near the surface and reduces water runoff with mulch at a coverage of 30 % or more. Plough less systems emit 17 % less CO_2 compared to systems with plough use (Gollner et al. 2019).

Economic impacts:

Reduced soil tillage may prevent soil compaction. Intact and firm soil structure may then carry the heavy load of machines with a reduced risk of further soil compaction. With plough less systems or reduced tillage depths, no losses in yield were observed in some studies (Pringas & Koch, 2004), while decreased yields (Bio Forschung Austria, 2022) or even an increase in yields (Gollner et al., 2019) have also been measured (Berner, 2008).

Savings in diesel and working time are possible because of fewer field traversals. However, the sowing equipment necessary for this method (disc coulter or tine seed drill) is expensive to purchase.

Possible obstacles and difficulties:

More complex sowing equipment for direct sowing using a disc coulter or tine seed drill is necessary. Otherwise, a reduction of yield is possible due to lower field emergence. Weed control is difficult in organic farming with reduced tillage, especially as pressure from seed weeds is increasing. Delayed nitrogen mineralization has been observed in spring on heavy soils, especially in cold springs, which may lead to reduced yield and crop quality such as low protein content in grains (BIOBO, 2019).

Some farmers report increased pressure from pests like rodents, molluscs, or wireworms, which could not be confirmed by recent studies. On the contrary, reduced tillage systems help beneficial predators to thrive, while “mobile” pests, not confined to spending their whole life cycle on one field, occurred more often in conventional than in reduced tillage systems (Rowen et al., 2020; Szczepanek et al. 2023).

Sowing on grassland or on the residues of cover crops is not always advantageous. Sunflowers, for example, require a well-prepared seedbed, and the excessive presence of residue delays their emergence. In addition, sunflower seeds on unimproved soils are readily available to birds. Furthermore, special equipment for a different cultivation technique, like reduced or conservation tillage, might be necessary and costs for this transition might be too high for farmers (outcome co-creation workshops Poland and Italy, 2023, pers. comm.).

2.7 LIMING EFFECT

Instructions for implementation:

There are different kinds of limes used for agricultural purpose. Calcium carbonate ($CaCO_3$), magnesium lime ($MgCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), and quicklime (CaO). Each of them has special properties. While calcium and magnesium lime increase pH, gypsum does not. But Ca^{2+}-ions of gypsum are more quickly available than those from calcium carbonate. Furthermore, gypsum provides sulphur, which is an important plant nutrient, especially for legumes. Quicklime dissolves very quickly and acids in soil are neutralised immediately. Additionally, there is the option of slaked lime, which is quicklime with added water to produce an easily scatterable product (Schmidt, 2022).

The fineness of grinding (degree of grinding) influences the solubility of carbonate and silicate limes. The finer the degree of grinding, the greater the conversion-active surface and thus the effectiveness of the lime (Schmidt, 2022).

Effects on carbon sequestration:

Ca^{2+} ions are known to bind to negatively charged humic and clay compounds, forming stable aggregates. Although the effects on carbon storage have not been fully explored, expectations are high for building and maintaining permanent humus and thus increasing soil carbon stocks. Exchangeable calcium is one of the best predictors of soil organic carbon and is positively related to carbon content (Rasmussen et al., 2018).

Of course, soil improvement after liming will be more visible in acidic soils-the lower the original pH, the more the pH will increase after liming-but even in neutral soils, liming will not raise pH above 7.5 (He et al., 2021; Goebel & Schmidt, 2021, pers. comm.). It is also possible to fertilize with gypsum, which does not raise pH but provides readily soluble Ca^{2+} ions. Although CO_2 release is also increased after liming, the potential for sustainable agriculture by mitigating climate change and increasing food security is great. However, as with most carbon farming methods, results vary by location and climatic conditions (Wang et al., 2021).

Environmental benefits:

Since agricultural management lowers the pH of the soil, liming can compensate for this negative effect and thus ensure sustainable soil fertility (Prudil et al., 2021).

By helping to aggregate soil particles, it prevents erosion and maintains moisture in the soil. Overall, liming can ensure stable soil structure and functionality. Stable soil structure can prevent the accumulation of CO_2 (produced by soil respiration) in soil air, which would damage microbial activity and plant roots and, again through the formation of carbonic acid, increase soil acidity. In addition, phosphate, an important nutrient for plants, is usually bound to iron and aluminium in acidic soils. Liming converts these phosphates into calcium phosphates, which can be taken up by plant roots after contact with protonic root exudates (Schmidt, 2022).

Economic impacts:

The costs of liming are usually very low and more than compensated by higher yields and income (Wang et al., 2021; Li et al., 2018).

Typically, one kilogram of CaO costs less than ten eurocents, meaning that for an annual maintenance requirement of 400 kg/ha of CaO, one pays less than €40, including application. This is less than the usual price for two dt of wheat. Before taking over new fields, a professional soil test or at least a quick pH test should be carried out (Schmidt, 2022).

Possible obstacles and difficulties:

The optimum method of transport and scattering may have to be selected. For dry and powdered forms, good flowability can be expected for spreading with an auger spreader. For moist lime forms, an optimum water content is required to ensure low dust spreading with a disc spreader. The granulated forms should have the lowest possible dust content (Schmidt, 2022).

According to the discussions at the co-creation workshop in Croatia (2023, pers. comm.), 76% of the farmers present have heard of carbon farming, and 59% apply liming as a corresponding method. The problems and obstacles mentioned were related to the unavailability of suitable machinery for application. Often there is no equipment of one's own, nor the possibility of renting one or hiring a liming service. In addition, the possible fine dust has a negative impact on tractors. Nevertheless, the possibility of using a manure spreader was also mentioned, as well as the sufficient availability of cheap lime on the market.

3. TWELVE BEST PRACTICE EXAMPLES

3.1 LIMING ON ACID SOILS SHOWS SPECIAL EFFECTS ON CARBON SEQUESTRATION

Liming is an established agronomic practice; the amount of liming to be done will depends on the soil acidity of the site. Liming in acidic soils will always increase pH and will help to increase above- and below-ground plant growth. The soil organic carbon input can certainly be increased by this measure. However, liming also can promote stable carbon stocks and form permanent humus through the binding ability of the double positively charged calcium (Ca^{2+}) to the negatively charged humic acids. Acidic conditions in soil are more likely to facilitate the mineralization of stored carbon. Liming results in a slower mineralization of soil organic carbon and results in carbon sequestration in the form of bound humic acids. It is known that the amount of mobile humic acids in soil will decrease, and the amount of stabilized humic acids will increase, with an increased intensity of liming. Though the total amount of soil organic carbon might not change, the share of carbon in permanent humus will increase and thus form a stable resource of soil fertility and at the same time relieve atmospheric carbon dioxide content, which will contribute to efforts for climate neutrality. These positive outcomes may serve as a best practice example and were reported after a long-term study in Vėžaičiai, Lithuania with slaked-lime and pulverized limestone at different rates (Mockeviciene et al., 2022).

3.2 CUT & CARRY SYSTEMS ON STOCKLESS FARMS INCREASE HUMUS

Sometimes, the relocation of aboveground biomass or harvest residues is the ideal measure to improve carbon and humus content of the soil. After conversion from animal husbandry to livestock-free agriculture, permanent grassland and fodder crop areas are areas of concern for farmers. What to do with the biomass that is still growing? Sometimes, grants can be raised by declaring areas as nature conservation areas. In this case, cutting is prohibited before a certain date. In the model case of Biohof Stirmayr in Gramastetten, Austria, large amounts of grassland biomass were collected and transferred to an arable field. There, it was incorporated into the soil before cover crop sowing. The area of biomass collection was about three times the size of the area of deposition. After 13 years, humus content on the arable land had increased by 0.5 – 0.6 %. The transfer of chaffed clover-grass, mainly grown to provide nitrogen for following crops in organic farming systems, to other fields is a similar and useful approach and can equally be presented as a best practice example (Bio Forschung Austria, 2022).

3.3 C-INPUT THROUGH ABOVE AND BELOW GROUND BIOMASS OF COVER CROPS

Additional cover crops (instead of fallow) or suitable cover crops for a specific location can bring additional C into the soil. This happens by root growth on the one hand and by the incorporation of above ground biomass into the soil in spring on the other hand. For the establishment of permanent humus, plant parts with a high C/N ratio are promising according to some theories, while others suggest that both organic matter with high and low C/N are promising for C sequestration and rather continuous microbial metabolism of C is important than complexity of C compounds. Plant parts with a low C/N ratio show a faster rate of mineralization, which can give immediate nutrients for the growing crops but are lesser likely to contribute to permanent humus with stored C. Roots, due to their high content of lignin and other C-containing compounds, as well as their higher chemical recalcitrance, contribute to soil organic carbon to a far higher share than shoots (Rasse et al., 2021; Schmidt, 2021). Specific, non-legume cover crop species provide a high C/N ratio and hence a high contribution to carbon sequestration. These are for example buckwheat (C/N 47-55), white mustard (C/N 36-51), hemp (C/N 58-75), radish (C/N 14-48), ramtilla (C/N 33-67.), and sunflower (C/N 44-141), which has already been shown on several experimental sites in Austria (Bio Forschung Austria, 2020). Since soil also maintains a certain C/N ratio, an additional C input also needs an additional N input for balancing. Therefore, longterm cover crop mixtures including legumes could be a success promising way of carbon sequestration (Lavergne et al., 2021).

3.4 INCREASE OF SOIL ORGANIC MATTER THROUGH PERENNIAL WHEAT

Perennial wheat was grown as a hybrid of *Triticum aestivum x Thinopyrum intermedium* in three stands in Bavaria, Germany, and compared with the annual and commercial wheat variety 'Capo'. The perennial forms could not compete with the yield of 'Capo', but after three years (2017-2020), topsoil and subsoil showed significant increases in soil organic matter, microbial biomass, and earthworm activity. Perennial rather than annual cultivation can be a long-term ecological and economic alternative, especially on marginal, extensively managed sites. Growing perennial forms has proven to be a worthy goal (Vogt-Kaute & Vogt, 2020; Andu et al., 2022).

3.5 ADDITION OF COMPOST INCREASES SOIL CARBON IN SHORT-TERM PERIOD

At two annual grassland sites in different bioclimatic zones in California, USA, the change in soil organic carbon stocks after a single application of composted organic matter was investigated. In both cases, an increase in bulk soil carbon was observed which was significantly higher than the control at one of the two grassland sites. After three years, organic carbon content was still elevated and stored in protective soil aggregates. Although the C/N ratio decreased, indicating higher N than C storage, this best practice example shows that even after a single compost application to grassland soils, soil carbon storage can increase within and over a relatively short period of time, contributing to climate change mitigation (Ryals et al. 2014).

3.6 REDUCED OR NO-TILLAGE INCREASES CARBON DEPENDING ON CONDITIONS

Several case studies across Europe compared the effects of non-inversive minimum tillage or no-till versus conventional mouldboard plowing systems on soil organic carbon (SOC) and microbial biomass (MBC) content. In Germany (Garte Sued, Göttingen, Lower Saxony), minimum tillage increased SOC and MBC content in the topmost ten centimetres of soil, while conventional tillage increased MBC content at depths of 20-30 cm. At other sites in different parts of Europe, results varied from no effect at all to positive effects at different depths. In most cases, we can expect an increase in microbial activity with reduced or no-till tillage, but the effectiveness of reduced tillage on actual soil carbon storage also depends significantly on external conditions such as pH, soil texture, and climate (Engell et al., 2022).

3.7 LONG-TERM INCREASE OF SOIL CARBON STOCKS UNDER AGROFORESTRY

Agroforestry is the combination of arable or pastureland with woody types of shrubs and trees, the former being grown primarily in a type of alley cropping. The higher belowground biomass and greater root system of trees provide higher carbon stocks in the soil, especially in deeper soil layers, compared to cropland. Long-term (6-40 year) studies were conducted at four silvoarable and one silvopastoral site in France to investigate changes in soil organic carbon (SOC). The mean values of the silvoarable sites showed an accumulation of SOC of 0.24 t C ha-1 yr-1 at a depth of 30 cm in the arable parts of the system. Within the tree alleys, the accumulation rate was even higher. In young plantations, the increase in carbon stocks was detected only below the tree alleys. This shows that agroforestry systems have significant potential to increase SOC in temperate regions, but it takes time for this effect to occur (Cardinael et al., 2017).

3.8 COMBINATION COVER CROPS, REDUCED TILLAGE AND FINANCIAL BENEFITS

Reported is an example of a farmer in Indiana, USA, who started with carbon farming techniques like growing winter cover crops rather than leaving the fields fallow. After freezing off the oats and sorghum cover crops in spring and before sowing the next main crop he left the leftovers of the cover crops in the field rather than ploughing and tilling. In this way he combined carbon farming techniques of cover crops and reduced or no tillage. But the special thing of this example is, that he did that all for money. He was paid to do so by a company that created carbon credits for agriculture and in turn sold them to companies that wanted to offset their own emissions from production. This example maybe shows that not only the knowledge about and the idealism of trapping carbon in the soil to mitigate climate change effects might drive carbon farming activities but also the prospect of economic benefits (Popkin, 2023).

3.9 LONG-TERM SOIL IMPROVEMENT THROUGH DIVERSIFICATION AND MANURE

In Italy, a long-term trial (50 years) was conducted at an experimental site of the University of Bologna and has recently been completed. The effects of crop rotation diversification and the effect of animal manure (cattle) compared to mineral fertilizer or control were evaluated. In this long-term experiment, a nine-year crop rotation with legumes (compared to a two-year rotation with wheat and corn or with continuous corn cultivation) clearly increased soil organic carbon and microbial biomass carbon and activity. The same results were obtained when cattle manure was used for fertilization. With the combination of a highly diverse crop rotation and carbon input from external organic fertilizers, we can increase soil carbon stocks and sequester atmospheric carbon while increasing soil fertility and yield, at least in the long term (Giacometti et al., 2021).

3.10 MUNICIPAL ORGANIC WASTE CAN ALSO BECOME A SOIL CONDITIONER

When we talk about external organic fertilizers, we usually think of green manure, animal manure or slurry from agriculture. However, there is also a demand for the use of organic municipal and industrial waste. In a review study treating experimental plots in Austria, Italy and other countries, organic municipal waste in raw and composted form was frequently used in long-term trials (3 - 60 years). In all cases, soil organic carbon content increased compared to mineral fertilizers. Composted material also increased the stability of soil aggregates. This, in turn, could have a positive effect on permanent carbon storage in the soil, as the protection of the aggregates could prevent mineralization of soil organic carbon. At the same time, the decrease in organic matter may be offset as a reason for soil degradation, especially in semi-arid regions of Europe (Diacono & Montemurro, 2010; Mockeviciene et al., 2022).

3.11 LOWER DECLINE OF SOIL ORGANIC CARBON IN MANIFOLD CROP SYSTEMS

We need to be aware that any anthropogenic disturbance of the soil by agriculture reduces soil organic carbon content and soil pH. Soil use affects plant biomass input, microbial activity, soil aggregation, mineralization of nutrients, and binding of compounds. On a long-term experimental plot in Žabčice, Czech Republic, different cropping systems were tested for their influence on soil organic carbon (SOC) content during 2017-2020. The monoculture with spring barley was evaluated against a four-unit crop rotation with legumes and showed a higher negative impact on SOC after the monoculture. The influence of different tillage systems (conventional plowing versus minimum tillage), which was also investigated, surprisingly showed no differences, nor did the type of straw treatment in the barley monoculture (incorporation into the soil, burning, or harvesting), although different organic matter inputs to or in the soil are thought to influence SOC. Nevertheless, the interaction of diverse crop rotation with minimal tillage showed significantly higher SOC values in the end than other land use combinations. Certainly, this example is also a case study under specific local soil and climate conditions, but it shows, among many others, the positive - or less negative - effects of a diverse crop rotation on SOC content (Prudil et al., 2021).

3.12 PREDICTING CO_2 SOIL RESPIRATION UNDER DIFFERENT TREATMENTS

In northeastern Hungary, CO_2 losses from soil respiration were measured weekly at a typical Central European agricultural site. The CO_2 emissions must be offset against the potential increase in carbon in the soil. A crop rotation with summer and winter crops was carried out for five years, once with ploughing and once with no-till. Unexpectedly, soil respiration rates were significantly higher with no-till (0.093 mg CO_2 $m^{-2}s^{-1}$) than with conventional ploughing (0.086 mg CO_2 $m^{-2}s^{-1}$). Soil temperature was the same at both sites, but soil water content was significantly higher under no-till. This fact could contribute to the results important for establishing general CO_2 balances of agricultural measures for carbon farming. In a further step, a modelling of soil respiration under different crops and different tillage options was developed, which explained only about 40% of the variability. Therefore, more long-term experiments are needed to develop a useful forecasting tool for farmers, policy makers and decision makers (Gelybo et al. 2022).

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