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Carbon Farming
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EUROPEAN UNION

Inventory of techniques for carbon sequestration in agricultural soils

Hans Marten Paulsen (Ed.)

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1 Introduction: Carbon sequestration in agricultural soils

Hans Marten Paulsen, Thünen-Institute of Organic Farming, Germany

Organic carbon bound in soils (SOC=Soil Organic Carbon) forms humus. SOC at least double the amount of carbon present in the atmosphere, whereas plants and animals comprise one tenth of total carbon (Lal 2019). These large carbon pools can be influenced and improved by farmers. Protection of humus in soils and improved carbon binding in soils (carbon sequestration) can help to mitigate climate change, to reverse soil degradation and to improve food security (Smith 2004 and 2016, Lal 2004, Lal 2018). Rapid effects can be expected with improved soil management, especially in highly degraded soils. Carbon sequestration by changing cropland to forest, to moor, or to permanent grassland can be particularly effective from a medium-term perspective, but has clear consequences for the amount of food production.

As a basic process, plants bind CO2 from the atmosphere and deposit the carbon into the soils through roots, root exudates, seeds and plant residues at different depths of the soil profile. This happens on site but carbon is also translocated via organic manures of different origins. Most of the carbon entering soils with fresh organic matter is re-emitted through biological decomposition. Only parts of it are stabilised in soils as humus (which is generally defined as organic matter content in soils) and its organo-mineral complexes that can be stored for longer periods. Due to the reversibility of the process, continuous carbon input and constant management is needed to keep carbon stocks in soil at a steady state (Kell 2012, Balrock et al. 2012). Further humus enrichment requires new improved management and inputs. Status and possible improvements can be roughly quantified by humus balances (Brock et al. 2013, Kasper et al. 2015) as development is slowly and variable and can be determined only after years of continuous analyses. Organic matter enrichment in cropland and grassland soils towards suitable but higher concentrations is seen as a veritable option to strengthen the buffer capacity of soils for water and nutrients in times of global warming. Also to reduce erosion, to green agriculture and to sequester carbon dioxide from the atmosphere during the development of climate friendly technologies for human civilisation.

Scenarios of possible developments of soil organic carbon on high yielding arable sites in Northern Germany over 150 years are given in Figure 1. Phases of agricultural intensification and improved productivity between 1950 and 1980, the steady state until today and future prospects on soil organic carbon stocks for the next 80 years are shown. Changes from grassland to cropland have taken place with agricultural intensification since 1950. Heavy losses in stored soil carbon followed (blue solid line). On the other hand, improved management of cropland since 1950 through better cultivation practices, plant growth and plant cover might have improved humus contents, e.g., until 1980 (ascending part of orange line). Both scenarios reached a steady state and same level of carbon content and carbon stock which can be kept for further years (orange line). But mismanagement and also climate change might lead to further humus depletion in the future (red dotted line), whereas improved management (carbon farming) might slowly improve levels back to the levels of grassland (blue dotted line) or somewhere in between (e.g., yellow dotted line).

In this example the difference between degraded cropland and restored grassland makes 66 t per hectare in 80 years, i.e., 825 kg carbon are bound additionally in soils per hectare and year. The difference between business as usual (orange line) and carbon-improved management (yellow dotted line) is 14 t carbon stock per hectare, which can be reached in maybe 50 years. This would mean 280 kg additional carbon binding in soils per hectare and year (28 g C per m2). 280 kg SOC equivalents 1,027 kg CO_2 (multiplying factor from C to CO_2 is 3.67)

With the yellow line the organic carbon contents in the topsoil of cropland should grow from 1.25 to 1.65 % C., i.e., from 2.2 to 2.8 % organic matter (multiplying factor from C to organic matter is 1.72). These dimensions are still challenging but, from a farmer's perspective, are nonetheless feasible. Additional sequestration of carbon in the subsoil can also be expected.

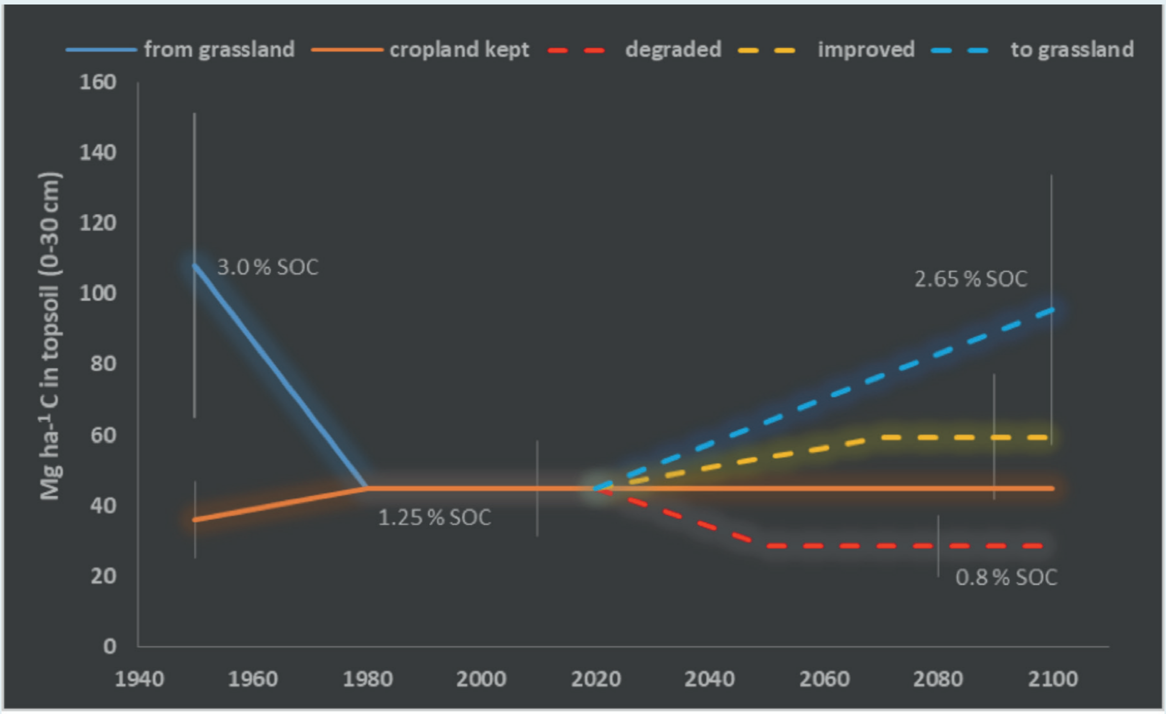

Figure 1: Schematic scenarios for possible ranges of development in the soil organic carbon (SOC) stock in the topsoil (0-30 cm) with land management changes. Estimations are in t ha-¹ and calculated by typical initial SOC concentrations [%, mg 100 g] of a North German site, with standard deviations of 30 % and 40 % of the measured values in cropland and grassland samples, respectively and for a soil density of 1.2 g cm-3 (dry). Different reaction times of 30-100 years were assumed to reach a new equilibrium of SOC after land management changes.

Possible carbon gains must be evaluated with a life cycle approach. They should outweigh the additional emissions of greenhouse gases connected to the enrichment efforts (e.g., additional fuel and fertilizer use, the keeping of more cattle or by connected land use changes at other sites of the world). Only then can the pressure of greenhouse gases on the atmosphere be reduced. Organic matter has long term positive effects on soil fertility, e.g., through improved soil structure, reduced erosion, improved nutrient retention and water infiltration. But despite the manifold positive effects of changes in crop rotations on biodiversity, e. g., protection of pollinators or breaking of weed establishment, an appropriate allocation of the emissions for the efforts taken to sequester carbon to mitigate climate change is not easy and might lead to wrong conclusions.

Against this backdrop, in this inventory the authors list different techniques to improve organic carbon stocks in soil with adequate local farm efforts. The recommendations can be used as basis for further development of climate friendly farming systems.

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2 Potentials of carbon sequestration by increasing biomass delivery with arable crops

2.1 Integrating cover crops

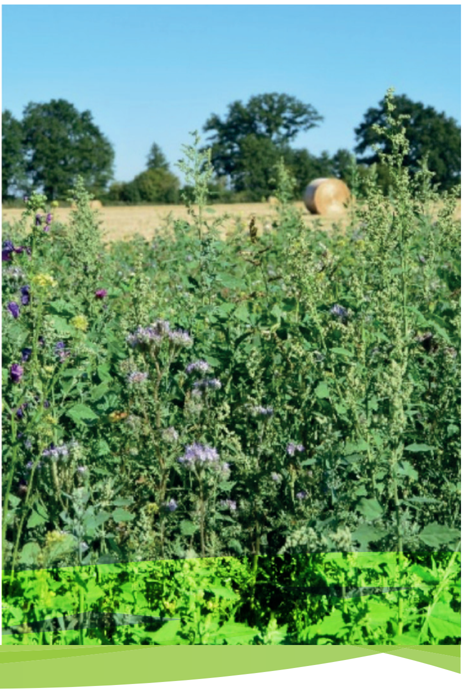
Hans Marten Paulsen, Thünen-Institute of Organic Farming, Germany

General

Cover crops can be integrated in crop rotations at different times and positions and for multiple agricultural usage. According to their purpose and position in the crop rotation, they are also called catch crops, intercrops or green-manure crops. They can be established as blank seed but also be undersown in other crops.

When introduced additionally to the crops which are normally grown, cover crops bind additional carbon from the atmosphere and offer additional biomass to the soil. They protect soils against erosion, can break infections with soil borne diseases, increase infiltration of water, bind nutrients and might increase agrobiodiversity and resilience of agricultural systems. They sometimes need additional fertilisation for proper establishment. Leguminous cover-crops add additional nitrogen to the system. Drawbacks are that additional costs for production are inevitable, time for mechanical weed management is limited and also cover crops might act as green bridges for pests and diseases. These points need special attention.

Cover crops are generally seen as positive for humus balances of soils. But carbon delivery to soils differs according to site, climate and nutrient supply, soil management, plant variety and biomass and root development. Drawbacks for the greenhouse gas balance in the production chain are additional efforts and related emissions for their cultivation (from fertilizers, equipment use, fuels) and increased soil respiration by additional soil disturbance for their cultivation. These additional emissions must be offset by C-delivery to the soil. Cover crops should always have perfect conditions for proper establishment to support their agro-ecological efficacy. But also weeds offer root and plant biomass and can contribute to soil carbon.



Ranges of C supply for soils

A wide range of C-supply for the soils is possible with cover crops due to site specific biomass development. Poeplau and Don (2015) reported significantly higher soil organic carbon stocks at 37 sites worldwide in a meta-analysis when winter cover crops were introduced and replace bare fallow. Cover crops in these studies were completely incorporated in the soil as green manure. The authors report an annual change rate of + 0.32 ± 0.08 t C ha^{-1} yr^{-1} in a mean soil depth of 22 cm with cover crops during the observed period of up to 54 years and compared to bare fallow. They modelled the development towards a new steady state of carbon stock in this top soil layer and found the new equilibrium to be reached after 155 years and a carbon stock accumulation of 16.7 ± 1.5 t ha^{-1} which would mean a yearly increase between + 0.1 t C ha^{-1} yr^{-1}. 50% of the increase already occurred in the first 23 years. This would mean a yearly increase of 0.36 t C ha^{-1} yr^{-1} in the topsoil.

Mutegi et al. (2013) estimated by trials in Denmark and modelling, that over a 30-yr period of continuous autumn fodder radish establishment, at least 4.9 t C ha^{-1} fodder radish C with a residence time of more than 20 years could be stored in the soil. This would mean + 0.245 t C ha^{-1} yr^{-1}.

12-year trials of Olson et al. (2014) in North-America resulted in gains in soil carbon by cover cropping with rye and hairy vetch in a maize soybean rotation respectively. The cover crops were burned in spring. Under different tillage intensities soil organic carbon increased between + 0.01 and + 0.46 t C ha^{-1} yr^{-1} in the topsoil (0-15 cm) with cover crops when compared to treatments with bare fallow over winter (C losses by erosion are excluded). In addition to this positive balance it must be mentioned that in the eroding slope position of the trial only in the no tillage system carbon gains in the top soil layer could outweigh and surpass the carbon losses that were related to soil erosion. Carbon enrichment in the subsoil (15-75 cm) of plots with cover crops was determined between 0.09 and 0.32 t C ha^{-1} yr^{-1} compared to bare fallows.

According to these studies estimates for the potential of soil carbon enrichment with properly established cover crops lie between 100 and 460 kg C ha^{-1} yr^{-1} in the topsoil and 10 and 320 kg C ha^{-1} yr^{-1} in the subsoil when cover cropping is regularly introduced instead of bare fallows over winter over longer periods from 12 to 50 years.

Practical informations

Cover crops will offer additional carbon to the soils and transport it in lower soil zones via roots. Mixtures of different plants might explore the soil better than single plants due to higher root density by different root types and their different rooting behaviour, e.g. in compacted soil layers (Burr-Hersey et al. 2017). Cover crops can be introduced in lots of crop rotations.

Stability of organic matter from roots, root exudations and plant material and the associated soil life is extremely variable (Kell 2012) due to various biochemial and physical processes (von Lützow et al. 2006). On the way to a new possibly higher steady state of organic matter in soil the integration of cover crops in crop rotations shall secure higher flows of organic substances for extended periods. In practice it must be considered that the decay of organic matter from cover crops is also source for nutrients. Soil management and fertiliser planning must take these nutrient pools into account to avoid unwanted losses to the environment. A lot of cover crops of different morphology and characteristics are available, e.g. with different rooting systems (tap roots: mustard, rapeseed, white and red clover, alfalfa; fibrous roots: grasses, cereals).

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Peas and wheat as elements of cop rotation (©Thünen Institute of Organic Farming/Paulsen)

2.2 Enriching crop rotations (main crops)

Jasper Vanbesien, Inagro, Belgium

General

Crop rotation is changing crops annually according to a fixed schedule on the same agricultural plot. The frequency with which a crop returns, determines the duration of the rotation. Crop rotation differs from continuous monoculture where one species is cultivated during consecutive years. The main reason for rotating crops is to avoid diseases and pests. The control of less mobile (soil) pests and diseases is easier when target crops do not return to the same field for some time (for instance clubroot in brassicas). Other reasons are: controlling weeds, improving soil structure (i.e. deep rooting crops) and -fertility (i.e. legumes that fix nitrogen) and preventing erosion. In organic farming (more enhanced) rotations are more commonly used than in conventional agriculture because synthetic pesticides/herbicides and chemical fertilisation, that can mitigate the negative effects of long-term monoculture, are prohibited. Drawbacks for a farmer to start with a (more enhanced) crop rotation are for instance the requirement of more knowledge and the necessity of the right agricultural machines/equipment.

When growing a wider diversity of main crops, a more diverse agroecosystem is created. More diverse crop rotations have the potential to provide a broad suite of ecosystem services including increasing SOC. Practically, the effect of different crop rotations on the SOC balance can be summarized as the sum of the effects of the individual crops. The effect differs mainly by the amount and composition of the harvest residues. For instance in Flanders harvesting grain maize can leave a huge amount of residue biomass on the field: 8.000 kg Dry Matter ha^{-1} (42.9% C, when above ground parts are left in the field) while for instance winter wheat stubble only delivers 1.000 kg DM ha^{-1} (43.7% C, Sleutel et al., 2007).

Farmers intentionally manage crop species differently based on particular management goals, which can determine the proportion of C that is returned to soil (King & Blesh, 2018). For instance in Flanders when the chaff and the straw of winter wheat is not harvested an extra amount of 4700 kg DM ha^{-1} (42.1% C) is left on the field. Leaving only stubble for, for instance, stable beddings, like earlier mentioned, recycles a much smaller amount of residues (Sleutel et al., 2007). Besides aboveground harvest residues, root residues and also root exudates are very important to raise the humus levels in soil. There is even a nascent body of research demonstrating greater retention of root-derived than residue-derived C in SOM (Kong & Six, 2010). Other important factors that have an influence on carbon delivery to soils are the site, climate, nutrient supply and soil management.

Potential C input to soils from growing a wider diversity of main crops

• CROP ROTATION VERSUS CONTINUOUS MONOCULTURE

McDaniel et al. (2014) reported in a meta-analysis that adding one or more crops in rotation to a monoculture (corn, soy, sorghum, wheat or miscellaneous) increased SOC by 3.6% based on 122 studies from all around the world that included field and/or vegetable crops. Most studies (59%) compared monoculture to a two-crop rotation. The mean duration of experiments was 18 years (range: 3-98 years) and rotations under study contained maximum 6 unique crops. Their results highlighted the benefits of crop rotations; even simple two-crop rotations, relative to monoculture, had an estimated soil C sequestration rate of 50.6 ± 22.7 mg C [g soil]-1 yr-1. The number of crops included in the rotation had a significant effect on SOC. Increasing the number of crops from 2 to 3 increased SOC from 1.9% to 7.5% relative to monoculture, but adding more than three appeared to have diminishing returns on SOC (3.7% for 4 crops and 7.7% for 5 crops or more).

The monoculture crop under comparison to rotation also significantly influenced the rotation effect on SOC. Soybeans showed the greatest response to rotation with an 11% increase in SOC, whereas introducing a rotation into corn monocultures did not increase SOC. In comparison to soybean, corn produces more biomass inputs, and these inputs are more chemically recalcitrant. Rotation increased SOC with 7.9% and 2.9% relative to monoculture of respectively Sorghum and of wheat. They stated that in order to maximize SOC gains, a producer must consider both the characteristics of the monoculture crop currently under continuous production and that of the rotated crop(s). Facing demands from biofuel production on harvesting corn residues Blanco-Canqui and Lal (2007) highlight the importance of recycling the corn stover in the fields sustaining SOC contents and soil structure.

West & Post (2002) analysed 67 long-term agricultural experiments (Marland et al., 2004). They reported that with the change from continuous cropping to rotation cropping using best management practises, an average C sequestration of 200 ± 120 kg C ha^{-1} yr-1 could be attained. Peak sequestration rates occurred during the initial years following the change in management. They stated that changes in crop rotations affect the quantity and quality of litter and thus the input of organic matter to the soil. The authors concluded that changing the quality of litter by moving from continuous cropping to rotation cropping increased C sequestration rates in most cases, regardless of whether there was a simultaneous increase in litter quantity (with the exception of a move from continuous corn to corn-soybean rotation where there is no increase because of less biomass produced).

• PERENNIAL CROPS

King & Blesh (2018) did a meta-analysis based on a worldwide database of experiments (median of durations: 14 years) at 27 cropping sites and categorized crop rotations into two broad categories: grain-only rotations and grain rotations with perennial crops. Grain-only crop rotations were further divided in sub-categories: cereal-only rotations and in cereal + grain legume rotations. Most focus in those studies was on corn and wheat as 'cereal-' and soy as 'legume grain crop'. A large part of the studies (41%) focused only on rotations of annual harvested grains. No horticultural crops (potatoes, tomatoes) and also no oilseeds (flax, canola) were included in the meta-analysis. Rotations with perennials contained also annuals and all perennial crops included legumes, 78% composed of a single legume species: alfalfa. The remaining crops were mixtures (11%) or legume/grass mixtures (11%).

The authors reported significantly higher soil organic carbon concentrations (12.5%, corresponding to approximately 5.7 t C ha^{-1} in the top 20 cm of soil) and carbon input (23%) in perennial cropped rotations relative to grain-only rotations. They also found that increasing the species diversity of grain-only rotations without adding perennial crops had no detectable effect on SOC concentrations. Perennial crops can use the beginning and end of temperate growing season that most grain crops, excluding winter wheat, would not harness for plant growth. They capitalize on windows of time that would have otherwise been unproductive. Also perennial crops, by increasing root C input over the rotation cycle, provide C input in a form known to be most readily stabilized in soil. Within grain-only rotations cereal + grain legume rotations decreased total C input (-16%) and SOC (-5.3%) relative to cereal-only rotations. Their conclusion is that increasing the functional diversity of crop rotations is more likely to increase SOC concentrations if it is accompanied by an increase in C input. As there is less C input from grain legumes to soil (less residue input and the C/N ratio is lower) than with cereals, also SOC decreases. But King & Blesh (2018) stated that a cropping system with a slight negative effect on SOC, such as cereal + grain legume compared to cereal only, may be associated with greater climate change mitigation potential if the inclusion of a legume grain sufficiently reduces the use of energy-intensive synthetic N fertilizer.

Replacing arable crops with leys (grass or grass+ clover) on a sandy loam soil can increase SOC but only for a limited period of time according to Johnston et al. (2017). During an experiment of more than 70 years (Woburn ley-arable experiment, Bedfordshire, United Kingdom), Johnston et al. (2017) reported that a 3-year grazed grass with clover ley in a 5-year rotation with arable crops increased percentage organic carbon (% OC) in the top 25 cm of the soil from 0.98 to 1.23 in the first 28 years, but with little further increase during the next 40 years when grass/clover is replaced by all-grass leys given nitrogen fertilizer. In this second period, OC inputs were balanced by losses, suggesting that about 1.3% OC might be near the equilibrium content for this rotation according to the authors. In all-arable rotation with mainly cereals, % OC declined from 0.98 to 0.94 over 70 years. In all-arable rotation with more root crops % OC declined to 0.82. Surprisingly they found that including 3-year Lucerne (Medicago sativa) leys had little effect on % OC (23 cm deep) over 28 years, but after changing to grass+clover leys, % OC increased to 1.24 during the next 40 years. They attributed it to the wide-spaced rows of Lucerne with its main tap root rather than a dense mass of shallower roots, typical of grasslands.

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Stripes with fast growing trees in an arable field (©Thünen Institute of Organic Farming/Paulsen)

2.3 Agroforestry Systems

Alokendu Patniak, Bionext, Netherlands

General

Four major groups of agroforestry systems have been commonly adopted worldwide: a) Alley cropping, b) Windbreaks (shelterbelts) c) Silvopastures d) Homegardens (multistrata systems - whose components (crops, trees, shrubs, livestock, wildlife, etc.) occupy distinct layers of the vertical structure of the community. Hedges (including riparian forests with lines of high-stem and medium-stem trees), alignments of intra-plot trees (trees combined with crops), pollarded trees, and spontaneous vegetation management are examples of where trees are being managed with crops and/or animals in temperate regions like Europe (www.agforward.eu).

The intercropped trees have deeper and broader root systems than crops, which will increase C allocation in deeper layers of soil. The soil aggregate formation for C stabilization is also improved under trees (Cardinael et al., 2015; Le Bissonnais et al., 2017). Established trees around or inside the croplands suppress wind, soil and water erosion, which reduces C losses (Béliveau et al., 2017). The deep roots of these trees help in catching, water and other nutrients from deeper soil and bring it back to the crops, e.g. by litterfall. Multiple mechanisms and processes are responsible for the increased C stocks in agroforestry systems. However, carbon stocks in agroforestry vary with geographical locations, climatic zones and are influenced by soil properties (texture, pH, structure, nutrient content), vegetation, tree species, etc.

Ranges of C supply for soils

In total the soil C stocks in agroforestry were 18% higher than the nearby control plots among 350 studies performed all over the world (Shi et al., 2017). These studies were highly affected by microclimate, soil and vegetation characteristics. As seen in figure 1, the highest increase in soil C stocks was in homegardens due to higher diversity of trees and litter production (Islam, Dey, & Rahman, 2015). Silvopasture has similar or even higher tree density than alley cropping and windbreaks, but it had the lowest increase or even had no changes in soil C stocks (Fig 1). An English study shows that soil C stocks in silvopasture are domianted by grass inputs, thus, soil C increase in silvopastoral systems was not significant (Upson, Burgess, & Morison, 2016). The soil C stocks in all agroforestry systems changed with tree age. With the tree growth up to 40 years, the mean soil C stocks in all agroforestry systems slightly increased from 30 to 40 t C ha^{-1}. Especially in younger age of the trees higher rates of C accumulation occurs. Cardinael et al. (2017) suggested that young plantations stored additional SOC mainly under the tree rows, possibly as a result of the herbaceous vegetation. Also in fast-growing tree species, chosen for most agroforestry systems, C inputs can also be quickly increased by litterfall and tree pruning and accumulate SOC especially at the early age (Singh & Gill, 2014). The meta-analysis of Shi et al. (2017) indicated that soil C stocks in the uppermost 60-80 cm were significantly higher in agroforestry than in cropland, but the differences decreased with soil depths. Especially in the topsoil layer the changes were sensitive to litter inputs by tree pruning and herbaceous vegetation root inputs. In this study, Europe has been characterized under the temperate climatic zone, and in this zone an enrichment between 5 to 25% SOC was observed after implementing agroforestry systems.

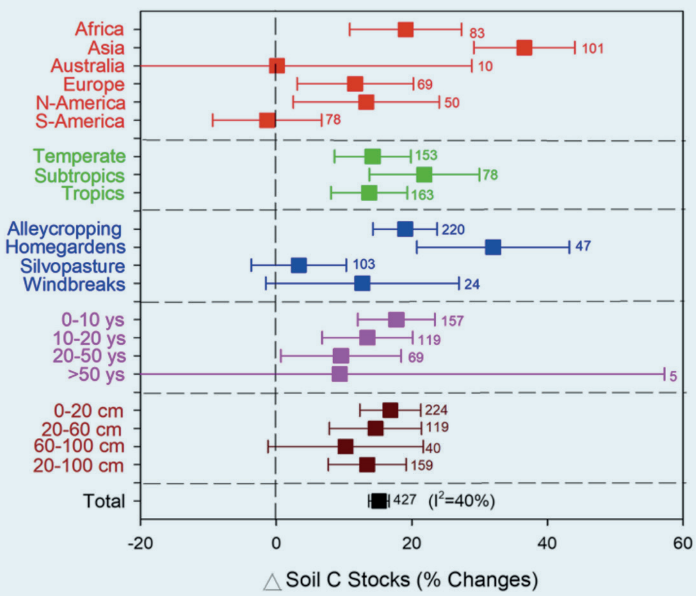

Figure 1: Changes (Δ) of soil C stocks in agroforestry (AF) compared with cropland (or pasture) on six continents, in three climate zones, across four AF systems and depending on tree age. Squares with error bars denote the overall mean response ratio ± 95% confidence interval (CI). The 95% CIs that do not cross the zero line indicate significant differences of C stocks between AF and cropland (or pasture). The numbers indicate the numbers of data pairs included. I2 is the measure of heterogeneity: 0–40% means little or no heterogeneity, 30–60% means moderate heterogeneity, 50–90% indicates substantial heterogeneity, and 75–100% indicates high heterogeneity (Graphic from: Shi et al, 2017).

Practical information

Agroforestry systems improve soil C sequestration through increased plant C inputs, improved microclimate, reduced soil erosion, and closed nutrient and water cycling (Shi et al, 2017). One of the major agroforestry characteristics is to increase plant diversity by additional tree planting in cropland or pastures. This can be an advantage for C enrichment in the soils as with diverse rooting patterns and continious leaf and litter input organic material enters the soil at different depth' and prolonged periods. Tree density and diversity are usually higher in homegardens, followed by alley cropping and silvopastures, and lower in windbreaks. Cropping trees also introduce microbial groups such as mycorrhizal fungi, N- fixing and P-solubilizing bacteria. Tree roots grow deep and deliver rhizodeposition deep into soils. The root exudates are important for long term preservation of soil organic carbon as they release various important organic C compounds (Zang et al, 2018). SOC in subsoil has three to 10 times longer mean residence time than in topsoil. Additionally, tree roots increase soil C stabilization by facilitating the formation of aggregates and mineral-associated organic matter. Compared with cropland/ pasture, trees have larger root biomass, rhizodeposition, and especially the hyphae of ectomycorrhizae and glycoproteins of arbuscular mycorrhizae, all of which bind minerals for aggregate formation. Windbreaks reduce soil loss by rain and wind erosion and can improve microclimate conditions. In those systems lower temperature achieved in hot seasons, and higher moisture increases crop growth, thus increasing plant C inputs to the soil. Trees used as windbreaks usually have stronger root systems than those in silvopasture, helping them stand against wind and use deep soil moisture during drought (Brandle et al., 2004).

Mean soil C stocks in agroforestry were 126 t C ha^{-1} which is 19% more than those in croplands or pastures. The species of trees and the combination of different species is important for increasing the soil C stocks. Intercropping with younger trees (<20 years) increased C in soil more than that of the old trees. Although agroforestry has proven to be beneficial with respect to carbon sequestration, it is important for a carbon farmer to optimize the area allocated to crops and trees within each system to achieve maximal C sequestration, maximize ecosystem services and improve environmental conditions. Some general mechanisms influencing soil carbon in different agroforestry systems are listed in Table 1

Table 1: Mechanisms of direct and indirect effects on C inputs and soil C stabilization in agroforestry (Shi et al. 2017)

C input and stabilization	Direct effects	Indirect effects
C input	**Above ground** ▲ Tree and crop stem and leaves litter biomass (+) (HG, AC, SP, WB) ▲ Dust deposition (+) (WB) **Below ground** ▲ Tree and crop root biomass (+) (HG, AC, SP, WB) ▲ Mycorrhizal fungal biomass (+/−) (HG, AC) ▲ Rhizodeposition of tree and crop roots (+) (HG, AC) ▲ Downward DOM transport (+) (SP)	▼ Reduction/stop of water and wind erosion (+) (WB, AC) ▲ Stem leaching (+) (AC, HG) ▼ Light by shading (−) (AC) ▼ Pathogenic fungi (+) (AC, HG)
C stabilization (solely belowground)	▲ Formation of mineral-associated OM (+) (HG, AC) ▲ Other GHG such as CH4 (+) (HG, AC) ▲ SOM decomposition (−) (HG, AC) ▲ Soil and rhizosphere CO2 (−) (HG, AC) ▲ Litter decomposition (+/−) (HG, AC, SP, WB) ▲ Fungi/bacteria ratio (+/−) (HG, AC) ▲ AMF (tropical/subtropical trees, crops, shrubs) (+/−) (HG, AC) ▲ ECM (boreal/temperate trees) (+/−) (HG, AC) ▲ ▼ SA fungi (+/−) (HG, AC)	▲ Soil structure (aggregation) (+) (HG, AC) ▼ Soil temperature (+) (WB, SP) ▲ Burrowing animals (+) (HG) ▼ Agriculture management such as tillage and fertilizer (+) (AC) ▲ Aeration and O2 availability (−) (HG, AC) ▲ Soil moisture in topsoil and subsoil (−) (SP)

Note. ▲ shows increase or improvement. ▼ means decrease or degradation. (+) or (−) means positive or negative effects on C sequestration, respectively. (+/−) means unclear effects or the effect depends on other environmental factors. AMF, ECM, SA, AC, HG, SP, and WB show especially strong effects under the agroforestry systems. AC: alley cropping; AMF: arbuscular mycorrhizal fungi; ECM: ectomycorrhizal fungi; GHG: greenhouse gas; HG: homegardens; SA: saprotrophic fungi; SP: silvopastures; WB: windbreaks

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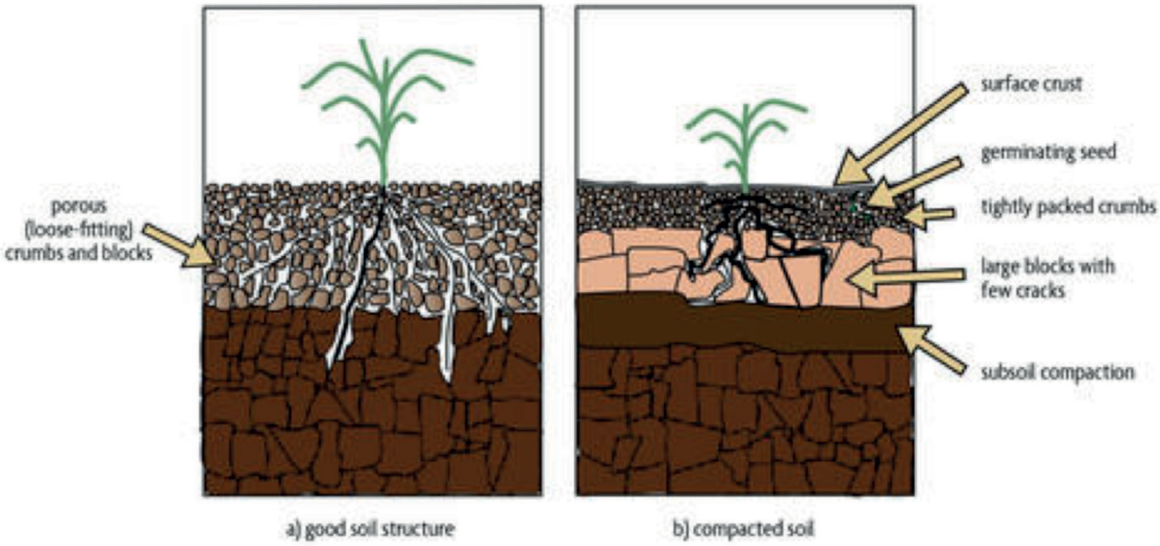
3 Potentials of carbon sequestration by protecting soil carbon during soil cultivation



Root development in different soil structure Source: Magdoff and van Es, 2010

3.1 Improved soil structure

Niels Heining, Bionext, Netherlands

General

Soil structure depends on biological, physical and chemical processes and the forming of soil aggregates. Good soil structure can be characterized by a crumbly structure, with spaces, pores and plant roots between aggregates (De Haan et al., 2016). Earth worms speed up the process of forming soil aggregates significantly. Pores of different sizes between soil particles play a key role in good water and air management. In a porous soil, infiltration is enhanced in case of high rainfall. Besides that, pores and organic matter in soils work like a sponge, increasing the water retention capacity. Thereby mitigating water scarcity over dry periods. Generally, 1% extra soil organic matter increases the water retention capacity by 6,8 mm on sandy soils and 9,3 mm on clay soils (De Haan and Postma, 2019). A good porous soil structure also improves the capillary capacity of the soil.

Another positive effect of a good soil structure is that plants can root intensively and homogenously, promoting an efficient uptake of nutrients from the soil (De Haan et al., 2016). In a well-structured soil, the roots will have many branches and tiny root hairs growing downwards, not sideways. This is also a prerequisite for a homogeneous and high carbon enrichment by roots.

The relation between soil structure and soil organic matter works both ways. Organic matter is one of the essential elements for the formation of aggregates. At the same time, aggregates protect labile organic matter, storing the carbon in the soil for the longer term (Six et al., 2000).

Practical information

The use of heavy weight machinery on the field can damage soil structure. Field operations carried out when the soil is too wet, causes soil compaction. The heavier the equipment, the drier the soil should be. Early spring sowing or drilling add to soil compaction (Godwin, 2001). Using controlled trafficking or wider tyres with less air pressure can help to reduce soil compaction (De Lijster et al., 2016).

With soil cultivation, there is a risk that aggregates will break down and that organic matter gets exposed to oxygen, to enhanced aerobic decay and mineralization. It will be released in the form of CO_2. Besides that, improper soil cultivation can disturb soil life, such as earth worms, and fungal threads can break down, reducing the forming of stable aggregates. A focus on limiting intensive soil cultivation techniques to improve soil structure, creates a favourable environment for carbon storage.

The effect of soil cultivation on the fate of soil organic matter and soil carbon has lot of facets. It has been shown that intensive cultivation can lead to the situation in which applied organic matter gets buried, creating an anaerobic (lack of oxygen) environment. Soil life needs oxygen and suffers from compacted soil, further increasing compaction. In a compacted soil, organic carbon is less stored in macro aggregates, reducing stable carbon storage in the soil (De Haan and Postma, 2019).

Most research on soil cultivation and soil carbon storage has been done on the potential effects of no– and reduced tillage on soil carbon. For other cultivation techniques and soil compaction that can have an influence on soil carbon, specific numbers for enhancing carbon storage are not available.

Soil compaction by machinery Source: Bootsma, 2017

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No tillage plot using mulching. Source: Garg et al., n.t.

3.2 No- and reduced tillage

Niels Heining, Bionext, Netherlands

General

Tillage is a basic agricultural practice. It is used for loosening and aeration of topsoil, facilitating planting and seedbed preparation, mixing of crop residues into the soil, destruction of weeds and drying of moist soils prior to seeding. However, tillage has some drawbacks as well. Generally, the aeration of the soil increases decomposition of organic matter. Also tillage might break stable carbon complexes in soil and exposes soil organic carbon to faster decomposition. Heavy traffic may increase soil compaction (i.e., formation of a plough pan) and the susceptibility to water and wind erosion and the energy operational costs can be high. Besides that, intensive tillage often has a negative impact on the soil biota and soil structure. Soil cultivation reduces the presence of earth worms, by disturbing their living environment. To mitigate these negative side effects of ploughing, less intensive tillage practices (conservation tillage or reduced tillage) and no-tillage practices are getting more attention. By waiving the plough and shallow cultivation, the aim is to preserve soil aggregates, organic matter and to maintain soil biodiversity (Haddaway et al. 2017; De Haan and Postma, 2019).

Practical information

With reduced or conservation tillage the soil is still mechanically loosened, but not deeply ploughed. With shallow ploughing for example, compaction can be prevented, but you can incorporate crop residues and weeds. With no tillage, the soil is not loosened at all and special machinery is needed for direct seeding. For both, reduced- and no-tillage, weed management has to be adapted. The topsoil will be a little bit more compacted. For mechanical weeding the harrow will not work optimal in the normal setting. A more aggressive setting might be necessary (Sukkel, 2014).

Cultivating crops with small seeds that need a very good seedbed preparation are challenging with no-tillage practices. The sowing machine has to go through a lot of crop residues what might cause clogging. Adaptions in the common machinery might be needed. Disk coulters or sowing machines pushing away the crop residues and strip cultivation, can be a solution.

Nitrogen mineralization starts later in no-tillage systems, as the organic matter breaks down slower. This can cause N shortage in the early stages of early crops and an extra N fertilization in this early stage might therefore be added (Sukkel, 2014) if possible according to regulations of the different EU member countries.

Finally, in no-tillage or reduced tillage practices, it is of high importance to minimize soil compaction. Therefore, when using no- or reduced tillage, a controlled traffic system for heavy machinery can be beneficial (Cid et al., 2014). In a controlled traffic system with standardized working width', machinery always uses the same tracks to drive over the field, leaving the majority of the field not impacted by machinery. Machinery equipped with GPS systems can help driving over the same tracks very precisely. In that way, only the soil under those tracks gets compacted.

It is hard to predict the exact costs associated with reduced and no tillage. Weed management can be more time consuming and adaptations and/or new machinery might be needed. On the other hand, costs related to ploughing such as diesel and labour, will decrease. Also reduction of tillage procedures according to actual site conditions can help for protection of soil aggregation and carbon binding.

Mulch-till farming system. Source: Garg et al., n.t.

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4 Potentials of carbon sequestration with recycling and import of carbon sources

Photo: ©Thünen Institute of Organic Farming/Paulsen

4.1 Organic fertilisers – Animal manure

Nick Quist, ZLTO, The Netherlands

General

The use of organic fertilisers has been common practice since the beginning of agriculture. Yet, with the invention of the Haber-Bosch process in 1909 accompanied with big steps in plant breeding and the development of plant protection agents, great improvements in crop production where made (Evenson & Gollin, 2003). This "Green revolution" is one of the reasons that in recent agriculture the strict integration of organic fertilisers in plant production is no longer a common sense. Organic matter is a key component for a well-functioning soil. Organic matter influences the dynamics of soil physical, chemical and biological processes. With recent increased concerns on the rise of atmospheric CO2 levels, together with a better understanding on the pivotal role of organic matter in soil functioning but also nutrient overloads in areas with high livestock density the proper use and distribution of organic fertilisers have gained renewed attention.

The soil organic carbon (SOC) (roughly half of the soil organic matter) content depends on management practices, the input of organic matter and its decay (Jenkinson, 1990). The input of organic carbon in agricultural systems depends via incorporation of crop residues is a direct path whereas organic fertilisers are an external source to feed the SOC pool and might deteriorate soil carbon reserves on the sites where the biomass is produced. This makes correct C-balancing of production and use difficult. Indeed, a recent extensive meta-analyses (132 studies) regarding the long-term effect (>10 years) of organic fertilisers showed that the incorporation of organic fertilisers is pivotal for increasing the SOC content (Chen et al, 2018). The term organic fertilisers includes a wide variety of fertilisers – from composts to all types of animal manures. Animal manures will be the focus of this factsheet.

Even within animal manures there is a wide variety of types to choose from. Their capability to effectively increase the SOC content depends partly on the manure's effective organic matter content. Effective organic matter is defined as the part of the organic matter that is still present in the soil one year after application (Table 1).

Nevertheless, securing the storage of organic carbon in the soil is more complicated than picking the manure with the highest effective organic matter content. For successful organic carbon storage, two types of organic matter are needed. A more recalcitrant animal manure (high in effective organic matter) such as goat manure is needed as a source around which aggregates can form. By the formation of aggregates around organic matter, the organic matter is protected against decomposition (Tidall & Oades, 1982). Yet, a more labile form of manure (lower in effective organic matter, e.g. cattle slurry) is needed as energy source for microbial soil life. An active microbial life also benefits the formation of soil aggregates (Cotrufo et al., 2013).

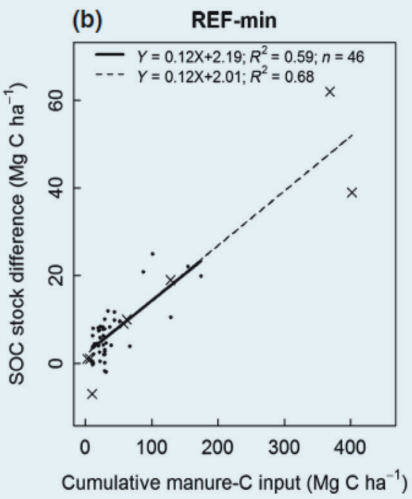
Table 1: The median organic matter content of animal manures, samples from 2017.
Source: www.handboekbodemenbemesting.nl.

Manure	Organic matter (kg t^{1})	Effective organic matter (kg t^{1})	Effective organic matter / P_2O_5 (kg kg^{1})
Slurry			
Cattle	71	50	33
Meat pigs	79	26	7
Sows	25	9	3
Rose calves	71	50	19
White meat claves	17	12	11
Solid manures			
Cattle	155	109	25
Pigs	153	50	6
Chicken	359	130	5
Sheep	195	137	30
Goats	174	122	23

Ranges of C supply for soils

The positive relation between the application of animal manure and SOC is due to 1) the direct input of organic carbon present in the animal manure and 2) increased general soil fertility and associated higher net productivity, which yields a higher return of crop residues (Bhattacharyya et al., 2010). Yet, the contribution of the latter pathway is expected to be neglectable compared to the first (Maillard & Angers, 2014).

Figure 1: The relationship between cumulative manure-C input and the difference in soil organic carbon (SOC) stock. The difference is based on manured vs artificial fertilisers.
(Graphic: Maillard & Angers 2014)

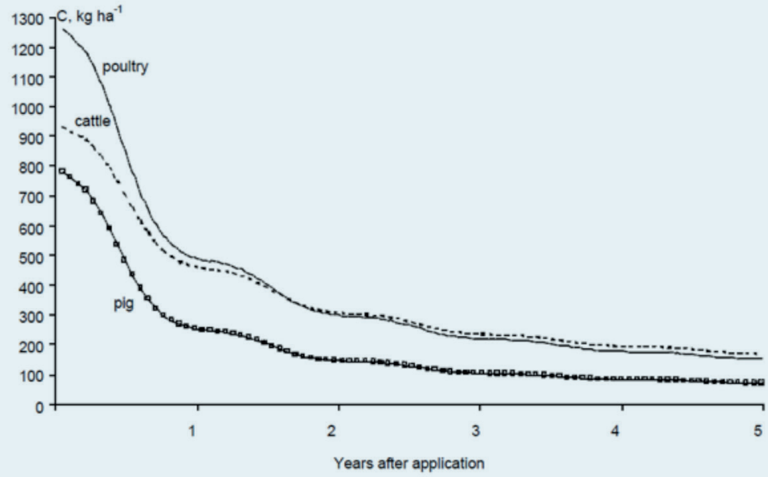


The earlier referred meta-analyses by Chen et al. (2018) showed that the organic carbon content increases with 29 ± 2% when organic fertilisers are used compared to control groups receiving only mineral fertilisers, for studies > 10 years. More specific, the organic carbon content of soils with more than 20 years of organic fertiliser application showed an increase of 4.5 g C kg-1 soil compared to the control groups with mineral fertilisation. Studies with organic fertiliser application between 10 and 20 years showed an absolute increase of 3.9 g C kg-1soil. Additionally, the study showed that the use of manures resulted in a higher SOC content when compared to plant-based organic fertilisers. Finally, the study showed that soils with an initial low organic carbon content and near neutral pH have the highest protentional for storage of organic carbon via the use of organic fertilisers.

The positive relation between animal manure and the SOC content is in agreement with a meta-analyses which specifically looked at the relation between animal manure application and the SOC content. Maillard & Angers, (2014) found a general linear relationship (Figure 1). The cumulative manure-C (carbon in manure) is a result of annual manure application and the duration of a study. The relation shows that increased cumulative manure-C input results in increased SOC stock differences compared to mineral fertilisation. From the slope op this relation a manure-C retention coefficient of 12 ± 4% was determined (regarding an average study with a duration of 18 years). In others words, the authors found that regardless of the initial amount of manure ~12 % of the carbon present in the manure will be stored in the soil.

The meta-analyses by Maillard & Angers (2014), also showed a trend difference between SOC increase vs manure type. Cattle manure showed higher and less variable increases of SOC compared to pig and poultry manure. This, as addressed before, could be the result of the quality of the organic matter present in the animal manure (labile vs recalcitrant). Velthof et al., (2000) presented similar results regarding the stability of added organic carbon by different animal manures (Figure 2). Although, the initial organic carbon content is highest for poultry manure it can be seen that, two years after the manure application the SOC content are similar for poultry and cattle manure.

Figure 2: The degradation of soil organic carbon content following the application of 30 ton ha-1. All three manures where applied as a slurry. Source: Veltman et al., 2000, after model calculations by Janssen (1996).



This indicates that the organic carbon brought via cattle manure is more recalcitrant compared to the organic carbon in poultry manure. In other words while on the short-term poultry manure might be the best choice for increasing the SOC content, cattle manure might on the long-term be the better choice.

Practical information

While the possibilities for the use of animal manure as an organic fertiliser for increasing SOC are promising, there are some restrictions. Using high amounts of manure may result in increased nutrient losses to the environment with associated eutrophication of surface waters as an example. Strict governmental regulations therefore limit the application of animal manure. These regulations limit the possibility of animal manures as a source of organic carbon. Furthermore, the distribution and thereby the availability of manure is a problem. In some regions there is to much animal manure, which results in a negative price, whereas for other regions the acquisition and transport costs are so high that the use of animal manure is too expensive.

Regarding the best practice to increase SOC by using animal manure is to choose for a combination of animal manures which complement each other in terms of labile and recalcitrant organic matter, e.g. the combination of a cattle slurry with a solid goat manure.

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ZLTO

Photo: ©Thünen Institute of Organic Farming/Paulsen

4.2 Straw and other harvest residues

Zaur Jumshudzade, Paulsen Hans Marten
Thünen Institute of Organic Farming, Germany

General

The incorporation of crop residues after harvest sequesters carbon (C) in soil organic matter (SOM) and thus can mitigate climate change by decreasing the amount of CO2 in the atmosphere (Blanco-Canqui, Lal 2007; Lu et al. 2009). The widespread recycling of straw in agricultural soils helps to control soil erosion, improves soil quality and fertility and thus increases the sustainability of agricultural ecosystems (Blanco-Canqui, Lal 2007; Chen et al. 2017; Lehtinen et al. 2014).

An estimated 25–50% of crop residues could be harvested without threatening soil functions (Blanco-Canqui 2013). Compared to green harvest residues, e. g. from vegetable production, straw has wide C:N-ratios, and will decay more slowly and also laughing gas emissions are lower so that overall greenhouse gas emissions differ according to the composition of the materials (Lehtinen et al. 2014). Also soil bulk density decreases with continuous input of harvest residues (Zhao et al. 2016). This might generally increase soil aeration, microbial activity and the turn-over of soil organic matter and has effects on physical soil structure. But generally C-sequestration and storage in agricultural soils with crop residues are inversely related to their CO2 efflux (Badía et al. 2013).

Due to the high importance of grain crops in agriculture the focus is set on effects of straw on the soil carbon pool in the following.

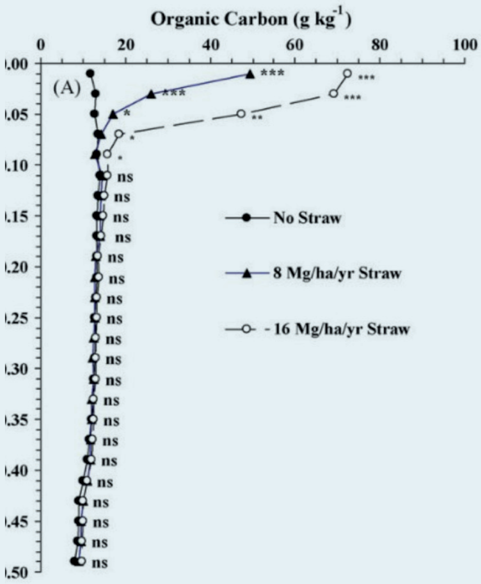
Straw is used as livestock bedding, sold or thermally utilized. In livestock systems this C only leaves the system temporarily and comes back to the fields as manure and will feed the SOC pool. The removal of straw and other harvest residues fits to reduced or no-tillage farming operations because high amounts of residual material can hinder soil cultivation or seeding (Blanco-Canqui, Lal 2007).

Straw return showed positively linear with SOC concentration and soil macro-aggregates formation (Liu et al. 2014). In no tillage and straw incorporation treatments the lowest proportion (34%) of wind-erodible (<0.83 mm diameter) aggregates and greatest proportion (37%) of larger (>12.7 mm) dry aggregates were found, compared to highest (50%) and lowest (18%) proportion of corresponding aggregates in conventional tillage with straw removal. This indicates less potential for soil erosion and related losses of SOC with reduced tillage and straw incorporation (Malhi et al. 2006).

Ranges of C supply for soil

In general straw return on fields was found to increase the SOC content. In trials with constant levels of straw application an enrichment of SOC occurred over 10-12 years before reaching a constant level (Liu et al. 2014). Above a general increase of SOC with straw application the is a response of labile organic C fractions (dissolved organic C, microbial biomass C, light fraction organic C, particulate organic C) and also changes in soil microbial community occur with that are seen as early indicators for soil quality changes (Chen et al. 2017; Xu et al. 2011). Also from a long term trial in Canada with barley, wheat and rapeseed over 27 years mean increases of SOC (+3.44 t ha-¹, i.e. 125 kg C ha-¹ a-¹) and significant increases in labile organic C fractions with straw return are reported (Malhi et al. 2011). Other studies reveal a linear increase of these values with higher straw input (Zhang et al. 2015; Wang et al. 2015). In figure 1 the enrichment and depth distribution of SOC for the 0-50 cm layer after 10 years of straw incorporation are shown. Incorporation of 8 and 16 t straw ha-¹ a-¹ increased the SOC concentration mainly in the 0-5 cm soil layers compared to the soils with straw removal.

Figure 1: Depth distribution of soil organic carbon in the bulk soil on a mass basis for the 0- to 50-cm soil depth following 10-year wheat straw mulch management on a Crosby silt loam (Blanco-Canqui, Lal 2007)



Soil incorporation of straw has measurable effects on the overall C:N-ratios in soils (Zhang et al. 2015) and also in the light organic fractions. C:N-ratios will be significantly decreased with increasing N supply (Malhi et al. 2011). After four crop seasons, Total OC and Total N, light fraction organic matter (LFOM), LFC and light fraction organic N (LFN) were generally increased with straw incorporation compared to straw removal treatments. Nevertheless, tillage and straw treatments generally had no effect on crop yield during the first three years (Malhi et al. 2006). An overview about the range of results of different straw management practices on C sequestration, is given in Table 1.

Practical information

Crop residue incorporation is important for maintaining SOC in different soil types and soil textures. Nutrient input and availability may favour crop growth, which can in turn increase ecosystem C input. Overall, long-term straw mulching increased SOC concentration in the upper soil surface and improved near-surface aggregate properties (Blanco-Canqui und Lal 2007). Straw return can increase carbon sequestration in an intensive agro-ecosystem and can be recommended as a long-term management practice to improve soil fertility and to sustain high crop yields, as well as to store carbon and reduce greenhouse gas emissions. Detrimental effects with increasing N2O emissions following the straw incorporation and fertilization are of higher relevance when managing green crop residues.

Table 1: Effects of cereal straw/crop residue incorporation on soil organic carbon
CR: Crop residue SR: Straw removal, SI: Straw incorporation

Author	Country / Number of studies	Effect	Concentration / storage	Soil layer
Lethinen et al. 2014	15 countries in Europe/39	+ 7 % SOC with CR	concentration	< 30 cm
Liu et al. 2014	World/176	+ 12.8 % SOC + 27.4 to 56.6% active C fraction (MBC,DOC,POC,LFOC,EOC)	concentration	different
Lu 2015	China/76	+ 12% soil C storage + 9% C with unchopped straw +13 % C with chopped straw	storage	0-20 cm
van Groeningen et. al 2011	Ireland	57.3 Mg C ha-¹ SR 68.9 Mg C ha-¹ SI 2.3 Mg C ha-¹ a-¹	storage no effect in lower depth	0-30 cm
Blanco-Canqui and Lal 2007	USA, Ohio	SOC with mulch/no tillage (-10 cm): SR: 16.0 Mg C ha-¹, 8 Mg ha-¹ SI: 25.3 Mg C ha-¹, 16 Mg ha-¹ SI: 33.5 Mg C ha-¹ SOC under mulching (0-50 cm): SR: 82.5 Mg C ha-¹ 8 Mg ha-¹ SI: 94.1 Mg C ha-¹ 16 Mg ha-¹ SI: 104.9 Mg C ha-¹ Annual sequestration (0-50 cm): 8 Mg ha-¹ SI: +1.2 Mg C ha-¹ a-¹ 16 Mg ha-¹ SI: +2.3 Mg C ha-¹ a-¹	storage 33% of straw C input were sequestered in 10 years no effect in lower depth	0-10 cm 0-50 cm 0-50 cm
Mahli et al. 2011	Canada, Alberta	SOC + 3.44 Mg ha-¹ after 27 years Annual sequestration (0-15 cm): 0.127 Mg C ha-¹ a-¹	storage	0-15 cm
Badía et al. 2013	Spain	SI: 6 Mg ha-¹ y-¹ C-sequestration: calcareous soils: 0.55 C ha-¹ a-¹ gypseous soils: 1.13 C ha-¹ a-¹ saline soils: 1.45 C ha-¹ a-¹	storage	0-10 cm

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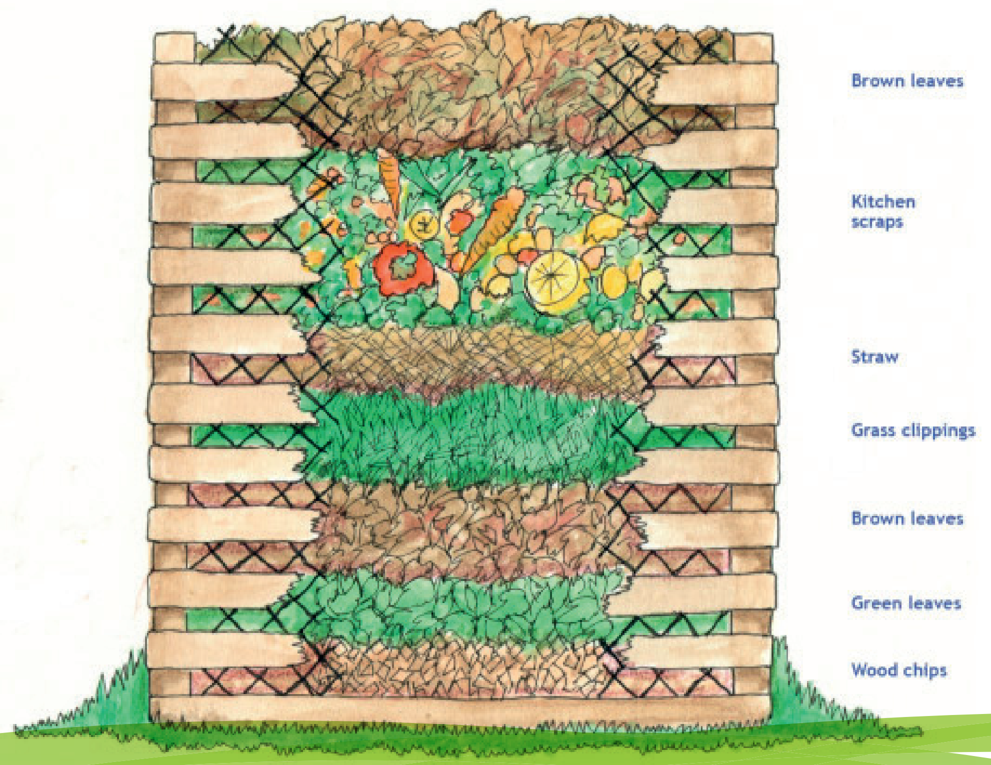
THÜNEN

4.3 Compost and digestate as soil conditioners

Alokendu Patniak, Bionext, Netherlands

General

Soil conditioners include a wide range of products aimed at supporting soil fertility, biological activity, and plant growth. They include microbial inocula, biostimulants that promote favourable microbial populations and plant growth (anaerobic digested organic matter also called as exogenous organic matter), composts and compost teas, etc. Exogenous organic matter (EOM) is defined as all organic matters added to soil which are valuable for fertilization and as soil amendment. There are different ways to increase EOM stability such as aerobic digestion (from composting) and anaerobic digestion of EOM (Béghin-Tanneau et al., 2019). The aim of using these inputs is to reduce the dependency and use of chemical fertilisers and agro-chemicals, hence these inputs may form the back-bone of sustainable farming systems. Application of EOM is one of the best soil management practices that may enhance soil carbon sequestration (Stockmann et al., 2013). The soil conditioners have substantial potential for facilitating the rehabilitation of degraded soils by increasing the storage of soil organic matter, enhancing water holding capacity, and providing nutrients for boosting plant growth (Delonge et al. 2014). Greenhouse gas emissions can be reduced significantly if composted organic matter is applied to the soil as compared to uncomposted organic material (DeLonge et al. 2103). Previous studies accross some diverse sites have shown that adding compost to soil leads to a measurable and visible increment in surface soil C stocks over a single growing season (Ryals et al. 2014). Soil amendments also include microbial inocula/biostimulants and a biological carbon sequestration is accomplished by microbial activities. These activities of microbes also improve the physical, chemical and biological soil properties. Soils rich in soil microbes like fungi and soil bacteria are known to have recorded higher carbon sequestration (Bailey et al, 2002).



Mixture of diverse elements that are used for composting (https://landscapeforlife.org/soil/use-compost/)

Ranges of C supply for soils

COMPOSTING (AEROBIC DIGESTION)

Composing is the systematic and controlled aerobic degradation of various types of organic matter like animal manure, woody material and other organic wastes. If woody materials are used it is better to use early/young material in the form of wood chips as the carbon contents are higher than in late/old materials (Lamlom et al, 2003). In general, around 50% of carbon is available in the form of humic substances when the compost attains maturity (Inbar et al, 1990) and at this stage the compost is thought to have high stability (Post et al, 2000). In a study comparing compost applications with other amendments by Farina. et al (2018), the compost collected from Municipal Solid Waste (MSW) had a C content of 30.1% and 34.9% for the first and second year, respectively, and a C:N ratio around 15 in these both years. In this study it was reported that, when this compost was applied at a rate of 30 Mg ha^{-1} yr-1 (10 Mg yr-1 C) for a time period of 5-8 years, compared to other organic amendments (green manures, barley crop residues) higher amounts of carbon could be sequestered in the topsoil (30 cm). Also Baldi et al. (2018) highlighted increased soil carbon contents and increased net primary productivity (the amount of carbon dioxide plants take in during photosynthesis minus the amount of carbon dioxide the plants release during respiration) in orchards with compost treatments.

ANAEROBIC DIGESTION OF EOM

EOM includes all organic matters arising from external sources from urban areas, municipalities, agriculture, forestry and industry, and their by-products (Béghin-Tanneau et al, 2019). EOM stability in soil determines the degree of carbon sequestration after application. When the decomposition rate of EOM reaches a similar decomposition rate to Soil Organic Matter (SOM), then the EOM is considered to be stabilized (Lashermes et al., 2009). Effects of modern anaerobic treatments of organic matter were analysed by Béghin-Tanneau et al. (2019). Here the application of anaerobicially digested maize silage together with animal slurry was compared to the application of maize silage or sucrose. The application of the digested material increased C sequestration by 63% (Table 1). This positive carbon balance is due to a high stability of its organic matter (59 % of applied carbon were still present in soil 178 days after application). Additionally a negative priming effect of 4 % was determined. This occurs when soil amendments decrease the rate of decomposition of soil organic matter. Based on this results anaerobic digestion of EOM favoured carbon sequestration and in total - including the CO2 emissions during digestion and energetic use of biogas - the CO2 emissons were 27% lower compared to the application of undigested EOM on soils (Béghin-Tanneau et al, 2019).

Table 1: Cumulative C sequestration or loss after EOM application relative to controls throughout 178 days partitioned into: Stable EOM left in soil and priming effects, represented as % of added C. Data are mean (n = 4) with standard deviation. Capital letters referred to the comparison of treatments according to the Tukey test (P < 0.05) (taken from Béghin-Tanneau et al. 2019).

Treatments	Stable EOM	Priming effects*	C sequestration or loss in soil**
Sucrose	2 ± 2 A	+ 24 ± 2 A	−22 ± 2 A
Undigested maize silage	9 ± 3 B	+ 13 ± 1 B	−4 ± 4 B
Digested maize silage	59 ± 1 C	−4 ± 1 C	+ 63 ± 1 C

* + / -: represent an increase or a decrease in native SOM mineralization respectively.
** + / -: represent a C sequestration in soil or a C loss to the atmosphere respectively.

Practical information

COMPOSTING (AEROBIC DIGESTION)

Based on Magdoff and Es (2009) composts are one of the most efficient and excellent organic amendments for soils. Composting helps in the reduction of the bulk of the organic matter, stabilization of soluble nutrients, and in fastening the formation of humus. Most organic materials, such as manures, crop residues, grass clippings, leaves, wood chips, sawdust, and many kitchen wastes, can be used as composting material. High temperatures with plenty of oxygen and moisture are the required conditions for the micro-organisms to perform efficiently for rapid composting of organic matter. If the factors like good aeration or the maintenance of elevated temperatures and sufficient moisture are inhibited, then the process of composting slows down. One of the important factors for the compost pile is the amount of moisture present within. About 40% to 60% of moisture content is ideal for composting. If the pile is too dry (35% or less) volatilization of ammonia occurs. As a result of volatilization, when the temperature of the compost moderates, the beneficial micro-organisms won't repopulate the compost. In this condition, the composts become populated by molds instead of beneficial micro-organisms. To assure an efficient composting process the combination of input materials should guarantee high amount of carbon and nitrogen available for the microorganisms. For example, chicken manure can be mixed with high-carbon containing materials like hay, straw, leaves, wood chips or sawdust. Compost piles are often built by alternating the layers of these materials, e.g. manure mixed with sawdust or wood chips used for bedding can be used for composting. By turning the compost pile, these materials get mixed efficiently. If the average C/N ratio of the materials in a range of 25–40, then composting occurs easily. Sometimes the pile may be too wet, too low in C/N (that means too high in nitrogen), or too high in C/N (low in nitrogen). To balance the compost pile, one may need to add other materials or change the C/N ratios used. These problems can be resolved by adding dry sawdust or wood chips in the first two scenarios or by adding manure in the third scenario. If the compost pile is too dry, one can add water to the pile.

ANAEROBIC DIGESTION OF EOM

Anaerobic digestion of biomass is one of the important means of treating biomass before its agronomic recovery. Organic materials having a C/N ratio of around 20 in the soil is optimal for plant growth (Bosch et al., 2016). The C/N ratio of the maize silage was 43/1 in the experiment of Béghin-Tanneau (2019) which are shon above and decreased to 17/1 during anaerobic digestion which is very close to the optimal C/N ratio for plant growth. A decrease in C/N ratio of EOM after anaerobic digestion occurs because carbon is exported as biogas, but nitrogen is kept (Möller and Müller, 2012). Since priming effects are described as interactions between living and dead organic matter (Kuzyakov, 2010), negative priming effect inhibits microbial activity or microbial enzymes activity on soil organic matter mineralization, which also reduces the microbial soil respiration. Negative priming effect reported with the application of digested EOM could be explained via the sorption of labile SOM and/or extracellular enzymes on digested EOM (Zimmerman et al., 2011). In result the bioavailability of soil organic matter is reduced. Anaerobically digested EOM have an increased proportion of recalcitrant and complex organic compounds (Wang et al., 2016). Besides accumulation of recalcitrant organic matter during anaerobic digestion Gómez et al. (2011) observed that the initial decomposition of readily oxidised compounds is followed by posterior transformation into complex compounds. These complex compounds have been associated with aliphatics, aromatics and phenols which are recognized as recalcitrant organic compounds (Tambone et al, 2013) . These coumpunds explain the stability of the digested EOM and the stability of native soil organic matter via assumed sorption mechanisms (Ahmad et al., 2014). In order to sequester carbon in soil, application of EOMs which have been anaerobically digested are more efficient than the application of fresh organic matter (Béghin-Tanneau et al, 2019).

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Useful Links:

https://landscapeforlife.org/soil/use-compost/

https://www.sare.org/Learning-Center/Books/Building-Soils-for-Better-Crops-3rd-Edition/Text-Version/Making-and-Using-Composts

Bionext

4.4 Effects of biochar application in soil

Zaur Jumshudzade and Hans Marten Paulsen, Thünen-Institute of Organic Farming, Germany

General

Based on the findings in Amazonian fertile 'terra preta, the use of charred biomass is discussed to improve soil fertility and carbon (C) storage (Sohi et al. 2010). Generally, biochar production is not developed for widespread agricultural use today. Technologies used for biochar production affect its physical and chemical properties. Also the response of soil to various carbonized organic matter can be different. Carbonisation technologies differ by reaction times (slow, intermediate and fast pyrolysis) and temperatures and there are different procedures, like gasification or hydrothermal carbonization (HTC). In HTC biomass will be set under elevated pressure and temperature in suspension with water. Flash carbonization will be carried out at elevated pressure with flash ignition (Meyer et al. 2011).

Sequestration of atmospheric C with biochar for millennial timescales seems to be possible in terrestrial ecosystems. 50% of initial C were found to be stabilised after incorporation in the soil. Worldwide it is estimated that 12% of anthropogenic emissions by land use change can be off-set annually if slush and burn agriculture will be replaced by slush and char (Ennis et al. 2012; Lehmann et al. 2006). With the retention of C in biochar for land application and decrease of fertiliser use, greenhouse gases can be avoided. Furthermore, biochar can increase soil fertility, nutrient retention and cycling and might also reduce contamination of ground water and streams. Moreover, biochar production from agricultural residues can be combined with energy production and replace fossil fuels (Gaunt and Lehmann 2008).

Nevertheless, there are still uncertainties among the researchers about the net C sequestration in soils with the application of various types of biochar. Questions about long-term interaction of biochar with the soil native organic C, on changes in physicochemical properties of the soil and on harmful organic substances developing in the pyrolysis process and heavy metals are still remaining (Ndirangu et al. 2019). On the other hand, biochar addition to soil can reduce trace elements uptake and toxicity to plants. Looking at the carbon balance researchers reported about both positive and negative priming effect (C mineralisation or sequestration in soil) of biochar, which is influencing the carbon storage potential with biochar application (Ding et al. 2016, Freddo et al. 2012) (Table 1).

Biochar effects on crop yields

Addition of biochar to soil can enhance aboveground productivity, crop yield and soil microbial biomass. The effects of biochar on crop yield depends on the experimental set-up, soil properties, type of crop and use of additional fertilisers. Positive effects on crop production are based on improved nutrient availability, water holding capacity and liming effect of biochar in soil. But also negative yield effects are reported. The mean increase of crop productivity found in a worldwide meta-analysis in various crops after biochar application was 10%. At a level of 100 t ha^{-1} biochar incorporation the greatest mean increase in crop yield (39 %) was found (Jeffery et al. 2011). Other studies Vaccari et al. (2011, Durum wheat) and Xie et al. (2013, rice) showed no significant yield increases. But in Durum wheat application rates promoted biomass growth and were not detrimental for gain yield and quality. Generally, the trials show that biochar pH, pyrolysis temperature, cation exchange capacity are strong predictors of yield response. In addition, it was found that yield responses increased over time since the initial incorporation (Jeffery et al. 2011; Schulz und Glaser 2012).

Ranges of C supply for soils

C sequestration (negative priming) and mineralisation (positive priming) after biochar application in soil Positive or negative priming effect of biochar amendments mean an improved C mineralisation or C storage in the soil, based on measurements of CO2 release. Mineralised C after biochar application can originate either from native soil organic carbon (SOC) or from biochar.

It is generally accepted, that independently of the used pyrolysis method, biochar has a potential to sequester carbon in soil by the carbon supply and (negative) priming. Depending on biochar quality and soil texture pH, cation exchange capacity (CEC), aggregation, and microbial parameters can be enhanced and thus the acceleration of crop growth. Manure-based biochar was found to promote microbial abundance more than biochar from woody feedstock (Lehmann et al. 2011; Liu et al. 2016). Concerning different C-fractions in soils Tian et al. (2016) reported an increase of total C by 47.7-50.4% and of particulate organic C (POC) by 63.7-74.6% after biochar application, respectively (POC: organic matter in soil with 53 – 2000 µm grain size, Wilson et al. 2001). Lu et al. (2014) measured lowered dissolved organic carbon (DOC) in soil after biochar amendment. They suggested, that biochar can reduce the decomposition of native organic carbon. Wang et al. (2017) also reported that biochar promotes soil aggregation and can stabilize SOC in the macro-aggregates.

Nevertheless, other studies found positive priming effects of biochar amendment compared to control. The suggestion is that positive priming occurs due to rapid utilisation of labile biochar components by soil life and negative priming because of stabilisation of labile biochar components on charge minerals of the soil. Spokas and Reisocky (2009) reported on their experiment with biochar about five variants that increased, three that reduced and eight with no significant impact on the observed CO2 respiration. Lu et al. (2014) found no significant impact of biochar alone on total soil CO2 emissions. Singh and Cowie (2014) reported, that manure-based biochar from low temperature pyrolysis mineralised faster than plant-based biochar from a high temperature process. Furthermore, they found out, that in low-C clayey soil biochar stimulates positive priming. However, this effect decreases with time probably due to the depletion of the labile soil C pool and/or due to the stabilisation of SOC in soil by biochar-induced organo-mineral interactions.

In incubation experiments, positive priming was found on soils supplemented with biochar produced at lower combustion temperatures (250-400 °C), from those produced from grass feedstock and in early stages of incorporation (90 days). This particularly in soils with low organic carbon content. Whereas, biochars produced at higher temperatures (525-650 °C) and from hardwood feedstock showed positive priming at later stages of incubation (250-500 days). In table 1 amounts of C mineralisation from biochar added soils are presented. In general the C mineralisation and the influence of soil properties on C mineralisation decreased but the adsorption of CO2 on biochar increased with raised pyrolysis temperatures in biochar production. Nevertheless it was found, that C could be sequestered in soil by biochar as the C input was generally higher than the possible loss of CO2 with positive priming (Steinbeiss et al. 2009; Spokas 2010; Spokas and Reicosky 2009).

Mean residence time (MRT) of biochar C in soils reported varies between 29 and 1600 years. Both, biochar and soil characteristics will determine the long term stability in soil. E. g., the molar ratio of O:C affects the stability of biochar. Biochar with an O:C ratio of 0.2 is reported to be recalcitrant for a minimum 1000 years (Spokas 2010). Higher MRT are suggested under field conditions with lower moisture, temperature and nutrient availability. Thus, MRT can be manipulated by design of the best biochar for a given soil type (Steinbeiss et al. 2009).

Table 1: Carbon mineralisation from labelled biochar in soil

Experiment duration	C mineralisation from labelled biochar in soil	Soil depth (cm)	Amount of biochar amendment	References
8.5 years	6%	0-15	2.4 g biochar kg^{-1} soil	Kuzyakov et al. (2014)
5 years	0.5-8.9 %	0-10	8.17 g biochar kg^{-1} soil, corresponding to 10 t ha^{-1}	Singh et al. (2012)
12 month	0.3-1.14 % and 0.97-2.71 %	0-15	At 20°C and 40 °C incubation, respectively	Fang et al. (2014)
110 days	1 % and 3 %	0-25	5 g and 10 g biochar kg^{-1} soil, respectively	Hansen et al. (2015)
84 days	2.8 %	0-30	Biochar application at equivalent to 18 t ha^{-1}	Zavalloni et al. (2011)
65 days	2.9 % and 5.5 %	0-25	50 g biochar kg^{-1} soil; slow and fast pyrolysed biochar, respectively	Bruun et al. (2012)
2.3 years	4.8-72.5 mg g^{-1}*	-	1 g biochar kg $^{-1}$ soil	Singh and Cowie (2014)

* In addition to C mineralisation from biochar Singh and Cowie (2014) reported about 4-44 mg g-1 mineralized C from SOC after 2.3 years of incubation experiment

Practical informations

Generally biochar is expected to increase carbon storage in soils, mainly by direct input of relatively stable C. Priming effects can enhance or reduce this effect. Positive effects of biochar are expected by nutrient retention and stabilisation of labile soil organic matter. Different materials and techniques in today's biochar production (by pyrolysis) lead to different material properties and reactions in soils. Also detrimental elements and organic substances can be contained. Therefore the use of biochar is not developed for legal agricultural use today.

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THÜNEN

5 Potentials of carbon sequestration in (permanent) grassland

5.1 Sward mixtures and management

Alokendu Patnaik and Niels Heining, Bionext, Netherlands

General

Grassland management plays an important role in the carbon cycle in animal production systems. Especially permanent grassland has a high potential for sequestering carbon because of its extensive rooting system and high turnover of crop residues. . The soil organic carbon (SOC) content is therefore generally higher under grassland than under arable fields (Van Eekeren et al., 2018). However, there is a high variability between the SOC content of different swards. These differences are caused by climatic differences and soil type, but also by different management strategies. This factsheet explains different grassland management options related to species mixture and restoration, with the goal to increase the SOC content. Factsheet 5.2 will give more information about different grazing strategies and the effect on SOC.

SOC is strongly influenced by: **(1) Grassland renovation and (2) grassland composition**. These two categories are highly interrelated. Grassland renovation is often a reaction to changing species composition and a focus on grassland composition can minimize the need for grassland renewal. The goal is to maintain a favorable sward mixture while minimizing grassland disturbance.

GRASSLAND MANAGEMENT AND RENOVATION

When grass swards become degraded and are unable or unfunctional to provide their services, it is usually recommended to restore grasslands. However, from the perspective of SOC it is beneficial to minimize grassland renewal (Kayser et al. 2018). Soil disturbance during grassland renovation can happen at different degrees. Ideally, the sward is improved by retaining the old sward without any soil structure disturbances. This could be achieved without seeding. Good sward management, like avoiding over/undergrazing, improving drainage, pH, nutrient balance, and weed management is then necessary. Partial reseeding (oversowing) with new competitive seeds is another option to renovate grassland while limiting disturbance and maintaining SOC. Complete grassland renewal by the means of ploughing and seeding causes a high level of disturbance. A way of grassland renovation in between these two extremes is improving the sward by letting the soil structure be slightly disturbed while adding new seeds (Kayser et al. 2018).

GRASSLAND COMPOSITION

The composition of the sward has a major influence on SOC in various ways. Grassroots are the main source of organic matter to the soil. Species with a high root density are therefore beneficial for the build-up of SOC. A more intensive rooting system can be promoted by choosing the right species and using a species mixture. The biomass and quality of the plant amendments to the soil are altered by diverse grassland communities and may deliver ecosystem services to different degrees (De Deyn et al 2011). Besides building up SOC, nutrient- and water-uptake are promoted by an intensive rooting system, while deep roots are also good for soil structure and soil life (Van Eekeren et al., 2011).

Mixture of diverse grassland species in swards (Photo: ©BLE, Bonn/Thomas Stephan)

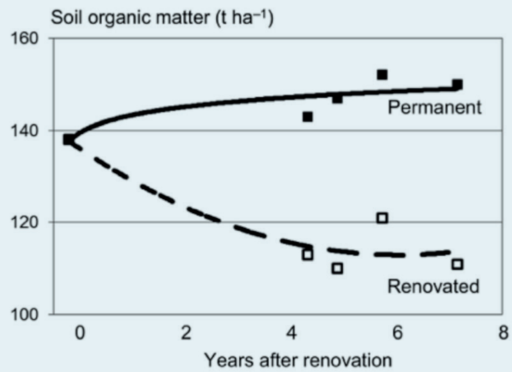
Grassland mixtures can consist of multiple species to increase SOC and provide the other benefits as mentioned above. Red clover for example is known as a keystone of grassland species and in short term biodiversity restoration experiments it was found to possess high potential to enhance C sequestration (De Deyn et al 2011). Red clover has shown to do well in a mixture with tall fescue and cock's-foot (De Wit et al., 2012). Herbs like ribwort plantain and chicory could also be added to a mixture of grass and legume species to increase production and carbon sequestration.

Ranges of C supply for soils

GRASSLAND MANAGEMENT AND RENOVATION

Research has shown that grassland restoration measures have highly variable consequences which might be different among different services. This is primarily because of the variation in the degree of sward disturbance before the new sward is sown (Kayser et al. 2018). Grassland renewal increases organic matter mineralization by the addition of oxygen during soil ploughing or milling, breaking down organic matter, releasing nitrogen and decreasing SOC. Contrary, permanent grassland often shows an increasing soil organic matter content over time (fig. 1). Lesschen et al. (2012) calculated that the potential CO_2 sequestration of not disturbing grassland can go up to 3.586 kg CO2 ha-[1] yr-[1] i.e. 1 t C per ha.

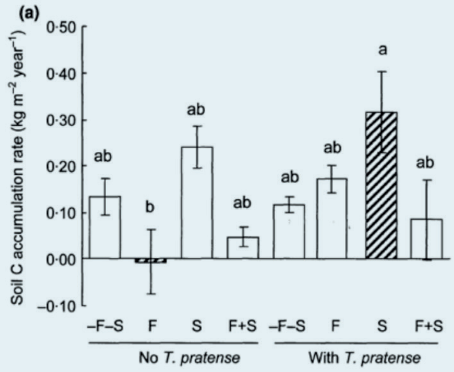
Figure 1: Soil organic matter content of permanent grassland and renovated grassland. SOM content increases over time, but decreases in the years after renovation. Adapted from: Kayser et al., 2018



GRASSLAND COMPOSITION

De Deyn et al. (2011) found in long-term diversity restoration measures that increasing the red clover cover resulted in C accumulation rates up to 320 g m2 a^{-1} in the top 28 cm of the soil (i.e. 3.2 t C ha^{-1} a^{-1}, Fig. 2). They compared to other values and found this effect over five times higher than the average estimated C sink of grasslands in Europe (60 g m-1 year-1; Janssens et al. 2005). This C accumulation rate was found to be within the annual potential of soil C input by roots (between 56 and 400 g C year-1, i.e. up to 4 t C ha^{-1} a^{-1} for a soil depth of 28 cm) in temperate grasslands that are species rich (Steinbeiss et al. 2008).

Figure 2: Soil C (a) accumulation rates in grassland as affected by new (No T. pratense = 0.4%, with T. pratense = 1.6% cover) and old combined restoration treatments (mineral fertilizer use: with = F, without = -F; sowing of seed mixtures: with = S, without = -S) (Graphic taken from De Deyn et al. 2011).



Practical information

GRASSLAND MANAGEMENT AND RENOVATION

The production level of the sward can be maintained at a high level over years. To minimize grassland renewal it is important to improve the sward management and focus at minimal invasive reseeding. By harrowing the sward to harm weeds and less productive grass species and giving space for the new seeds, grassland renewal can be avoided. Research has shown that the productivity of permanent grassland can go up by 15% by adding new seeds every year (Staps, 2018). Above carbon protection, reseeding instead of grassland renewal saves labour costs (Staps, 2018, table 1). In case grassland renewal is unavoidable, renewal without deep ploughing might be a good option to protect SOC contents. An experiment with spring seeding of a herb-rich grassland mixture in oats without herbicide use showed to be successful with a decent production and limited weed growth (Staps, 2018).

Table 2: Costs renewal and reseeding of grassland per ha in euro's. Adapted from Staps, 2018

Cost	Renewal	Reseeding
Soil measurements (mandatory in the Netherlands)	€75	n.a.
Basic fertilization/liming	€300	n.a.
Herbicides	€55	€55
Digging	€132	n.a.
Seeds	€145	€145
Seeding	€95	€95
lid manures	**€802**	**€295**

GRASSLAND COMPOSITION

The primary drivers for the rapid increment in soil C and N accumulation rates are due to the changes in the quality (C/N ratio) of the plant community; the inputs of organic C compounds via root exudates belowground, the roots and their rapid turnover in species rich plant communities (Ayres et al. 2007). The combined availability of low quality resources (high C/N) and high quality material (low C/N) and nutrients at finer spatial scales are essential for sustaining the soil microbes and the protection of recalcitrant and resident organic matter in soil (De Deyn et al 2011). So although increased inputs of C and N rich root exudates from legumes typically stimulate the growth of soil microbes (Denton et al. 1999), their introduction can improve C sequestration. The rapid increase in soil C and N sequestration by integration of red clover will be further enhanced by the changes in the soil physical structure and physical protection of soil organic matter (De Deyn et al 2011, Holtham, Matthews & Scholefield 2007). Thus, increasing red clover cover in sward mixtures can be an effective long-term measure for promoting SOC and C sequestration.

In addition to C sequestration including multiple grass species, herbs and other legumes in grassland will also provide more resilience to weather extremes, but needs special management and initial investments in seed mixtures (Wagenaar et al., 2017)

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Bionext

Grazing livestock (Photo: Coopman/Inagro)

5.2 Increase carbon sequestration with grazing livestock

Franky Coopman, Inagro, Belgium

"When livestock take a bite of grass, the grass plant sloughs off an equal amount of root mass below ground. That dead material is full of carbon. Microbes in the soil eat the carbon, and turn it into a stable substance so the carbon is safely sequestered below ground. So grazing creates more forage, more meat production, and a healthier climate."

(Voth and Gilker , 2019).

General

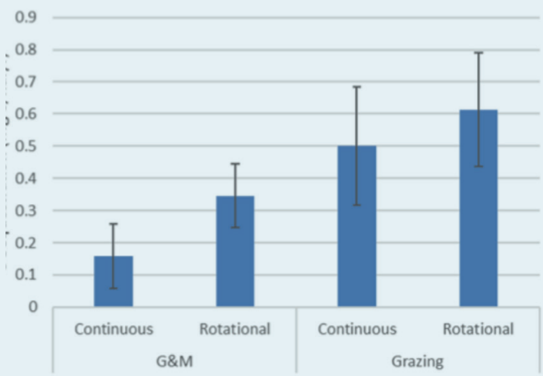
Grazing lands have high importance for sequestering carbon (C) in soils (Hewins et al., 2018). The global estimates are that grazing lands occupy 3.6 billion ha and account for about one-fourth of potential C-sequestration in world soils. They remove the equivalent of 20% of the carbon dioxide (CO2) released annually into the earth's atmosphere from global deforestation and land-use changes (Follet and Reed, 2010). Possible environmental benefits provided by grassland include maintenance and immediate protection of surrounding soil and water resources, air quality, human and wild life habitat, and aesthetics.

Global studies have found that grazing can have either positive or negative impacts on rangeland vegetation and soils, depending on the climatic characteristics ecosystems, grazing history and effectiveness of management (Milchunas and Lauenroth, 1989).

Ranges of C supply for soils

Improved grassland management, including the improved management of grazing animals can contribute to organic matter build-up in various ways (e.g. Conant et al., 2017, Soussana and Lemaire, 2014, Khalil et al 2019). Conant et al. are summarizing that improved grazing management, fertilization, sowing legumes and improved grass species, irrigation, and conversion from arable land into grassland all tend to lead to increased soil C, at rates ranging from 0.105 to more than 1 t Cha^{-1} ·year-1. Also it was found that grazed pastures may sequester more C than grasslands used for silage or hay production, due to the recycling of organic matter and nutrients (C and N) from faeces and plant residues (ungrazed leaves and roots) (Figure 1).

Figure 1: Mean Carbon (C) sequestration rate (t C ha-¹ yr-1 from mixed grazing and cutting systems (G&M) or grazing only systems in the EU, NZ/AU, US (Graphic taken from Van Eekeren et al. 2018)



Newest gas flow measurements in central European grasslands revealed a mean net CO2 sink capacity of grassland in the range between 490 to 24 g C m2 year-1 (i.e. 4.9 to 0.24 t C ha-¹ year-1). Only 21 % of this emissions were offset by N2O and CH4 emissions on the sites when calculating the greenhouse gas balance (Hörtnagl et al. 2019). Chang et al. (2015) modelled a mean sink activity of 15 g C m-2 year-1 in grassland ecosystems over all European climate zones (i.e. 0.15 t C ha year-1) under consideration of the stocking densities over the last 50 years. The calculated net C sink activity is halved (to 0.08 t C ha year-1) when direct backflow of carbon with manure is subtracted. Looking at GHG-emissions on whole farm level (in CO2-equivalents) in this study the average ruminant system with grassland is a net GHG source, when additional to C sequestration in soils and in remaining biomass the complete respiration of harvested forage in the stables and the global warming potential of CH4 and N2O are considered. Generally in grassland systems reducing livestock numbers will decrease feedstuff demand, GHG-emissions by livestock and its manure, mineral fertilisation and might increase the input of unused plant residues on-site.

Practical informations

Common grazing management practices that could increase carbon sequestration include:

- (i) stocking rate management,
- (ii) rotational, planned or adaptive grazing and
- (iii) enclosure of grassland from livestock grazing.

Conventional rangeland science suggests that sustainable management of grassland can be achieved by grazing livestock at stocking rates that do not exceed the grassland carrying capacity. Many grasslands increase biomass production in response to frequent grazing, which, when managed appropriately, could increase the input of organic matter to grassland soils. However, there have been few studies of the effects of rotational grazing on soil carbon stocks. Studies on mob-grazing (keeping high animal numbers for short term on small areas) indicate positive results on soil organic matter contents in European mixed swards, due to high organic-matter turn-over and trampling of plant residues in the soil (e.g. Zaralis and Padel 2017).

Grazing intensity should be properly regulated to enhance carbon sequestration. GHG emissions should be considered in conjunction with C-sequestration when analysing the impacts of livestock on GHG emissions and climate change. It has been suggested (FAO, 2009b) that a sustainable livestock distribution could be operated to sequester carbon in soils, including a rotational grazing system combined with a seasonal use of land. The proposal is based on the hypothesis that a reduced grazing intensity would result in increased soil carbon stocks.

Finally, Conant and Paustian (2002) demonstrate that grazing management drives change in soil carbon stocks by influencing the balance between what goes into the soil (inputs) and what comes out of it (outputs): effective livestock management systems that adopt better feeding practices and use specific dietary additives have a positive effect on food security (enhancing productivity and meat quality) and soil carbon stocks.

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Other resources: FAO- Grasslands, Rangelands and Forage Crops website

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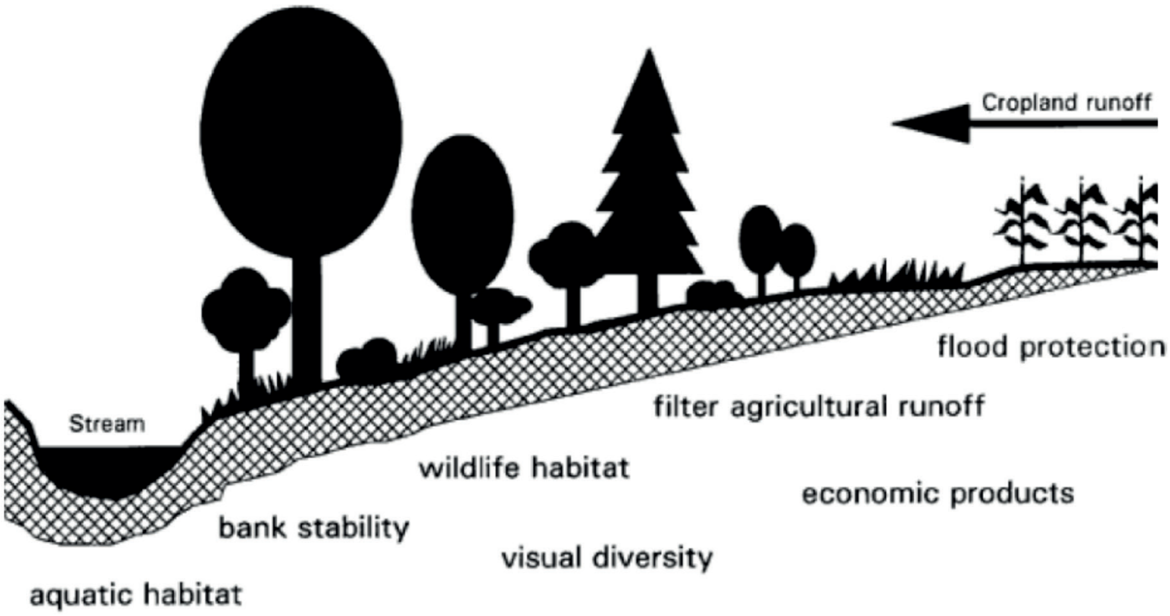
RESEARCH & ADVICE IN AGRICULTURE & HORTICULTURE

6 Potentials of carbon sequestration with landscape design integrating carbon farming (3N)



Benefits that a riparian buffer can provide (Dosskey et al. 1997)

6.1 Strips for water protection, erosion control and biodiversity

Ernst Kürsten, 3N-Kompetenzzentrum e.V., Germany

General

A riparian buffer is land next to streams, lakes, and wetlands that is managed with perennial vegetation (grass, shrubs, and/or trees) to enhance and protect aquatic resources from adverse impacts of agricultural practices, and stabilize eroding banks on small streams and lakes (Dosskey et al. 1997).
On slopes exceeding an inclination of 5% it may make sense to prevent soil erosion by water with contour planting. Such stripes will have basically the same effects as riparian buffers. In areas affected by strong winds, and/or droughts shelterbelts are traditionally planted to stop wind erosion and to reduce moisture losses. Not only crops, but also livestock may benefit from protection by trees and shrubs, some of them may even become an additional source of feed, especially valuable in periods of drought. Even very simple strips of herbs, flowers and even grass are increasing biodiversity and soil carbon storage.

Ranges of C supply for soils

Besides all these positive ecological effects, especially the CO_2 mitigation effects of rows of trees and bushes in agricultural land are important and manifold:

1. **Carbon uptake and storage in (woody) plants and in the soil within the stripes:**
   In Europe, natural woodland regeneration on arable land lead to a carbon accumulation in the vegetation of 2.8 t C ha^{-1} yr-1 and 0.62 t C ha^{-1} yr^{-1} in the soil (Falloon et. al. 2004) These values can be applied for tree lines and shelterbelts from trees and shrubs as well. Udawatta and Jose (2011) estimated the C sequestration rate for major agroforestry practices in temperate North America to be 2.6 t C ha^{-1} yr^{-1} in riparian buffers, and 3.4 t C ha^{-1} yr^{-1} in alley cropping systems (above ground only). An increase of about 0.6 t C ha^{-1} yr^{-1} hot water extractable organic carbon in the surface (0 – 30 cm) was measured in north-eastern Germany (Mosquera-Losada et al. 2011). Of course, the period of C-accumulation is limited and depending on rotation periods.

2. **Increase of soil organic carbon on the adjacent fields:**
   Pardon (2018) found a net increase in soil organic carbon stock of 5.3 t C ha^{-1} in the 0 - 23 cm soil layer up to a distance of 2 - 30 m from rows of 15 – 49 years old hardwood trees in Belgium. Even just up to 10 year old alley cropping stands in North America contributed about 1 t C ha^{-1} yr^{-1} by litterfall to the soil carbon stocks in the fields 15 m and more from the tree rows (Udawatta and Jose 2011).

3. **Reduced CO2-emissions from fossil fuels by the sustainable production of biomass for energy:**
   The energy substitution potential can be calculated as 2.1 t C ha^{-1} yr^{-1} (Falloon et al. 2004) or even up to 3.1 t C ha^{-1} yr^{-1} in case of in short rotation coppices (Burschel et al. 1993). While the C-storage in plants and soil (1. and 2.) is always limited to a specific level, the substitution effect of fossil energy can be achieved again and again with every rotation period.

Practical information

There are several funding possibilities for the integration of permanent multi-annual vegetation stripes to fulfil environmental goals, mainly based on the Common Agricultural Policy in the EU (CAP).
The Nitrate-Directive prescribes to keep on the Codes of Good Agricultural Practice e.g. on land application of fertiliser to steep slopes and near water courses.

Wildflower strips can increase soil carbon as well as farmers income if there is an appropriate funding scheme. Photo: ©3N/Kürsten

In Germany, for multi-annual wildflower strips farmers may receive subsidies of up to 975 € per ha if they are meeting beekeepers needs. Thus the profit margin of 600 – 800 €/ha may be higher than for wheat production on lower grade and medium sites, and only 2 - 4 working hours per ha are needed for this. Wildflower strips are an interesting option if grain production is below 9 t ha^{-1}, on fields of an area less than two 2 ha hectare or of irregular shape, and in the shadowed areas along forest stands (Meier, 2019). Mixtures of herbs with different roots systems can increase the humus creating root dry mass up to 8 t ha^{-1} as compared to only 0.8 to 3 t ha^{-1} in case of crops like grain, potatoes, and sugar beets (Braun, 2008).

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Useful Link

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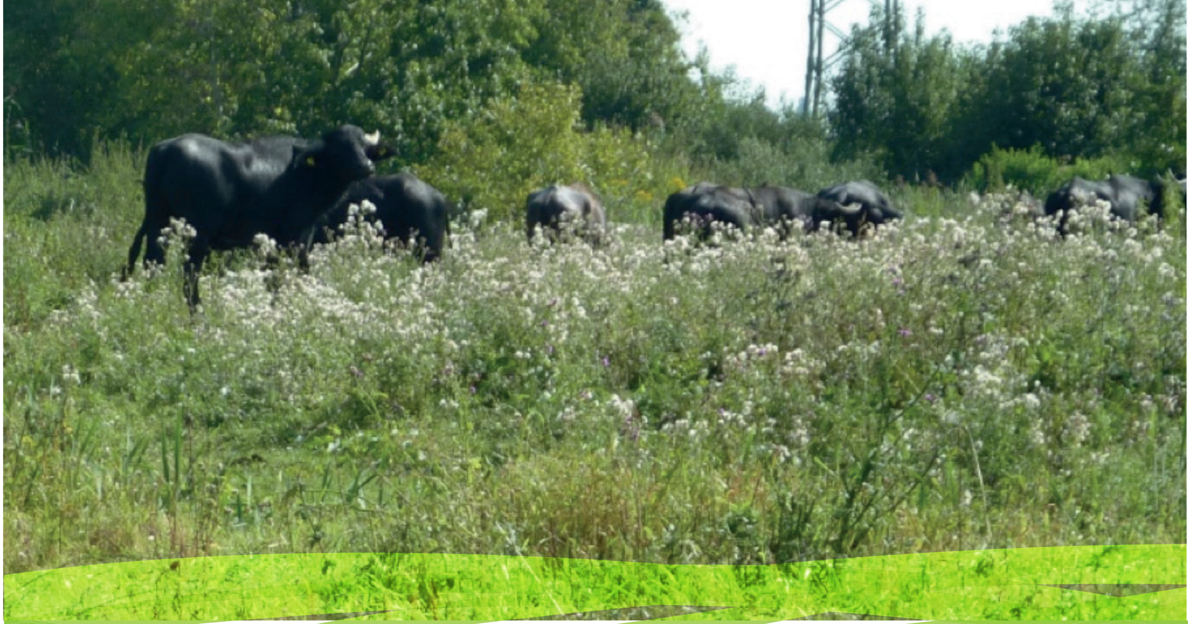


Water buffalos are a special option for value addition on wet meadows. Photo: ©3N/Kürsten

6.2 Management of wetlands, peatlands and paludiculture

Colja Beyer and Ernst Kürten, 3N-Kompetenzzentrum e.V., Germany

General

Agriculture and forestry on organic soils are mainly based on drainage. This results in peat oxidation, land subsidence, high amounts of greenhouse gas emissions (especially CO_2) and nutrient release. Additionally an improved nutrient supply (e. g. N, P, K) influences the relations to soil organic carbon (SOC) and might enhance the decomposition of organic matter and CO_2 release additionally. Constant raise of water tables will decrease SOC losses from those layers (Freibauer et al. 2004) whereas considerable yearly losses can still occur with changing water levels from the aerated topsoil.

Accordingly on organic soils a complete management change to wet systems would be the most consequent approach to avoid emissions and possibly to enrich additional peat and sequester soil carbon in the long term. Therefore in the following paludiculture is described as consequent option to avoid future release of carbon on peatland soils.

Carbon balance of peatland soils

As determined in German sites by rewetting peatland soils on average a loss of 7.5 t SOC . ha^{-1} .a^{-1} in grassland and arable systems can be nearly completely avoided (Jacobs et al., 2018). As example:
The data for grassland sites used in this recent study reveal that increasing ground water levels below soil surface from - 0.50 m to - 0.03 m will significantly decrease the C balance from an average of + 11 t C . ha^{-1} .a^{-1} (mean value, range +-50%) to values close to zero (range - 1 to + 1 t C . ha^{-1} .a^{-1}).

Practical Information on Paludiculture

Paludiculture (from Latin “palus” = “mire, swamp”) is agriculture or forestry on wet or rewetted organic soils. It is a sustainable commercial location-adapted land use concept where the aboveground biomass is harvested and mainly used as a renewable resource, replacing fossil resources and supporting regional value chains. Belowground biomass is not used. Although wetland biomass has been used already for many centuries, the idea of paludiculture is very new.

The implementation of paludiculture should take place only at drained sites, but not in pristine mires, natural sites or for areas rewetted for nature protection. Several environmental restrictions need to be considered when starting paludiculture.

In Central and Northern Europe there are three approaches of paludiculture

1. Wet meadow, species: Phalaris arundinacea, Carex ssp., Animal stock
2. Paludicultures in bog soils, species: Sphagnum ssp., Drosera ssp.
3. Paludicultures in fen soils and other organic soils, Species: Typha latifolia, Typha angustifolia, Phragmitis australis, Alnus glutinosa.

Selected approaches and cultivation of different species are described in the following.

WET MEADOW

A very environmentally friendly option for all organic soils is to extensify grassland fields and increase the water level until near ground surface. The field might not be accessible any more for conventional agricultural machinery. Beside conserving the peat and reducing the greenhouse gases to almost zero, it enhances many other ecosystem services. The area serves as habitats for many birds, some of them are endangered. The soil is a sink for nutrients and water. These areas are also beneficial for ecotourism. Typical plants are reed canary grass and sedges. Reed canary grass yields 3.5 to 22.5 t ha^{-1} a^{-1} dry mass. Sedges yields 3.3 to 12 t ha^{-1} a^{-1}. The biomass can be utilized as energy source or as fodder. In addition, grazing with robust livestock like water buffalo to produce meat is possible (Dahms und Wichtmann 2014).

SPHAGNUM

The commercial cultivation of peat mosses („Sphagnum farming") is especially applicable at nutrient poor sites with a low pH-value, because Sphagnum species are adapted to these conditions. It should be the first choice in bog soils, because peat mosses are the typical vegetation in bogs. There is a high variety of different Sphagnum species for harvest as living biomass. Sphagnum farming is an excellent option for sustainable as well as environmental- and climate-friendly land use.

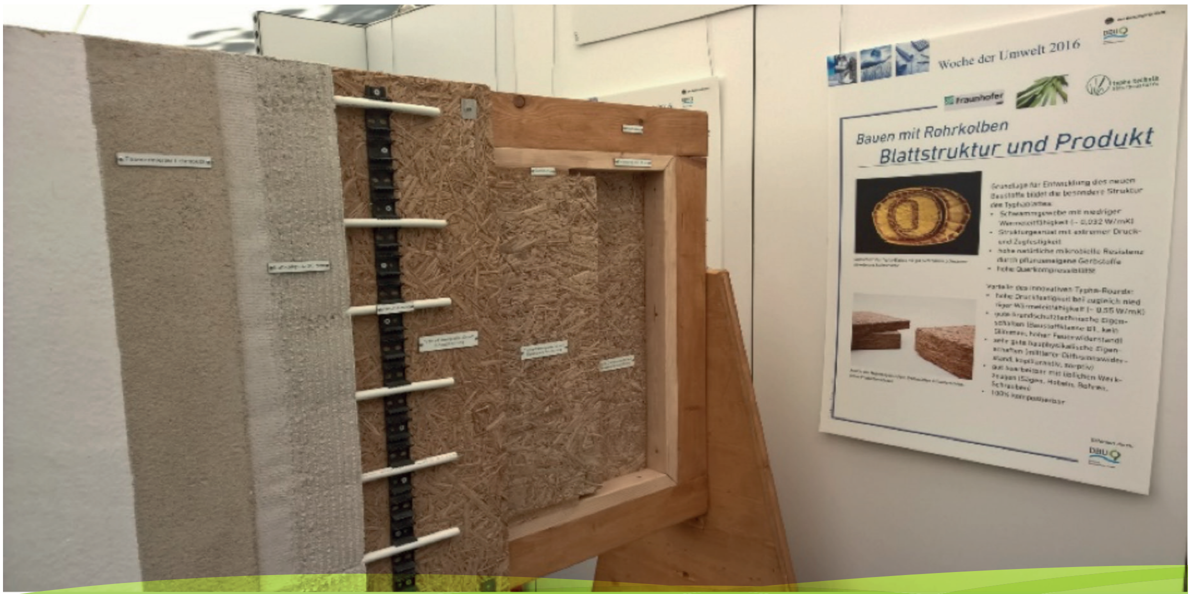
It is very important to maintain an even water level throughout the whole year and to remove other emerging plants. Fertilizer and pesticides are not necessary and not wanted.

The yield is variable and depends on many factors, e.g. the location. In Germany, a yield of approximately 5 tons dry mass per hectare and year were observed. One harvest each 5 years is recommended. The biomass can be used for different purposes. The main utilization is to produce horticultural substrates and the replacement of peat in horticulture (Gaudig et al. 2017, Temmink et al. 2017).

TYPHA

The cattail species narrow-leaved cattail (Typha angustifolia), broad-leaved cattail (Typha latifolia) and their hybrid (Typha x glauca) are native in Central Europe and can be used for a variety of purposes. Due to the high productivity a high yield can be expected: 4.3 to 22.1 t ha^{-1} a^{-1} dry mass. Cattail is not a peat-forming plant. But organic soils planted with cattail can keep the existing peat, if the water level is kept near the ground surface. Cattail tolerate fluctuating water levels up to 1.5 meters above surface level. Cattail is suitable for eutrophic sites, due to its high demand of nutrients.

There are different ways to grow cattail, it is also possible that cattail develop itself. Pesticides are not necessary and not wanted. It is not clear, if cattail can be grown over many years without fertilizer. Cattail can be very useful, if the cultivation is connected with his function to clean water.



Cattail has been proven to be a good raw material for construction board making and insulation. Photo: ©3N/Kürsten

The harvest of cattail is up to now very expensive. The biomass can be used for insulation due to the aerenchyma of the leaves and for other construction materials. Other utilisations might be e.g. substrate for horticulture or thermal use. It is also eatable (Gaudig et al. 2014, Pfadenhauer and Wild 1998).

PHRAGMITIS AUSTRALIS

The highest yield in dry mass can be achieved from the peat-forming reed. The crop yield amounts to 6.5 to 23.8 $t\ ha^{-1}\ a^{-1}$ dry mass or 3.7 to 15 $t\ ha^{-1}\ a^{-1}$ dry mass in winter. The time of harvesting depends on the utilisation of the biomass. In summer it contains more nutrients, whereas in winter the nutrients are mostly relocated to the rhizomes or washed out by precipitation. Similar to cattail, it demands high amounts of nutrients and is otherwise quite undemanding. Reed prefers wet soils. It tolerates fire, frost, high pH-values, salt, high weed pressure and water level fluctuations with high water levels up to 2 meters. There are different ways to grow reed.

Reed is mainly used as construction material (roofing), but there are also other possibilities. Reed is an ideal source for lignin and cellulose, which can be utilized versatile in bioeconomy (El Bassam 2010, Gaudig et al. 2014, Wichtmann et al. 2014).

ALNUS GLUTINOSA

Black alder (Alnus glutinosa) might be peat-forming and grows in wet, nutrient-rich, base-rich fen soils, but it doesn’t tolerate water levels above ground level over a longer period. Highest peat-forming rates can be achieved at a mean water level of 0 to 20 cm below ground level. Black alder yields after 20 to 40 years at least 10 m^3 of logs per hectare and year, which equals approximately 5.5 t dry mass. The trees can be used to produce wooden furniture or as energy source (Gaudig et al. 2014).

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Links

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www.moorwissen.de/de/paludikultur/paludikultur.php
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3N

Paulsen Hans Marten (Ed.)
Thünen Institute of Organic Farming

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