Draft descriptions for at least six carbon farming techniques:

Carbon farming techniques should

A) add external C to the soil,
B) incorporate by plants through photosynthesis bound atmospheric CO_2 to the soil,
C) avoid loss of C/CO_2 from the soil

and thereby improve humus balance, decrease the greenhouse gas CO_2 in the atmosphere, and increase C content in the soil.

Measures in detail:

A.1 Use of manure, biogas slurry, compost or biochar for fertilization

All the mentioned organic, external fertilizers have a higher organic matter content (and therefore higher C content, soil organic carbon accounts for approx. 50% of the organic matter) and a higher effective organic matter content (part of the organic matter that is still present in the soil after one year) than mineral fertilizers. Solid manure has higher organic matter content than liquid manure. By forming protecting aggregates, particularly the effective organic matter content is important for the establishment of stable humus (Quist, 2020).

To date it is not clear whether biochar as pyrolytic carbon can have positive effects on soil carbon content in European soils and at the same time have positive effects on yield as it was shown for tropic soils. Furthermore, studies concerning the long-lasting effects on soil biota are missing (BAFU, 2023). On the contrary, also positive effects on crop production based on increased water and nutrient availability and liming effect are mentioned (Jumshudzade & Paulsen, 2020).

Trials could be arranged by adding versions of animal manure (liquid or solid, from different animal species), by adding different amounts of uniform biogas slurry, compost or biochar to the experimental plots. As control or baseline may serve untreated plots or plots fertilized with mineral fertilizers in a usual way.

A.2 Relocation of harvest residues, for animal nutrition not needed forage crops (grass-clover) to another field

As increasingly more farms in Central Europe waived livestock, these systems have no direct use for alfalfa clover grass, which is widespread mostly in organic farming systems to provide nitrogen for subsequent crops. In order to relocate unused on-farm carbon reserves in above-ground biomass farmers can resort to the innovative carbon farming technique “transfer mulch”. Alfalfa clover grass is chopped.in June. and the material (2-3 cm pieces) is pneumatically transported onto a compost spreader driving alongside. The biomass is relocated to another field where row crops, e.g., maize, potatoes, sunflower, root or tuber crops are grown. The green chops are spread as fresh, water-rich mulch before row closure, when the soil temperature is at its highest. The “transfer mulch” reduces soil evaporation during hot, dry periods especially at the end of June and can therefore reduce drought stress of plants (Liao et al., 2021), while adding carbon to those crops which entail humus degradation (Kolbe, 2007).

Other possibilities to relocate harvest residues are composting or the exchange of forage crops for manure in form of a farm-to-farm-cooperation or the exchange with biogas residues in cooperation with biogas plant (see A.1).

Trials can be arranged in strips according to farm common working width by adding a standard version of 70 m³/ha mulch material to targeted crop. This corresponds with an average first harvest amount of clover grass in the first year in dry regions. If quantification is not possible, or harvest amount differs strongly, mulch should rather be relocated with quantified proportion 1:1 from one field to another, quantification methods [m3] or [t] are both possible. Different amounts, e.g., twice the mulch material is optional. Plots with no mulch material may serve as control or baseline.

B.1 Additional cultivation of cover/catch crops instead of fallow

This item includes catch/cover crops that are added to the crop rotation instead of bare (winter)fallow and therefore give additional carbon input to an agricultural site (in contrary to B.2 diversification of crop rotation, which also can include catch/cover crops). These crops are called catch crops because they can catch nutrients from the soil which would otherwise leach to the ground water or be washed away by surface water or cover crops because they give a vegetation cover over winter avoiding soil erosion. In this case, these crops will be either incorporated into the soil in spring as green manure or left on the field as mulch after cutting, entailing a special sowing system (e.g., strip till) for the following main crop. Still, if they are harvested for fodder, their remaining roots and root exudates deliver organic carbon. Typical cover crops include solely or in a mixture species of grasses (rye, oats, etc.), legumes (hairy vetch, clover, pea, etc.) and Brassicaceae (radish, mustard, etc.) (Woolish & Jagademma, 2023). A world-wide review of Poeplau & Don (2015) revealed a significantly higher soil organic carbon stock after cover crop treatment than on cropland with winter fallow. With the passage of time, the soil organic carbon stock increased linearly.

Though we do not have the opportunity to test the effect of cover crops for many years, we can rely on the long-lasting (up to 54 years; Poeplau & Don, 2015) and proven experiments of soil organic carbon and humus accumulation. Any comparing trials (fallow/different cover crops) will be welcomed.

B.2 Diversification of field crop rotation, including undersowing, intercropping and mulching practices, leaving crop residues in the field, incorporating crops with distinct root development and root exudate release

The idea behind this item is to enhance the input of carbon into soil by the on-site grown vegetation, above- and below-ground. This can happen by diversifying crop rotation, by toothing crop cultivation, e.g., by under-sowing additional crops (clover, grasses, etc.) in maize, soybean, sunflower or rape, which can grow up quickly as soon as the main crop is harvested, by changing harvest management in a way, that more crop residues are left on the field (Vanbesien, 2020).

Furthermore, different publications have shown that a hitherto underestimated contribution to soil C derives from roots and particularly, from root exudates. Even, an active release of exudates fosters biotic soil life, plant growth promoting rhizobacteria and/or mycorrhiza for example, which on the one hand enhances above ground biomass and thereby potential crop residues and on the other hand provides - after breakdown and death of soil biota – even more left-over carbon. About 46% of stabilized humus derives from root input, while only 8% comes from shoot biomass. Diversification of crop rotation therefore can the more effective sequester soil carbon the stronger root development over the crop rotation is, particularly in deeper soil layers (Schmidt, 2021; Rasse et al., 2005).

Moreover, increasing atmospheric CO_2 seems to increase the release of phenolic root exudates with signal function, particularly, those initiating the N-fixing nodulation in clover (*Trifolium repens*) (Stöber, 2007).

Any trials which can compare the effect of a more diverse crop rotation (e.g., comparing consecutive cultivation versus under-sown cultivation of crops), of establishing crops with a high root/shoot ratio and/or high root exudate release versus control or of management changes in crop residues will be welcomed.

B.3 Intercropping strategies in orchards and horticulture

Intercropping in orchards has proven effects on insect communities and species abundance (Song et al., 2012) and in younger publications positive effects on soil organic carbon and soil aggregate stability were shown compared with monocrop systems. Particularly, the effects seem to improve in the sense of agro-ecological diversification if aromatic plants are used as secondary crops. Furthermore, these systems may apply more for semi-arid, Mediterranean conditions avoiding water loss from the soil without causing water competition with the main crop (Almagro et al., 2023).

Trials may be set up or already existing randomized plots with and without specific intercrops or with natural vegetation.

Similar effects, increasing total organic carbon levels in soil, were also reported for intercropping in horticultural systems, even in short-term experiments (Cuartero et al., 2022). Trials for one vegetation period may include different monocrop plots and diverse versions of mixed cropping.

B.4 Systems of agroforestry with interactions of the agricultural and the forestry part

In general, there are sometimes difficulties to define agroforestry and to distinguish it from other forms of mixed woody and herbal cultivation (like intercropping orchards). Anyhow, mostly we have the requirements for agroforestry systems of the synergetic interaction of agricultural and forestry parts (Augère-Granier, 2020).

Four agroforestry systems are commonly agreed:

- alley cropping
- windbreaks (shelterbelts)
- silvopastures
- homegardens (multistrata systems combining trees/shrubs with vegetal production and livestock)

According to a meta-analysis of Shi et al., 2018, agroforestry reveals 19% more soil C stocks (1m depth) than nearby control plots of cropland or pasture.

If we can evaluate soil carbon sequestration in running or newly established agroforestry plots in Europe, this surely would be an asset in our project.

C.1 Reducing tillage to different extents

Reduced or conservation tillage, as well as no-tillage systems have been widely discussed as potent methods to preserve soil carbon. High tillage and deep ploughing systems increase aeration and oxygenation of soil organic matter, resulting in increased release of CO_2 from the soil. Also, soil biota is disturbed - which could fix organic matter in soil aggregates. Secondly, compacting of soil by heavy machinery causes anaerobic conditions, which also hinders or stops biological activity necessary to form humus rich soil aggregates (Heining, 2020).

Still, obviously not all soil layers in different depths react in significantly increased carbon storage to reduced or omitted tillage practices. No-tillage and intermediate tillage systems seem to increase soil organic carbon in the topsoil (0-15 cm) compared with conventional ploughing, while results in the layer of 15-30 cm depths do not always show beneficial changes. In a meta-analysis of Haddaway et al. (2017) no-tillage systems significantly increased carbon stocks in 0-30 cm depths in over 10 years. Minimum tillage (5cm disking-direct sowing) might give the best results in dissolved and bound organic carbon in soil (Sae-Tun et al., 2022).

Establishing or participating in experimental plots focusing different tillage intensities could provide further experience in carbon sequestration techniques.

C.2 Peatland restoration

To combine the idea of keeping or regaining soil organic carbon in former peatlands with agricultural cultivation (required for Carbon Farming), no rewetting for natural protection or use of – still – natural mires is proposed for the technique ‘peatland restoration’, but the rewetting of already drained areas. This technique should increase ground water level and at the same time use aboveground biomass for harvesting, while belowground biomass remains unused. In this case, different species of Juncaceae and Cyperaceae can be harvested as energy crops, as woody building material, as source of cellulose and hemicellulose or similar. Sometimes also the use as feed is proposed, but these grasses – as being non-Poaceae – will not provide a good fodder quality. These approaches avoid huge losses of CO_2 from the soil (7.5 t per ha and year, according to Jacobs et al., 2018) and at the same time conduct land cultivation as so-called paludiculture. Several national legal requirements for such projects must be considered.

In case two project partners could arrange measurements of on-going or newly set-up trials in paludiculture, we can include this promising technique in the project.

C.3 Conversion of arable land to grassland or forest

Permanent grassland might include sites for fodder production and harvest as hay or silage or sites with grazing livestock. The interactions of grazing animals and soil carbon are various, including C inputs from animal faeces and possible C outputs like methane emission by ruminants. Nevertheless, properly kept pastures are thought to sequester more carbon than fodder grassland and these more than arable land (Coopman, 2020). In fact, a conversion of arable land to grassland could maintain soil carbon content, that might be lost by mineralization in arable land. Conversion of arable land to grassland has a yearly carbon sequestration potential of 0.6-3.3 t CO2/ha (Gattinger, 2023).

Also, afforestation and reforestation are mentioned as potent carbon farming measures due to the storage of organic C in soil – after development of forest floor from litterfall - and aboveground biomass (Survila et al., 2022). After all, abandoned agricultural land left to natural succession was also found to be a net carbon sink (Thibault et al., 2022).

These measures hold a great potential of carbon sequestration. However, the implementation within our project could be difficult due to necessary long timeframes for visible results.

C.4 Liming effect for aggregation of Corg and clay minerals

Liming increases the soil pH and thereby shifts the active microbial community. This might result in an increased mineralization and CO_2 release. But the effect of improved and buffered aggregation of clay minerals and organic matter and the enhanced input of C by litter and root exudates of increased plant growth might overweigh the first effect and result in an increase of carbon stock in soil (Wang et al., 2021; Horn, 2023). Soils rich in clay and in available Ca^{2+}have the highest humus content (Schmidt, 2021). A worldwide meta-analysis of published experiments showed an average increase of soil carbon stocks of 8%, depending on kind and amount of lime and N fertilization, on soil textures, initial soil pH and initial soil organic C (SOC) (Butterbach-Bahl, 2023).

To test liming effects on different soils would be an innovative and promising approach to improved soil carbon stocks.

Trial arrangement:

WP1 leaders have agreed that all partners can decide themselves how to design their own trials, as consistent comparability between countries and partners will not be possible due to different environmental conditions, different equipment and resources, different country-specific priorities and different requirements on results. Design therefore can range from simple demonstration plots to encourage farmers to come deeper into the topic humus and carbon sequestration to scientifically sound experiments with statistical analysis and publishable results.

Here, we suggest a way to meet the minimum requirements for a scientific approach:

All trials should be arranged in a way that the conditions for all factor variations are kept equal and that there are at least two replications per factor variation, organized as randomized plots. One of the factor variations can be the control without treatment (=baseline).

E.g., growing maize after a cover crop (the same over the whole field at the same site) with different tillage system plots

Strip till	Minimum ploughing 5-10 cm	Deep ploughing 25 cm
Deep ploughing 25 cm	Strip till	Minimum ploughing 5-10 cm
Minimum ploughing 5-10 cm	Deep ploughing 25 cm	Strip till

Suggestions for measured and calculated traits will be elaborated shortly. Potential losses of carbon/CO_2 by respiration from the soil due to additional disturbances or by consumption of additional fuel or mineral fertilizers – caused by the incorporation of a new technique, will probably not be considered. Anyhow, respective, constructive inputs of partners are welcomed.

As the vegetation period 2023 and the field cultivation is already running or at least already planned, our trials for 2023 (two for each country) could either include already set-up / running experiments or could start with autumn sowing/ winter crops in 2023. Combined trials with winter crops 2023 and following summer crops in 2024 could be a feasible solution for the short-term period of 18 months for field trials and could be analyzed by two-way analysis of variance.

Possible combinations of trials in the first and the second year on the same site could be for example:

- Ploughing with different depths (C.1) and afforestation (C.3)
- Catch crops (B.1) and cultivation of crops with high/low root/root exudates development

(B.2)
- Catch crops (B.1) and liming effect (C.4)
- Liming effect (C.4) and leaving crop residues on the field or not (B.2)
- others

Using already running/set-up experimental sites could be reasonable for example in case of perennial crop combinations like intercropping orchard sites (B.3) or agroforestry sites (B.4). Probably, we could also discuss using available data of recently established conversion of arable land to grassland (C.3) or peatland restoration (C.2).

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