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JOINT TESTING REPORT OF CARBON FARMING TECHNIQUES FOR FARMERS

DELIVERABLE D.1.2.1

April 2025

CONTENT

INTRODUCTION AND SCOPE OF THE TASK

The objective of Deliverable 1.2.1 is to provide a summary report of the testing of 36 trials of seven different carbon farming techniques carried out by nine project partners over two summer seasons. The testing activities are based on Activity 1.1 preparatory action summarized in D.1.1.

For each tested Carbon Farming Technique all trials carried out can be found in detail in 36 appendices (App A.1.1 – C.4.8).

Broad feedback from the practical and institutional perspective of implementing carbon farming techniques was generated through SWOT analysis developed by local stakeholder groups for each tested technique.

In addition to guidance on implementation, this deliverable provides insight to farmers into how carbon farming techniques affect agricultural systems. It also discusses environmental impacts, economic impacts, and potential barriers and difficulties with practical implementation.

Also included is a ranking of tested techniques based on every partner's evaluation of three main criteria in the final subchapter of each technique, as well as a separate final ranking chapter at the end of the report.

These compiled results of all trials can be used for training material for farmers and advisors and will be incorporated into the train-the-trainer event (WP3) and the CE Guide for Carbon Farming techniques.

SUMMARY REPORT OF TECHNIQUES CHOSEN BY AT LEAST 2 PARTNERS

2.1 EXTERNAL ORGANIC FERTILIZERS (A.1)

The carbon farming technique *external organic fertilizers* (A.1) was chosen by six partners for testing (Tab. 1).

Tab. 1: Overview of all A.1 trials, including scoring on a scale from 1 (very low) to 5 (very high) of the three main criteria *impact* (Estimation of the positive impact on carbon sequestration), *feasibility* (incl. costs and labor demand), and *acceptance* (of farmers, consumers, public)

Appendix Number	Institute (country)	Trial location	Key data	Impact	Feasi-bility	Accep-tance
A.1.1	KIS (Slovenia)	Jablje (central Slovenia, sub alpine climate, 46°08'35.7"N 14°33'23.6"E) and Rakičan (eastern Slovenia, Pannonian climate, 46°39´N, 16°11´E)	two long term trials, established in 1993 main factors: fertilisation with organic fertilisers (management practices) and fertilisation with synthetic nitrogen (N). Management practices: control - **System A** (removal off all above-ground crop biomass **without external organic fertilization), System B - fertilization with 30 t/ha of farmyard manure** every third year and removal of above-ground crop biomass, **System C - annual incorporation of crop harvest residues along with a cover crop every third year**. 3 variants fertilized with synthetic N, 1 control variant	4	2	4

A.1.2	GAK (Hungary)	MATE University educational and demonstration farm, Szárítópuszta; Gödöllő, Szárítópuszta	Different treatments: Control – K-with no fertilizer, organic fertilizer (K2- compost and K1-stable manure) and K3- chemical fertilizer as control. Compost/organic manure is spread in amounts of 20, 15, 10 and 5 t/ha in consecutive years Applied farming actions: Ploughing / Basic tillage with cultivator;	4	3	3
A.1.3	RI.NOVA (Italy)	RI.NOVA experimental farm "Martorano 5" in Cesena (FC)	6 variants: 1.-3. V: Three types of urban compost (from 3 different HERA plants) were applied at 30 t/ha on 20/06/2023; 4. V. an organic soil amendment (ORGA-KEM), 5. V. synthetic fertiliser (NITROFOSKA 12-12-17) 6. V. type of compost (from Voltana-RA plant) was applied at the end of September 2023 (30 t/ha) just before transplanting the second crop in rotation (cabbage).	3	2	3
A.1.4	IUNG-PIB (Poland)	Agricultural Experimental Station of IUNG-PIB in Grabów nad Wisłą (Masovian Voivodeship) 51°21'11.8"N 21°39'30.2"E, Poland	Treatment includes: A control without any mineral or organic additions, B cattle slurry (30 m^3/ha), C solid cattle manure (30 t/ha), D digestate (30 t/ha)	4	3	3
A.1.7	AIO (Croatia)	Agricultural institute Osijek, Južno Predgrađe 17, 31000 Osijek, Croatia	Application of 3 different amounts of digestate (D200 - 110 kg/ha, D300 – 220 kg/ha, D500 – 310 kg/ha of applied digestate, Control – without applied digestate	3	4	2
A.1.9	ART (Czech Republic)	Pro farm Blatnice, Blatnice 18, 657 51 Jaroměřice nad Rokytnou, Czech Republic	Control variant without compost compost variant (rate of 20 t/ha) analysis of humic and fluvic acid ratio	5	4	3

2.1.1 Joint conclusions

The partners testing the carbon farming technique A.1 external organic fertilizers came to the following conclusions. Most frequently denoted conclusions are mentioned first (App. A.1.1 - A.1.9).

- Results demonstrate the slow rate of change in SOC with standard agricultural practices, highlighting the need for long-term experiments for their accurate evaluation.
- SOC increase in soils with higher initial SOC is smaller compared to SOC stock increase in soils with lower initial SOC stocks
- Use of manure, crop residue incorporation or compost increased SOC stocks, even under conventional tillage with plowing.
- It is important to consider site-specific factors like soil type, climate conditions and present SOC stocks when designing strategies for SOC management.
- Alternative manuring methods should not focus on yield quantity, but other parameters of the production, like sustainability or environmental health.
- The effect of synthetic N on SOC was only linked to the amount of biomass incorporation.
- Removing aboveground crop biomass without organic fertilization reduced SOC stocks. This negative effect can be compensated with natural weed growth on some soils.
- Comparisons of sampling results from 2020 in 2023 showed the sensitivity of unstable SOC to weather variability.
- Organic amendments and digestate increased maize yield.
- Amendments like cattle slurry, solid manure, and digestate affect soil microbial communities. A reduction in amine and amide metabolism could reflect shifts in microbial diversity or competition for resources. These changes may influence carbon cycling and nitrogen dynamics in the soil.
- Organic amendments reduce carbohydrate metabolism by soil microbes, potentially slowing organic matter turnover and promoting carbon retention
- Applicability of external organic fertilizers, like compost, depends on machinery used and can be difficult to distribute due to certain characteristics in size and shape.
- Application of digestate showed beneficial effects on soil acidity.
- Compost increased the quality of organic matter in terms of HA/FA ratio, which suggests the formation of more stable, humified organic matter.
- Organic fertilizers like compost stimulate soil microbial activity (A.1.8, A.1.11).

2.1.2 Joint SWOT analysis

SWOT analyses were carried out in focus groups with different stakeholders (such as farmers, advisors, scientists, agroeconomic and educational experts and representatives of legal authorities) in each country which conducted a trial of the carbon farming technique application of external fertilizers (A.1) with regard to the trials' results and experiences. The outcomes of these SWOT analyses are gathered and summarized in this chapter.

Strengths:

- **Soil health improvement**: The addition of organic matter improves soil structure, enhances microbial activity, and boosts overall soil health.
- **Soil fertility**: Organic fertilizers provide essential nutrients over time, ensuring sustainable soil fertility and reducing nutrient leaching.
- **Physical soil properties:** Organic fertilizers enhance soil structure and reduce bulk density. This leads to improved trafficability, which is particularly appreciated by farmers.
- **Carbon sequestration**: Organic fertilizers promote carbon storage and stabilization in the soil by adding organic matter and promoting microbial activity.
- **Climate resilience**: Soils treated with organic fertilizers become more resilient to extreme weather conditions, such as drought and heavy rainfall.
- **Improved moisture regime**: Organic fertilizers enhance the soil's water retention capacity, reducing water stress and improving crop resilience.
- **Soil biodiversity**: By enriching the soil with organic materials, an increase in soil biodiversity is fostered, which includes a variety of beneficial organisms and vital soil microorganisms.
- **Reduced chemical input dependence**: Organic fertilizers have a complex composition of nutrients, which helps reduce dependence on the purchase and use of mineral fertilizers and therefore dependence on fluctuating prices of mineral fertilizers.
- **Sustainability and waste reduction**: Composting is an efficient method of recycling organic waste, such as agricultural residues, manure, and food scraps, turning it into valuable soil amendments. This process reduces waste and mitigates the environmental impact of organic waste disposal.

Weaknesses:

- **Higher costs**: Specialized equipment for the application of organic fertilizers can be expensive, increasing initial investment costs, especially for farms without livestock, when organic fertilizers must also be transported over long distances. Certain requirements for adequate storage facilities may lead to additional high construction costs.
- **Complex logistics**: Transporting, storing, and applying organic fertilizers requires careful planning, adding logistical challenges for farmers, especially for small farms and for fertilizers with powdery matrices for which there is no specific equipment available in some regions.

- **Higher weed pressure**: Organic fertilizers, especially manure, can introduce weed seeds, requiring additional weed management efforts.
- **Lower field capacity**: The bulkiness of organic fertilizers may require more frequent applications, decreasing efficiency in large-scale operations.
- **High quantities** of some organic fertilizers like compost and repeated distributions are necessary to be able to appreciate an effect of increasing of C in the soil, as well as to improve the soil organ-mineral balance.
- **Readily available nutrient**: Using slowly-degradable organic fertilizers, the supply of readily available nutrients for the crops is sometimes limited compared to the use of a mineral fertilizer. For this reason, complementary fertilization may be necessary to ensure a sustainable yield, especially for nutritionally demanding crops.
- **Legal restrictions:** In some cases, the use of organic fertilizers is restricted during certain periods (e.g., winter, requiring investments in storage facilities) or within narrow time slots after delivery (digestate), or in specific areas (e.g., water protection zones).
- **Odors:** the application of organic fertilizers can produce unpleasant odors, especially close to settlements.

Opportunities:

- **Circular economy**: Their adoption creates a closed-loop system by turning waste into valuable inputs, promoting sustainability and resource efficiency.
- **Multiple ecosystem services**: The use of organic fertilizers supports biodiversity, improves water quality, and enhances ecosystem services such as pollination and pest control.
- **Effective waste management:** Organic fertilizers provide a sustainable method to recycle agricultural and animal waste, reducing environmental pollution.
- **Scalability and potential for large-scale impact:** Composting is scalable, making it suitable for both small and large agricultural operations.
- **Alternative economic opportunities**: The production, marketing, and distribution of organic fertilizers can open new income streams for farmers and businesses.
- **Research and innovations** offer the potential for newer technologies that improve efficiency and reduce losses related to the use of organic fertilizers.
- **Financial incentives:** Increasing support for equipment purchases and simplifying regulations could significantly enhance adoption rates of this technique
- **Educational campaigns:** Workshops and advisory services are also necessary to address the current knowledge gaps and raise awareness about the benefits of these practices.

Threats:

- **Potential contamination**: If improperly processed, organic fertilizers may carry unwelcome weed seeds, or even pathogens that pose risks to plant health and food safety. They may also contain heavy metals and contaminants, such as plastics or glasses in composts.
- **Competition from synthetic fertilizers:** The dominant use of synthetic fertilizers in conventional agriculture presents a challenge for the adoption of external organic fertilizers. While organic fertilizers offer clear environmental benefits, synthetic fertilizers are often more readily available and less labor-intensive for farmers.
- **Reducing animal stock**: A reduction in livestock farming could limit the availability of manure, a primary source of organic fertilizer.
- **GHG (greenhouse gas) emissions:** Improper management of organic fertilizers, such as manure, can lead to increased emissions of methane and nitrous oxide.
- **Regulatory policies:** Changing regulations may impose restrictions on organic fertilizer use, processing, or application methods. E.g. in Slovenia, there is also a reduction in financial incentives for livestock farming.
- **Problems in fodder production structure:** Challenges in fodder production could indirectly affect organic fertilizer availability by disrupting livestock operations.
- **Specialization of farms** leads to concentration of livestock farms in specific areas, which in turn causes a higher concentration of manure and slurry use on smaller land areas.

2.1.3 Farmer's viewpoint

As farmers were a main group of stakeholders in all SWOT analyses, their opinion and point of view was considered strongly and is described there. For further details of regional aspects see appendices A.1.1 – A.1.9).

2.1.4 Environmental impacts, CO2 and biodiversity

The use of organic fertilization has been shown to increase soil organic matter. Soil organic matter is an important indicator of soil quality and fertility. It comprises living and dead organisms, as well as their organic excretions and decomposition products. Organic matter influences numerous chemical, physical, and biological properties of the soil. From a biological perspective, organic matter is a vital source of energy and nutrients (primarily nitrogen, phosphorus, and sulfur) for soil organisms and plants, thereby reducing the need for mineral fertilizers. Agriculture accounts for approximately 72% of N_2O emissions in the EU, with most of these emissions arising from losses associated with the use of synthetic nitrogen (N) fertilizers. N_2O emissions represent about 5.6% of the total greenhouse gas emissions in the EU-27. Reducing the use of synthetic N fertilizers would directly lower the carbon footprint associated with their production and application. In addition to being a source of energy and nutrients, organic matter enhances soil and crop resilience to the effects of climate change by improving water retention and availability in soils.

This supports sustainable production under diverse climatic conditions and for a wide range of plant species while also enhancing biodiversity at the field level (App. A.1.1).

2.1.5 Economic analysis

For an economic analysis, a site-specific overview of all costs and labor is indispensable and can be found in all referring appendices (A.1.1. – A.1.9).

2.1.6 Ranking of Technique

Tab. 2: Joint mean scoring of the present technique on a scale from 1 (very low) to 5(very high), x indicates one partner scoring

Criteria / Score	1	2	3	4	5	Mean score
Estimation of the positive impact on carbon sequestration			xx	xxx	x	3,8
Feasibility (incl. costs and labor demand)		xx	xx	xx		3,0
Acceptance (of farmers, consumers, public)		x	xxxx	x		3,0
Sum						9,8

Compared to all other tested carbon farming techniques A.1 external fertilizers is ranked 4 out of 7 according to the sum of mean criteria scores of 9,8.

2.2 RELOCATION OF HARVEST RESIDUES (A.2)

The carbon farming technique of relocating of harvest residues (A.2) was chosen by five partners for testing:

Tab. 3: Overview of all A.2 trials, including scoring on a scale from 1 (very low) to 5 (very high) of the three main criteria *Impact* (Estimation of the positive impact on carbon sequestration), *Feasibility* (incl. costs and labor demand), and *Acceptance* (of farmers, consumers, public)

Appendix Number	Institute (country)	Trial location	Key data	Impact	Feasi-bility	Accep -tance
A.2.1	KIS (Slovenia)	Infrastructure Centre Jablje, Agricultural institute of Slovenia, Grajska cesta 1, 1234 Mengeš, Slovenia	Cut and carry approach was tested Alfalfa biomass was used as residue versus control Trial with maize, on organic experimental field In total 4 plots, 28 m^2 each plot	3	4	4
A.2.5	BFA (Austria)	Joachim Lumplecker's organic farm, Weixlgarten 1, 4441 Ramingdorf, Austria	Silage storage of cut clover grass and its suitability for application was tested collected parameters: - clover grass quantities - carbon and nutrient balance after processing - duration and cost of work processes - suitability and application settings tested	4	2	4
A.2.6	No Gravity (Slovakia)	919 04 Smolenice, Trnava district (western Slovakia) Slovakia GPS – 48.50°N, 17.43 °E	2 variants: with harvest residues – grape leftovers (1,5 kg per m^2 in October 2023) and mulch (1,5 kg per m^2 in July 2024), control variant without harvest residues Within each 25 m^2 area, 1 replication per variant	2	3	2
A.2.7	AIO (Croatia)	Agricultural institute Osijek, Južno Predgrađe 17, 31000 Osijek, Croatia	Plots: 3 treatments and 3 repetitions (plot size 24 x 3 = 72 $m^{2)}$ Treatments: 1. Control – corn (no relocation of harvest residues) 2. Alfalfa crop residues – 66 kg/treatment (~70 m^3/ha) 3. Alfalfa crop residues - 132 kg/treatment (~140 m^3/ha) Pre-crop winter barley, relocation of alfalfa residues was May 13, 2024.	5	4	2

A.2.9	ART (Czech Republic)	Zabitý, Troubsko, 664 41 Troubsko, Czech Republic	300 m² each (30x10m), three replications per variant Two variants: control variant without harvest residues variant involving the application of post-harvest residues (Galega orientalis), two phases (May and July) of application post-harvest residues (Galega orientalis) on the same trial (field) variant Spreading on the harvested rye field (for silage)	4	3	4

2.2.1 Joint conclusions

The partners testing the carbon farming technique A.2 relocation of harvest residues came to the following conclusions. Most frequently denoted conclusions are mentioned first (App. A.2.1 - A.2.9).

- Future research should focus on assessing the long-term effects of this practice on soil carbon dynamics and its broader environmental benefits.
- Relocating post-harvest residues led to a noticeable increase in total organic carbon (TOC) content.
- Results indicate that the relocation of post-harvest residues may stimulate soil microbial activity.
- In addition to the increase in TOC, there was a slight improvement in the quality of soil organic matter, as reflected by the increase in the HA/FA ratio
- Cut-and-carry treatment using alfalfa straw showed a smaller reduction in Corg, compared to control plots. This suggests that the addition of biomass through the cut-and-carry practice helped mitigate soil organic carbon (SOC) losses.
- Slow release of nitrogen from the decomposing alfalfa straw, combined with potential slower mineralization colder covered soil, might have limited the early growth of maize and resulted in the lower yield of the cut and carry treatment.
- The residual cover of decomposing alfalfa straw persisted in the field for an extended period, even after three months. This prolonged decomposition may have been a result of the relatively dry conditions and the initial drying of the alfalfa straw, which slowed the decomposition process.
- Logistics for harvesting and relocating harvest residues must be planned carefully to ensure economic efficiency. Farmer cooperations had a very positive influence on a successful conduction.
- Producing silage out of fresh biomass is an efficient way to make harvest residues storable for later relocation. Silage fertilizers proved to be spreadable by using common devices for solid manure application. Its decomposition rate is comparable to those of strawless solid manure, commercial organic fertilizers or even cover crop biomass.
- Silage fertilizers' decomposition rate can be compared to those of strawless solid manure, commercial organic fertilizers or even cover crop biomass.

2.2.2 SWOT analysis

SWOT analyses were carried out in focus groups with different stakeholders (such as farmers, advisors, scientists, agroeconomic and educational experts and representatives of legal authorities) in each country which conducted a trial of the carbon farming technique relocation of harvest residues (A.2) with regard to the trials' results and experiences. The outcomes of these SWOT analyses are gathered and summarized in this chapter.

Strengths

- **Enhanced soil carbon sequestration:** Relocating post-harvest residues has been shown to significantly increase soil organic carbon (TOC), which plays a crucial role in long-term carbon sequestration.
- **Improved soil health and fertility:** The relocation of post-harvest residues boosts soil organic matter, enhancing soil structure, soil biodiversity, water retention and nutrient cycling. Poorer soils can be upgraded by using surplus biomass produced on richer soils.
- **Weed surpression:** Mulching relocated residues succesfully prevents the growth of weed, which would compete with crops for nutrients and water.
- **Soil prevention:** Soil **c**overage with relocated harvest residues reduces soil erosion and improves soil conditions by balancing surface temperature during extremely hot periods.
- **Retaining soil moisture:** This approach helps to retain soil moisture, ensuring that crops have a steady supply of water even during dry periods.
- **Cost-effective fertilization:** By repurposing post-harvest residues, a natural by-product of farming, this method reduces the need for expensive synthetic fertilizers.
- **Reduction of C-losses:** Relocation of harvest residues shows potential to reduce on-farm C-losses due to a more efficient use of organic matter.

Weaknesses

- **High initial investment and operational costs:** The implementation of residue relocation requires significant investment in equipment, such as machinery for residue collection and relocation, as well as additional labor costs. For small-scale or resource-constrained farmers, these upfront expenses can be challenging.
- **Labor- and time-intensive:** The process of collecting, relocating, and managing residues can be labor-intensive and time-consuming, particularly during busy harvest periods.
- **High energy input:** Transportation of fresh matter necessitates increased use of fossil fuel as high water contents in organic matter result in higher tonne-kilometers. Therefore, distances longer than 5 kilometres of transport should be avoided to justify carbon emissions.
- **Lack of knowledge and technical expertise:** There is often a gap in knowledge and technical expertise regarding the proper implementation of post-harvest residue relocation. Depending on C/N ratio of the residues, immobilization of nitrogen can occur, leading to a higher need for nitrogen fertilizers. Resources available from advisors and research institutions to provide adequate support may be limited.

- **Uncertain impact on short-term yield:** While residue relocation offers long-term soil health benefits, it may not immediately translate into higher crop yields.
- **Pest problems:** An increase in pest problems (including snails and mice) occurs because some plant residues can serve as hosts for pests or create a favorable environment for them.

Opportunities

- **Farmers' cooperations:** By using **e**xternal, rentable machines for harvesting and relocating high on-farm investments can be avoided, which is crucial for a widespread adoption of this technique. These special devices can be organized and shared by farmer cooperations.
- **Possible cost reduction:** Utilizing mulch effectively minimizes the number of agricultural operations required on crops, as it acts as a barrier against weeds, reducing competition for resources and enhancing crop growth. This not only streamlines the farming process but may also contribute to overall efficiency in managing crop production.
- **Support critical times in crop rotation:** Relocation of harvest residues can help to mitigate crucial time slots within a crop rotation when carbon decreases and soil erosion is likely, as in maize, soybean, sunflower, rape or potato. These risks can be reduced with on-farm resources from carbon-increasing crops like the utilization of fodder legumes.
- **Market demand for sustainable practices:** As consumer demand for sustainably produced agricultural products continues to rise, farmers have an opportunity to differentiate their products by adopting environmentally friendly practices. The relocation of post-harvest residues could become a significant selling point, especially for products marketed as eco-conscious or carbon-neutral.
- **Policy and financial incentives:** Government policies and financial incentives, such as subsidies, grants, or tax breaks for sustainable farming practices, can make the adoption of post-harvest residue relocation more financially attractive.
- **Collaboration with research institutions and advisors:** Collaboration between farmers, agricultural advisors, and research institutions can help facilitate the adoption of residue relocation. These partnerships can bridge knowledge gaps, provide technical expertise, and improve the effectiveness of the technology, making it more accessible to farmers of all sizes.
- **Long-term soil fertility and reduced fertilizer dependence:** By enhancing soil organic matter, post-harvest residue relocation may reduce the need for synthetic fertilizers over time. This can help lower input costs for farmers, promote soil sustainability, and minimize the environmental impact of fertilizer use.
- **Combinable with reduced tillage:** The benefits of harvest residues can be successfully combined with carbon farming technique reduced tillage (C.1) to enhance effectiveness in SOC sequestration in soil.

Threats

- **Availability of sufficient mulching material:** Many farmers are unaware of the limited availability of alfalfa for mulching. This lack of awareness could lead to financial losses, as the technique may not produce the expected returns.
- **Harming main crop**: There is a risk of unintentionally harming the main crop during the application of the mulch, which could negatively affect its growth and overall yield.
- **Delayed economic benefits:** The positive impacts of post-harvest residue relocation, such as improved soil health and enhanced carbon sequestration, develop over the long term. This delayed return on investment might deter some farmers, especially those focused on short-term financial gains.
- **Environmental challenges:** Extreme weather events, such as droughts, floods, or frost, may compromise the viability and effectiveness of post-harvest residue relocation.
- **Profitability**: Farmers mentioned that alternative uses for surplus alfalfa—such as selling it as livestock feed—offer a more profitable opportunity. This approach not only takes advantage of the surplus but also better aligns with current market demands, maximizing (short-term) profitability.
- **Policy and regulatory instability:** The regulatory landscape surrounding carbon credits and sustainable agricultural practices is still evolving. Changes in environmental policies, subsidy schemes, or carbon credit regulations could affect the financial viability and adoption of residue relocation. Uncertainty or inconsistencies in regulations may discourage farmers from investing in this technology.
- **Farmer resistance to change:** Farmers, especially those with long-standing traditions in conventional farming, may be reluctant to adopt new technologies. Resistance to innovation is common, particularly when the perceived benefits of residue relocation are unclear or have not been proven in specific local contexts.
- **Market competition for carbon credits:** As the carbon credit market expands, competition for credits may intensify, potentially diminishing the financial incentives for farmers. Fluctuations in the value of carbon credits could undermine the economic viability of residue relocation as a primary source of income.
- **Technical challenges in large-scale adoption:** While residue relocation is manageable on small to medium-sized farms, scaling up to large agricultural operations could present technical and logistical difficulties. Managing larger quantities of residues and ensuring their uniform relocation may require advanced equipment and infrastructure, which could act as a barrier to widespread adoption.
- **Uncertainty in long-term effectiveness:** The long-term effectiveness of post-harvest residue relocation on soil carbon storage and fertility is still under investigation. Although early results are promising, the benefits of the technology may vary based on local soil conditions, crop types, and environmental factors.

2.2.3 Farmer's viewpoint

As farmers were a main group of stakeholders in all SWOT analyses their opinion and point of view was considered strongly and is described there. For further details of regional aspects see appendices A.2.1 – A.1.9).

2.2.4 Environmental impacts, CO2 and biodiversity

The environmental impact of post-harvest residue relocation technology extends far beyond soil health and carbon sequestration. Post-harvest residue relocation promotes carbon storage in the form of stable organic compounds, particularly humus, which builds up the soil's carbon stock over time. By returning organic residues to the soil, farmers can improve the land's ability to sequester carbon and reduce the carbon footprint of farming practices.

Beyond carbon sequestration, relocating post-harvest residues can positively affect biodiversity. Soils rich in organic matter create a more conducive environment for a wide range of soil organisms, including microbes, fungi, and earthworms, all of which play crucial roles in soil structure, nutrient cycling, and overall ecosystem health. As organic matter increases, the diversity of soil organisms also grows, leading to more resilient and productive agricultural systems. This enhanced biodiversity benefits not only soil health but also the broader ecosystem, as healthy soils are essential to maintaining ecological balance in surrounding environments.

Using post-harvest residues as an organic matter source also helps reduce the need for synthetic fertilisers and pesticides. Conventional farming practices often rely heavily on chemical inputs, which can degrade soil health, reduce biodiversity, and harm surrounding ecosystems. By replacing synthetic chemicals with organic amendments, post-harvest residue relocation can alleviate the chemical burden on the environment, contributing to healthier ecosystems both on and off the farm.

However, the environmental advantages of residue relocation require careful management. The success of this technology in reducing CO2 emissions and enhancing biodiversity is influenced by several factors, including soil type, crop systems, and local climate conditions. Mismanagement or excessive use of post-harvest residues could lead to negative outcomes, such as nutrient imbalances or soil degradation. Therefore, farmers must integrate residue relocation into a comprehensive, sustainable farming system, adopting best management practices to ensure lasting environmental benefits.

In conclusion, the environmental impact of post-harvest residue relocation technology is wide-ranging. It not only helps mitigate climate change by enhancing soil carbon sequestration but also supports biodiversity by promoting a healthy soil ecosystem. By reducing the need for synthetic chemicals and improving soil health, this practice can play a crucial role in advancing sustainable agriculture and reducing the environmental footprint of farming. As research on its benefits continues, this technology has the potential to make significant contributions to both climate change mitigation and biodiversity conservation (App. A.2.9).

2.2.5 Economic analysis

For an economic analysis, a site-specific overview of all costs and labor is indispensable and can be found in all referring appendices (A.2.1. – A.2.9).

2.2.6 Ranking of Technique

Tab. 4: Joint mean scoring of the present technique on a scale from 1 (very low) to 5(very high), x indicates one partner scoring

Criteria / Score	1	2	3	4	5	Mean score
Estimation of the positive impact on carbon sequestration		x	x	xx	x	3,6
Feasibility (incl. costs and labor demand)		x	xx	xx		3,2
Acceptance (of farmers, consumers, public)		xx		xxx		3,2
Sum						10,0

Compared to all other tested carbon farming techniques A.2 Relocation of harvest residues is ranked 3 out of 7 according to the sum of mean criteria scores of 10,0.

2.3 ADDITIONAL COVER CROPS (B.1)

The carbon farming technique of planting additional cover crops (B.1) was chosen by seven partners for testing:

Tab. 5: Overview over all trials of B.1, including scoring on a scale from 1 (very low) to 5 (very high) of the three main criteria *Impact* (Estimation of the positive impact on carbon sequestration), *Feasibility* (incl. costs and labor demand), and *Acceptance* (of farmers, consumers, public)

Appendix Number	Institute (country)	Trial location	Key data	Impact	Feasi-bility	Accep-tance
B.1.1	KIS (Slovenia)	Trials at the Infrastructure Centre Jablje, Agricultural institute of Slovenia, Grajska cesta 1, 1234 Mengeš, Slovenia, farm Jani Pucihar, Žalna 10, 1290 Grosuplje and farm Andrej Šuvak, Bohova 19D, 2311 Hoče	15 plots per location, 150-500 m^2 each **13 different legumes species** (*Trifolium repens* (white clover), *Trifolium pratense* (red clover), *Trifolium resupinatum* (Persian clover), *Trifolium alexandrinum* (egyptian clover), *Trifolium hybridum* (alsike clover), *Ornithopus sativus* (serradella), *Melilotus* sp. (sweet clover), *Vicia sativa* (common vetch), *Vicia pannonica* (Hungarian vetch), *Vicia villosa* (hairy vetch), *Lathyrus latifolius* (grass pea), *Trifolium incarnatum* (crimson clover), and *Medicago sativa* (alfa-alfa), **2 commercial mixtures** (Bodenfit und Nitrofit) for green manure, seeded as strip plots sowing in the late summer of 2023, after the harvest of winter wheat	3	3	4
B.1.2	GAK (Hungary)	MATE University educational and demonstration farm, Szárítópuszta	**Plot 1**: Rotation with cover crops: Sunflower → Cover crop winter oat (***Avena strigosa*, also called oat or black oat**) → maize. Field size: 1 ha. **Plot 2**: Rotation without cover crops: Sunflower → fallow → maize. Field size: 1 ha.	4	2	3
B.1.3	RI.NOVA (Italy)	commercial farm (Az. Dell'Agape) at Migliarino, Ferrara (FE).	5 variants (plots) of 2700 m^2 each: TO) rye grown as a cover crop and enticed just during sowing of the main arable crop; T1) no cover crop, no chemical weeding with 4 minimum tillage; T2) no cover crop, 2 minimum tillage and use of chemical weeding; T3) multicomponent winter cover crop with field bean (Vicia faba var. minor), radish and barley; T4)	3	3	4

			multicomponent winter cover crop with radish and leguminous species (commonly used by the farmer). Main crop soybean was sown at the end of May 2023.			
B.1.4	IUNG-PIB (Poland)	Trial on IUNG-PIB Research Farm - Błonie - Topola, Central Poland) 52°05'87'' N, 19°10'24'' E, Błonie 138, 99-100 Łęczyca, Poland	Plot 1: Rotation with cover crops: (1) winter wheat → (1.1) cover crops (mix of Lacy phacelia (Phacelia tanacetifolia) and Oilseed Radish (Raphanus sativus var. oleiformis), → (2) maize → (3) winter wheat; Plot 2: Rotation without cover crops: (1) winter wheat → (2) maize → (3) winter wheat;	5	2	4
B.1.5	BFA (Austria)	Bio Forschung Austria institute, Esslinger Hauptstraße 132, 1220 Vienna	- 6 cover crop mixtures are compared, each containing 9 to 18 species, totalling 30 different species - Includes a 2-phase cultivation method combining freeze-killed and winter-hardy cover crops	4	3	4
B.1.7	AIO (Croatia)	Agricultural institute Osijek, Južno Predgrađe 17, 31000 Osijek, Croatia	Plots: 4 treatments and 3 repetitions (plot size 30 x 15 = 450 m^2; Pre-crop was winter wheat, sowing date of peas was July 12, 2023 and after peas biomass soil incorporation, on April 15, 2024 corn was sown. 1. Control - fallow 2. Spring fodder peas OS Bera - 200 kg/ha 3. Spring fodder peas OS Uran - 220 kg/ha 4. Winter fodder peas Adam - 150 kg/ha	3	3	4
B.1.8	OBG (Germany)	farm: Michael Grimm, Roter Rain 2, 97900 Külsheim, Germany	- 5 plots, 600 m^2 each - Five variants of cover crop (CC) mixtures: - Legume-oriented mixtures with spring clover species (LO) - Legume-free mixture (LF) - Partially freezing mixture for maize as a subsequent crop (PF) - Fast-growing and greening mixture (FG) - Farmers' own winter-hardy mixture (WH)	5	3	4

2.3.1 Joint conclusions

The partners testing B.1 Additional cover crops came to the following conclusions. Most frequently denoted conclusions are mentioned first (App. B.1.1 - B.1.8).

- The results suggest that the duration of testing (over one or two growing seasons) is too short to seriously expect valuable outcomes. Therefore, future long-lasting experiments are recommended.
- Annual changes in soil organic carbon are challenging to analyze accurately, and drawing meaningful conclusions from the gathered data is difficult due to various environmental and management factors affecting soil carbon pools.
- The timing of sampling is an important consideration as soil disturbance and aeration likely accelerated organic matter mineralization, contributing to SOC loss.
- No significant overall difference in soil organic carbon (Corg) was observed between autumn 2023 and spring 2024 across most variants.
- There is a high and significant variability in TOC values due to the specific location and soil, but repeating patterns cannot be identified over a one-year period.
- Even in simple experiments, adhering to the cultivation technology was not easy, and the weather had to be taken into account during implementation.
- Using cover crops for a short period of time, over a season, can demonstrate the positive effect of cover crops on the soil and the next cash crop. Obviously, this does not occur in extreme weather conditions.
- The right cultivation time is relevant also for drought tolerant species.
- Different cover crop mixtures never had any influence on TOC values, neither in a single year as time point evaluation, nor in the development between two years. Also, the presence of legumes did not cause any change of TOC.
- Nitrogen fixed by legumes with their narrow C:N ratio may have stimulated microbial decomposition, further contributing to the temporary loss of SOC. Despite this, the data suggests that even short-term cultivation of legumes as cover crops can help offset these losses by adding organic biomass to the soil.
- A higher plant diversity in the mixtures showed positive effects, however, different sowing depths of various components must be taken into account in order to achieve optimum results. Some species did not emerge because of an inappropriate seed placement.
- A higher diversity of species also means utilizing the rootable space as fully as possible considering the effect of roots as soil organic matter and of root exudates for carbon sequestration.

- The positive effects of this technique in 2024 can be observed in higher mean values of total organic carbon in the soil compared to 2023. It can be concluded that plowing different varieties of peas (winter and spring) had a small but not statistically significant effect on the increase in TOC in the soil. Statistical significance was determined only in the Control treatment in which peas were not sown, but weeds sprouted uncontrollably, which probably affected the organic matter of the soil.
- Non-overwintering cover crop mixtures showed higher above-ground biomasses and carbon contents than single cover crops tested.
- Soils were covered significantly better with a second-phase cultivation (winter-hardy cover crops were spread into a freeze-killed cover crops biomass in October). Consequently, weed pressure was much lower. The inorganic N content tended to be lower, but the values were generally low.
- Persian clover emerged as the most productive legume in terms of above-ground biomass and nitrogen fixation, while red and sweet clover had the highest root biomass, indicating their suitability for improving soil structure and promoting long-term carbon sequestration.
- Alsike clover and sweet clover exhibited the largest increases in Corg, while Hungarian vetch, hairy vetch, and grass pea clover showed higher decreases. However, all changes were below 2 %.
- Winter turnip sown in late August continued to grow until March and developed high biomass correlating with field emergence and seeding rate of the species. Considering the factors biomass, soil cover and practicability, winter turnip in a cover crop mixture appears interesting.

2.3.2 SWOT analysis

SWOT analyses were carried out in focus groups with different stakeholders (such as farmers, advisors, scientists, agroeconomic and educational experts and representatives of legal authorities) in each country which conducted a trial of the carbon farming technique additional cover crops (B.1) with regard to the trials' results and experiences. The outcomes of these SWOT analyses are gathered and summarized in this chapter.

Strengths

- **Soil protection:** Cover crops protect the soil from erosion with their root system and reduce nutrient leaching into water bodies, improving the resilience of crops to pests and diseases due to a healthier soil ecosystem.
- **Simple cultivation**: The cultivation of cover crops is relatively simple, making them an accessible option for farmers.
- **Enhancement of humus content** is a highly effective method for drought control, and cover crops have been shown to contribute to organic matter enrichment through their above-ground parts, as well as their substantial root mass.
- **Improvement of soil structure and water retention** which benefits subsequent crops, especially in situations of water stress that have become more frequent in many regions of Central Europe following drought waves in the summer.
- **Improving biodiversity**: Cover crops help increase both soil and above-ground biodiversity, creating valuable habitats for various organisms, e.g. food for microorganisms, earthworms and pollinators. It is therefore possible to influence the composition of the fauna in a given area by using different cover crop mixes.
- **Reduction in herbicide use**, as cover crops are effective in suppressing weeds, reducing the need for chemical treatments and thus lowering associated costs.
- **Reduction in fertilizer costs:** Cover crops can fix nitrogen or recycle nutrients from the soil.
- **Reduction in fuel costs**: Cover crops help improve soil structure and consequently facilitating machinery operations in the field.
- **Availability**: A wide range of plant species can be cultivated as cover crops, many with different traits to target a site-specific main goal of cover crop cultivation.
- **No or low investment costs:** Technique can be implemented with common on-farm machinery to a sufficient extent. Some advanced management practices might still need special machinery.
- **Community effects:** By reducing the negative effects of heavy rain falls, cover crops help to save communal costs of water erosion and floods.
- **Secondary use of biomass:** In some cases, certain cover crops can be used as food and feed if necessary. Alternatively, biomass can be cut and relocated or processed to compost or silage (see carbon farming technique A.2).
- **Surface enhancement:** Cover crops enhance the surface support of soils for farming machinery, making them an easily accepted measure for farmers.

- **Melioration effect**: Cover crops can serve as break crops, helping to expand crop rotation (see carbon farming technique B.2).
- **Lower evapotranspiration**: Cover crops reduce water loss from the soil surface, helping to conserve moisture and support plant growth in dry conditions.
- **Facilitating soil loosening**: The incorporation of specific cover crop varieties has been also found to facilitate soil loosening, thereby mitigating the impact of compacted layers on crop growth.

Weaknesses

- **Lack of advanced knowledge:** Cover crops have the potential to alleviate site-specific challenges to harvest quantity and quality, but there is a lack of knowledge of advanced management practices to realize the potential of cover crops. Multiple effects and their interactions are often not considered, like cover crops influencing nutrient mobilization and nutrition influence on subsequent crop, especially regarding nitrogen, and influences on organic nutrient stocks in soil.
- **Termination timing:** The timing for terminating cover crops is crucial, and if weather or soil conditions delay certain operations (e.g. sowing or cutting the cover crops), the benefits could be lost, such as a reduction in soil moisture or difficulty in preparing the seedbed for the main crop. Termination of winter-hardy cover crops is more challenging than for freeze-killed cover crops.
- **Seed costs of valuable mixtures** are considered too expensive for the majority of farmers
- **Misinterpretation of workload:** Lack of awareness among farmers about the benefits of using cover crops may lead to a limited adoption rate of this carbon farming practice. In the early stages of learning how to grow cover crops, the cost of seed purchasing, planting, and maintaining them can be higher than the cost of traditional farming practices. In the short term many farmers consider this technique as additional workload as they are not aware of the multiple positive effects, which often lead to net savings in costs and labor.
- **Inaccessibility of regional seeds:** The accessibility of seeds can vary depending on the species. Many regions of Central Europe depend on imported seeds and have a very limited domestic seed production.
- **Rigid CAP rules:** Challenges arise with farms hunting for CAP funding and rules of intervention not in line with the best practices for the cultivation of cover crops.
- **Strong need for time management of crop rotation:** Incorporating cover crops into the rotation requires careful planning and scheduling, which can complicate farm operations, especially if some unforeseen factor makes it necessary to carry out sub-optimal interventions. As the frequency of unpredictable weather patterns increases, this could pose a particular challenge.
- **Rising costs**: In the early stages of learning how to grow cover crops, the cost of seed purchasing, planting, and maintaining them can be higher than the cost of traditional farming practices. Although some argue that cost reductions can be achieved in the longer term, the difficulty of calculating returns and the very different process from „normal” management practice can negatively affect farmers' attitudes.

Opportunities

- **On-field seminars:** Knowledge-transfer: from scientists, advisors and experienced farmers to farmers within seminar and workshops discussing best practices on the field.
- **Established subsidies:** In general, CAP subsidies for cover crops are well established, farmers are quite familiar with them. Still, improved and simplified state support systems are desirable.
- **Farmers as multiplicators:** Successful implementation of cover crops will be multiplied by farmers in the region (on-field talk with colleagues).
- **Fixing nitrogen:** Leguminous cover crops can fix atmospheric nitrogen, enriching the soil and reducing the need for synthetic fertilizers, thereby facilitating rapid and sustained initial growth of the main crop.
- **Water savings:** Preservation of soil moisture decreasing the leakage of water and nutrients into the deeper layers of the soil. This means that farmers can save on the irrigation of fields.
- **Seed production**: Cover crop seed production can be an economic opportunity, best organized in contract agriculture in cooperation with a seed production company. The development of seed production for cover crops is seen an important step in expanding the range of local species available.
- **Adopting sustainable agriculture:** The use of cover crops integrates well in farm contexts that are moving towards the adoption of organic, conservative or regenerative farming systems. Moreover, cover crops are a good practice that may help to deal with climate change, as they improve soil health, increase water retention capacity, and contribute to carbon sequestration.
- **Heat-loving species:** Warming caused by climate change can offer opportunities for later sowing and successful growth of more productive heat-loving species as cover crops.
- **Combination with reduced tillage:** Less intensive soil tillage methods (see carbon farming technique C.1) can be more effective when combined with the proper use of cover crops.
- **Increasing awareness** of ecological interactions, e.g., in relation to drinking water supplies, which could be improved through lower costs for water treatment if cover crops prevent nutrients from leaching into the groundwater. The ecological benefits should be better communicated to the public.
- **Combination with root weed management:** In dry conditions at the time of sowing cover crops, a later sowing date seems reasonable and can be advantageously combined with the control of root weeds.

Threats

- **Availability of seeds:** Limited access to high-quality or regionally adapted seeds can hinder the successful adoption of cover crops.
- **Risks of plant diseases or pests:** If the share of specific crops like legumes or brassicaceae in the crop rotation gets too high, the risk of plant diseases or pests increases. In the absence of knowledge, new diseases and pests can harm primary crops.

- **Termination timing**: If cover crops are not terminated at the right time due to delays caused by weather conditions or machinery availability, it could lead to reduced yield in the subsequent main crop. Effectively managing the timing of operations to minimize delays is crucial for ensuring that the benefits of cover crops are fully realized.
- **Soil moisture management**: For heavier, clayey soils, increased costs are associated with the termination of cover crops. The presence of cover crops in the spring months increases the moisture content in the soil and this can cause a slow-down in the preparation of the seedbed for the next main crop. On the other hand, if the termination of cover crops is delayed too much, the plants can deplete the soil's moisture through transpiration, reducing water availability for subsequent crops.
- **Biomass management: W**hen cover crops produce a large amount of biomass, managing them through mowing or rolling becomes difficult, leading to delays in sowing or transplanting main crops, especially when working with contractors or in unfavorable weather conditions.
- **Risk of poor germination** or crop failure during critical times of the year, such as the summer, which could necessitate reseeding and additional costs.
- **Drought vulnerability**, as cover crops may compete with cash crops for limited water resources during periods of drought, potentially reducing their effectiveness.
- **Habitats for pests:** Cover crops can provide habits for pests leading to potential infestations in subsequent crops.
- **Overregulation in CAP fundings**: Uncertainty of successful implementation due to overregulation with fixed time slots for CAP fundings
- **„Pretending" cover crops:** Some farmers might primarily aim to just fulfil CAP criteria for funding when cultivating low-cost cover crops without actually considering the impact on soil health, protection or carbon sequestration.
- **Creating neophytes**: The threat that some of the non-native species used as cover crops could become weed species is another concern, as they could escape into natural environments, and be difficult to manage.
- **Measurability of ecological values and benefits:** A lack of measurability of ecological values and benefits, such as the impact on biodiversity and the spatial and temporal variability of soil conditions and parameters, also makes it difficult to argue the point to governments and other decision-makers. Without adequate funding, support, or carbon farming business models cover cropping may economically not be attractive for farmers.

2.3.3 Farmer's viewpoint

As farmers were a main group of stakeholders in all SWOT analyses their opinion and point of view was considered strongly and is described there. For further details of regional aspects see appendices B.1.1 – B.1.8).

2.3.4 Environmental impacts, CO2 and biodiversity

The use of cover crops aims to increase organic matter and soil quality and can make the soil more resilient to extreme events due to climate change. Specifically, increasing SOM content positively influences soil quality in terms of physico-chemical properties (such as soil structure, water retention and fertility, reducing soil erosion and nutrient leaching), biochemical properties (for example microbial biomass and some enzymatic activities which play a role as catalysts in important nutrient cycles e.g. C and N) and functional properties (such as microbial, mesofauna and macrofauna biodiversity).

The use of cover crops may reduce SOM degradation as plants cover and protect the soil, therefore, in the long term they can contribute to increasing the stock of stabilised organic carbon in the soil and thus to atmospheric CO2 sequestration.

Another environmental benefit of applying cover crops between one main crop and another (especially on extensive crops such as wheat, soybean and processing tomatoes) is the reduction of herbicide use in the pre-seeding/transplanting phase of the second main crop. This can help reduce the environmental impact associated with herbicide use and promote a more sustainable approach to weed management, preserving the biodiversity of the agro-ecosystem.

However, their application must be carefully evaluated according to the soil and climatic conditions of the farm. Effective management also requires careful monitoring and timely intervention, paying attention to plant vegetative stages and soil conditions (App. B.1.3).

2.3.5 Economic analysis

For an economic analysis, a site-specific overview of all costs and labor is indispensable and can be found in all referring appendices (B.1.1. – B.1.8).

2.3.6 Ranking of Technique

Tab. 6: Joint mean scoring of the present technique on a scale from 1 (very low) to 5(very high), x indicates one partner scoring

Criteria / Score	1	2	3	4	5	Mean score
Estimation of the positive impact on carbon sequestration			xxx	xx	xx	3,9
Feasibility (incl. costs and labor demand)		xx	xxxxx			2,7
Acceptance (of farmers, consumers, public)			x	xxxxxx		3,9
Sum						10,5

Compared to all other tested carbon farming techniques B.1 Additional cover crops is ranked 2 out of 7 according to the sum of mean criteria scores of 10,5.

2.4 DIVERSIFICATION IN CROP ROTATION (B.2)

The carbon farming technique diversification in crop rotation (B.2) was chosen by six partners for testing:

Tab. 7: Overview over all trials of B.2, including scoring on a scale from 1 (very low) to 5 (very high) of the three main criteria *Impact* (Estimation of the positive impact on carbon sequestration), *Feasibility* (incl. costs and labor demand), and *Acceptance* (of farmers, consumers, public)

Appendix Number	Institute (country)	Trial location	Key data	Impact	Feasi-bility	Accep-tance
B.2.2	GAK (Hungary)	MATE University educational and demonstration farm, (in Gödöllő), Szárítópuszta	In 2023 sunflower, in 2024 corn was planted The effects of crop rotation can only be evaluated in a longer term (not yet). Sampling by different treatments **and tillage methods**: Ploughing / Basic tillage with cultivator, **Treatments**: Control, Manure, Compost, Fertilizer (NPK)	3	4	3
B.2.3	RI.NOVA (Italy)	RI.NOVA experimental farm "Martorano 5" in Cesena (FC).	5 non-randomised plots of 500 m^2 each 4 different types of green manure (with a single species or a mixture of essences) and with different quantities of seed used per hectare were compared to a plot where no green manure was sown (bare soil) 1. Barley (cv. Marjorie)+ field bean (cv. Vesuvio) + horseradish (cv. Orca) (150 Kg/ha of seed) 2. Barley (cv. Marjorie)+ field bean (cv. Vesuvio) + horseradish (cv. Orca) (100 Kg/ha of seed) 3. White mustard + brown mustard + horseradish 4. Horseradish 5. No green manure (bare soil)	3	4	4
B.2.5	BFA (Austria)	Field trial at Franz Stadler's organic farm, Stürzenbühel 104, 2162 Falkenstein near Poysdorf	7 variants, 5 of which were 240m^2 trial plots and 2 on the remaining field area Plants tested: ▪ Millet (Panicum miliaceum) Kornberger Mittelfrühe ▪ Millet (Panicum miliaceum) GL Arabella ▪ Foxtail millet (Setaria italica) Pipsi ▪ Maize (Zea mays) DKC 4717 DieSonja	4	4	3

			▪ Cob sorghum (Sorghum bicolor L.) RGT Ggolden ▪ Cob sorghum (Sorghum bicolor L.) Rosario ▪ Silage sorghum (Sorghum bicolor L. x S. sudanese) Susu			
B.2.7	AIO (Croatia)	Agricultural institute Osijek, Južno Predgrađe 17, 31000 Osijek, Croatia	3 treatments and 3 repetitions (plot size 50 x 3 = 150 m^2) 1. Control - corn 2. Intercropping corn and alfalfa 3. Intercropping corn and red clover Sowing date of corn was April 15, 2024, sowing date of alfalfa and red clover was April 12, 2024.	4	3	3
B.2.8	OBG (Germany)	Trial on farm Lothar Erhard, Morlesauer Straße 7, 97797 Wartmannsroth, Germany	9 plots, 150 m^2 each (10x15m), randomised Latin square design, three replications per variant ▪ Crop variants: **white lupins** (Cultivar: Frieda), **buckwheat** (Cultivar: Druschina), **summer-barley** (Cultivar: Elfriede) ▪ Sowing of lupines and s-barley on 8 April, 2024, buckwheat on 14 May, 2024	5	3	3
B.2.9	ART (Czech Republic)	Niva Mělčany, Mělčany 163, 664 64 Dolní Kounice, Czech Republic	▪ 300 m^2 each (10x30m), three replications per variant ▪ control variant without intercropping ▪ intercropping variant -maize with rye ▪ sowing of maize: first decade of May 2023	4	3	3

2.4.1 Joint conclusions

The partners testing B.2 diversification in crop rotation came to the following conclusions. Most frequently denoted conclusions are mentioned first (App. B.2.2 - B.2.9).

- The Diversification in crop rotation technique has positively influenced soil and by enhancing soil organic matter this technique could be viable for carbon farming and carbon sequestration.
- Within one growing season TOC values in soil might change due to external reasons like climate, moisture, temperature or the abundance of relevant micro-organisms, irrespective of the growing crop.
- The results suggest that the duration of testing (over one growing season) is too short. The highly significant influence of different crops in crop rotation on soil C relevant parameters even in only one growing season shows that valuable and positive outcomes concerning carbon stocks can be expected in long-lasting experiments which are therefore highly recommended.
- Findings indicate that incorporating corn, red clover, and alfalfa harvest residues positively impacted soil pH, humus content, and TOC, while maintaining good soil nutrient supply levels.
- The factor ‘crop’ showed an overall significant influence on all C release by root exudates values (per ha and per root biomass), including the composition of organic acid root exudates.
- The factor ‘crop’ showed a significant influence on root biomass at the growth development stage BBCH 10-11. Still, in the time frame given, there was no significant correlation between C output of acids or root biomass and TOC at the end of the experiment or the TOC difference between the beginning and the end of the experiment.
- The lack of a significant increase in TOC in the Corn/alfalfa treatment can be attributed to biomass loss due to competition between intercropped corn and alfalfa. C/N ratio increased significantly in the Control and Corn/red clover treatments.
- Horseradish is predominant in many mixtures. This further consolidates the results of previous projects in which the importance of brassicas in supplying readily available nitrogen was highlighted.
- The number of fungi decreased in the final soil state compared to initial state and the average number of bacteria also slightly decreased. The combined data with the evaluation of soil microbiomes seems very prospective and is recommended for future research.
- Lupines significantly slowed the decrease of TOC in comparison with summer-barley. Thus, the factor ‘crop’ showed a tendency to influence the development of TOC during the experiment, favoring a positive input from legumes.

- Future research should focus on elucidating the effect of additional N (by N fixation of legumes) on soil organic carbon development and storage.
- For some mixtures, a reduction in the amount of seed/ha does not lead to a reduction in biomass. Rather, it leads to a greater development of biomass. This is certainly related to a reduction in competition between the plants.
- Soil analyses show that the presence of winter green manure may replace an application of background fertilization in the spring-summer period.
- Some differences in SOM can be observed after the green manure burial compared to the baseline (pre-trial analyses). However, to attribute them to the different soil management practices and not to variability, a further comparison between the treatments within one or two years is necessary.
- Bulk density analyses show that the green manure plots have better porosity than the non-green manure plots.
- C4 plants have potential to support carbon sequestration with their root exudates that differ from those of C3 plants especially in quantity. Sorghum, Setaria and Panicum millets could act as partial substitutes for maize in a crop rotation pattern as they are very dry tolerant and uncomplicated to cultivate leading to a competitive contribution margin in dry years. The millet crops investigated differ in their main carbon inputs to soil. Silo sorghum showed by far the highest root masses, followed by maize and grain sorghum varieties. Results suggest that foxtail millet and grain sorghum are likely to contribute somewhat more to long-term carbon accumulation (MAOM). Grain yields of grain sorghum, which is the deciding factor for farmers, also showed very positive results.
- Intercropping maize with rye promoted enhanced TOC in the soil. The quality of humus in the soil also improved, as reflected by the increase in the HA/FA ratio from 0.71 to 0.97 over the same period. This ratio is a critical indicator of the stability and sustainability of organic matter in the soil, essential for maintaining carbon storage over time.
- The improvement in both the quantity and quality of organic carbon in the soil highlights the potential of intercropping as an effective strategy for promoting sustainable soil management and carbon sequestration within the framework of carbon farming.

2.4.2 SWOT analysis

SWOT analyses were carried out in focus groups with different stakeholders (such as farmers, advisors, scientists, agroeconomic and educational experts and representatives of legal authorities) in each country which conducted a trial of the carbon farming technique diversification in crop rotation (B.2) with regard to the trials' results and experiences. The outcomes of these SWOT analyses are gathered and summarized in this chapter.

Strengths:

- **Increased biodiversity:** Crop rotation encourages biodiversity by introducing a variety of crops, which supports healthier ecosystems and reduces the prevalence of pests and diseases. Positive phytosanitary effects can be realized by cultivating partly underutilized crops like buckwheat, black oat or oil radish and mustard varieties.
- **Yield stability:** Rotating crops helps maintain consistent yields over time by reducing soil depletion and pest build-up. Thereby economic resilience, risk diversification and independence of farmers can increase.
- **Improved and more efficient plant protection**: Alternating crops disrupts the life cycles of pests and diseases, reducing the need for chemical interventions.
- **Soil fertility:** The practice enhances soil nutrient levels by diversifying crop demands and incorporating nutrient-restoring plants, such as legumes. Utilization of green manure can lower fertilizer costs significantly.
- **Increase of carbon stocks:** By cultivating cover crops and leaving crop residues on the field, soil organic matter is boosted, which contributes to carbon sequestration. Intercropping also showed improved humus quality (HA/FA ratio).
- **Increasing rhizosphere:** A greater utilization of agricultural areas without soil degradation if intercropping of two crops with different root depths is done. This ensures a greater mass of crop residues in the soil, increases the rhizosphere and the number of microorganisms, improves the efficiency of assimilation of nutrients, and prevents soil erosion by wind and water.
- **Soil structure and water retention:** Applying green manure improves soil structure and water retention, which benefits subsequent crops, especially in situations of water stress that have become more frequent in Central Europe following drought waves in summer.
- **Synergy effects with other techniques:** A combination with carbon farming techniques B.1 additional cover crops and C.1 reduced tillage can provide synergy effects, e.g. if a farm has a no-till seed drill, it is possible to do conservation tillage within this technique.

Weaknesses:

- **Know-how intensive:** Effective crop rotation requires a deep understanding of crop characteristics, soil needs, and pest dynamics, which can be challenging for farmers to master.
- **Lack of knowledge:** Many farmers may lack the expertise or training to design and implement optimal crop rotation systems.
- **Accessing marketing chains:** Diversified crops may not align with existing market infrastructure, making it harder for farmers to sell certain crops.
- **Complexity of machinery and related investment:** Different crops or cropping systems may require specialized machinery, increasing costs and operational complexity.
- **Lower short-term financial return:** Transitioning to crop rotation can lead to reduced income, increased working time and production costs in the short term as farmers adjust to new systems and markets.

- **Lower yields:** Crop competition in intercropping systems or inappropriate crop sowing for innovative crops can result in lower yields.
- **Challenging crop protection**: It is more difficult to use plant protection agents, specifically herbicides, in intercropping systems because a herbicide for one crop can harm another crop.
- **Potential variability in results across locations:** Results may differ depending on soil types, climates, and agricultural practices at other sites. The generalizability of findings to other regions or farming systems requires further validation through extended trials conducted in diverse conditions.
- **Dependency on crop selection:** The effectiveness of intercropping systems is reliant on selecting appropriate crop combinations. The success of maize-rye intercropping may not be replicable with all crop species, necessitating further research into crop compatibility and optimal combinations for carbon sequestration.

Opportunities:

- **Better field utilization:** Rotating crops allows farmers to use their fields more efficiently by managing soil health and maximizing productivity.
- **Educational training:** Applied research with technology transfer to farmers. Further research should focus on crop/species mixtures for intercropping, and the use of perennial grasses.
- **Increase of fodder and biomass base:** Introducing crops like legumes and grasses to the rotation provides a reliable and sustainable source of animal fodder or biomass that can be relocated (see carbon farming technique A.2 relocation of harvest residues)
- **Climate change adaption strategy:** A wide crop rotation, intercropping and green manure like cover crops represent good practices that may help to deal with climate change, as they improve soil health, increase water retention capacity, and contribute to carbon sequestration. Crop rotation improves soil structure by diversifying root systems and minimizing soil compaction.
- **Former foreign crops** may also be cultivated in new regions due to climate change.
- **Lower pesticide usage and related costs:** By naturally controlling pests and diseases, crop rotation reduces reliance on chemical pesticides, lowering costs and environmental impact.
- **Income diversification:** Additional earnings from secondary crops in intercropping systems, or from the production of edible crops for farmgate marketing. For wider crop rotations, state financial support can probably be realized.
- **Finding market niches:** As a lot of innovational spirit is necessary to try out new crops, market niches may be found for innovators
- **Seed development:** The development of adapted seeds of underutilized crops and other adjacent techniques, like ecologically justifiable seed treatment, provides a future chance to increase diversification in crop rotation.
- **Scalability for widespread implementation:** Given the demonstrated benefits this technique has the potential for widespread adoption. Its scalability could play a key role in achieving broader objectives for soil carbon management and climate change mitigation.
- **Policy and funding support:** Governments and environmental organizations could offer incentives for farmers to adopt practices of diversifying in crop rotation as part of broader carbon farming initiatives.

Threats:

- **Uncertainty of Production:** Changes in weather, pest outbreaks, or other unforeseen factors can affect the success of certain, especially innovative crops within the rotation.
- **Decrease of Potential Crop Species Due to Climate Change:** Rising temperatures and altered rainfall patterns may limit the range of crops suitable for rotation in specific regions.
- **Lack of immediate financial return:** The benefits of intercropping, such as increased soil carbon and improved soil health, may not yield immediate financial returns for farmers. This delay in experiencing tangible benefits could serve as a barrier to widespread adoption, especially for farmers who may not see short-term financial gains.
- **Predictability of income and marketing costs**: The variability in crop prices and market demand can make long-term financial planning challenging for farmers practicing crop rotation.
- **Uncertainty of selling:** As markets are small or completely missing for innovative crops, buyers have to be found in advance. Most farmers are not trained to find new purchasers on their own.
- **System complexity:** The complexities of changing a running system might discourage farmers from diversifying.
- **Loss of state support**: If support conditions are not met any longer, e.g. if farmers produce seeds of uncommon crops, they might lose out on government subsidies.
- **Climate variability:** Uncertainties due to climate change, including temperature fluctuations, droughts, or excessive rainfall, could influence growth and the rate of carbon sequestration of new crops as well as the overall success of intercropping.
- **Potential increase in farm costs:** While intercropping offers long-term benefits, it may require higher initial investments in terms of time, resources, and labor. This could discourage farmers, particularly those with limited financial resources,
- **Pest and disease management:** Intercropping can sometimes result in pest and disease challenges due to the proximity of different crops. Competition for resources between maize and rye, as well as potential pest-related issues, may affect crop yields and impact the success of the technique.

2.4.3 Farmer's viewpoint

As farmers were a main group of stakeholders in all SWOT analyses their opinion and point of view was considered strongly and is described there. For further details of regional aspects see appendices B.2.2 – B.2.9).

2.4.4 Environmental impacts, CO_2 and biodiversity

Intensive conventional agriculture can alter the chemical, physical, and biological properties of soil, especially when it is systematically depleted without investment in restoration measures. This often leads to harmful consequences like reduced humus content, nutrient depletion, pH changes, soil compaction, and erosion. Both conventional agriculture and high proportions of monoculture have significantly contributed to the decline in humus levels and release of CO2 from the soil to the atmosphere.

Diversification in crop rotation can provide substantial environmental benefits, particularly in terms of CO_2 reduction and biodiversity enhancement. Extended crop rotation can sequester up to 0.64 metric tons/ha/year of carbon dioxide by incorporating diverse crops and organic practices. Different crops contribute to the soil organic carbon pool through roots and organic residue outputs. For instance, legumes in a rotation pattern could help fix atmospheric nitrogen and reduce the need for synthetic fertilizers, ultimately decreasing greenhouse gas emissions. Compared to monocultures, diversified crop rotations result in lower CO_2 emissions from the soil due to improved soil structure and reduced soil erosion. Diversified crop rotations also contribute to better water retention in the soil. By varying crops, it is possible to create a more hospitable environment for different soil microorganisms. This practice boosts soil microbial diversity, which is crucial for maintaining healthy soils and high productivity. Crop rotation breaks pest and disease cycles by disrupting the habitat continuity for various pests. This reduces the need for chemical pesticides and supports the proliferation of a range of beneficial insects and organisms. Additionally, incorporating cover crops and green manures improves habitat for wildlife and beneficial insects, creating a biodiversity-friendly environment.

Overall, diversifying crop rotations can significantly mitigate CO_2 emissions and enhance biodiversity, bolstering the sustainability and resilience of agricultural ecosystems (App. B.2.7).

2.4.5 Economic analysis

For an economic analysis, a site-specific overview of all costs and labor is indispensable and can be found in all referring appendices (B.2.2 – B.2.9).

2.4.6 Ranking of Technique

Tab. 8: Joint mean scoring of the present technique on a scale from 1 (very low) to 5(very high), x indicates one partner scoring

Criteria / **Score**	**1**	**2**	**3**	**4**	**5**	**Mean score**
Estimation of the positive impact on carbon sequestration			xx	xxx	x	3,8
Feasibility (incl. costs and labor demand)			xxx	xxx		3,5
Acceptance (of farmers, consumers, public)			xxxxx	x		3,2
Sum						10,5

Compared to all other tested carbon farming techniques B.2 Diversification in crop rotation is ranked 1 out of 7 according to the sum of mean criteria scores of 10,5.

2.5 AGROFORESTRY (B.4)

The carbon farming technique Agroforestry (B.4) was chosen by two partners for testing:

Tab. 9: Overview over all trials of B.4, including scoring on a scale from 1 (very low) to 5 (very high) of the three main criteria *Impact* (Estimation of the positive impact on carbon sequestration), *Feasibility* (incl. costs and labor demand), and *Acceptance* (of farmers, consumers, public)

Appendix Number	Institute (country)	Trial location	Key data	Impact	Feasi-bility	Accep-tance
B.4.4	IUNG-PIB (Poland)	Silvopastoral trial on IUNG-PIB Osiny Experimental Station farm, 24-103 Osiny, Żyrzyn, Poland	Plot: 1,5 ha field: willow, willow-alder, mulberry, linden and caragana rows, in between 24 m grassland Soil water content and SOC samples taken in intercropping areas (middle) and tree rows, and in comparison in a grass field beside the agroforestry system Tree and grass biomass growth and flora biodiversity of the respective stands with different tree species was measured Agroforestry system is newly established in 2024	5	1	2
B.4.8	OBG (Germany)	Trial on farm Sebastian Frey, Monbrunn 9, 63897 Miltenberg, Germany	Plot: 5 ha field, Robinia and poplar rows, in between 65 m rye with undersown crops Samples taken in Robinia and poplar rows and in rye (middle), and in comparison in a clover-grass field beside the agroforestry system Agroforestry system was established in 2021, at date of first sampling, development was in the second year	2	3	3

2.5.1 Joint conclusions

The partners testing carbon farming technique B.4 Agroforestry came to the following conclusions. Most frequently denoted conclusions are mentioned first (App. B.4.4 - B.4.8).

- Lower values of soil carbon in the agroforestry system than in the control fields were observed in both experiments. Probably climatic conditions and extent of tillage in different systems account for this effect.
- Seasonal, climatic conditions and direct soil cultivation seem to have more influence on TOC values than the basic agricultural system.
- Results only show the development in a small-time frame. Better insights could be gained through long-term experiments over several years.
- Measures, i.e. different tree species (poplar, Robinia), field between rows or clover-grass in non-agroforestry system did not exhibit any differences in TOC values at any time of the experiment, nor in slopes of the trendline.
- Higher biomasses were measured for specific fast-growing species: A higher average tree height for Caragana compared to Linden, Mulberry and Alder, a higher shoot diameter for Mulberry and Alder compared to Caragana and Linden.

2.5.2 SWOT analysis

SWOT analyses were carried out in focus groups with different stakeholders (such as farmers, advisors, scientists, agroeconomic and educational experts and representatives of legal authorities) in each country which conducted a trial of the carbon farming technique agroforestry (B.4) with regard to the trials' results and experiences. The outcomes of each of these SWOT analyses are gathered and summarized in this chapter.

Strengths

- Highly valuable for carbon sequestration due to long-lasting maintenance, deep rooting systems, shedding of foliage and avoidance of wind erosion
- Multiple other benefits like
    - Enhanced biodiversity
    - Improved microclimates
    - Better soil protection against erosion
    - Potential to reduce impacts of drought and extreme rainfall
    - Enrichment of nutrient cycling
    - Limiting spread of soil-borne pathogens
    - Shading and sheltering livestock

Weaknesses

- High initial costs of establishing and maintaining an agroforestry system within its first years
- Need for large land areas
- Ownership structures of land if fields are leased
- High grade wood stems grown using this method will probably still not reach the quality of stems grown in real forests due to a faster development

Opportunities

- Additional income can be gained from fruits, nuts or wood
- Revision of current Eco-Schemes to provide adequate funding and simplified documentation, flexible support tailored to regional conditions, soil types, and farm sizes would significantly boost interest
- Expanding workshops, training programs, and advisory services would help farmers understand agroforestry's benefits and management practices.
- Establishing demonstration farms and sharing best practices could inspire confidence in adopting these systems
- Increased information transfer particularly towards landowners

Threats

- Limited knowledge or expertise of management
- Leasing contracts of fields are often too short to establish agroforestry
- Too small field sizes in some regions
- Lack of financial incentives and restrictive regulations under the current Common Agricultural Policy (CAP)

2.5.3 Farmer's viewpoint

As farmers were a main group of stakeholders in all SWOT analyses their opinion and point of view was considered strongly and is described there. For further details of regional aspects see appendices B.4.4 – B.4.8).

2.5.4 Environmental impacts, CO2 and biodiversity

Polish farmers are looking for innovative low-input ideas, that will make it easier for them to manage on agricultural land, particularly on soils of poor quality (due to the predominance of poor and acidic soils in Poland) and of large land fragmentation. Customers need access to safe and nutritious food, as a result of food alteration scandals and the influx of low quality food from Ukraine as a result of market opening. Additionally, the livestock sector is getting to be orientated towards low carbon footprint products and reducing intensive animal husbandry, being still an important source of protein for the country's society.

The silvopastoral system, combining trees and animal production, improves biomass productivity (Pent, 2020), soil quality and greenhouse gas mitigation (Amorim et al., 2023). Trees (fresh leaves and small branches) are a good source of nutrition and compare favorably with grasses grown in the same environment (particularly alfalfa and ryegrass) (Luske, 2017 a, b, Mahieu, 2021). Through the presence of condensed tannins, good quality protein is available as rumen-bypass protein. Trees can also provide micronutrients and vitamins (Whistance, 2018). Silvopastoral systems are found to improve livestock productivity and welfare (Mitlohner et al., 2001; Prudencio Lemes et al., 2021) and the quality of the meat (omega-3 fatty acids, vitamins) (Cantoni Marcinelli et al., 2019, Dal Bosco et al., 2016). Despite these benefits, there is a large knowledge gap in research on silvopastoral temperate systems, designed for modern agricultural systems.

Beef cattle grazing in the agroforestry system on poor-quality or limited-access land might increase productivity per unit of agricultural land, although proper management of animals is labor intensive. Intensifying biomass production through the introduction of nutritious fodder tree belts on grassland can improve the quantity and quality of consumed feed, decrease costs, enhance animal welfare and provide more valuable meat (App. B.4.4).

2.5.5 Economic analysis

For an economic analysis, a site-specific overview of all costs and labor is indispensable and can be found in all referring appendices (B.4.4 – B.4.8).

2.5.6 Ranking of Technique

Tab. 10: Joint mean scoring of the present technique on a scale from 1 (very low) to 5(very high), x indicates one partner scoring

Criteria / Score	1	2	3	4	5	Mean score
Estimation of the positive impact on carbon sequestration		x			x	3,5
Feasibility (incl. costs and labor demand)	X		x			2,0
Acceptance (of farmers, consumers, public)		x	x			2,5
Sum						8,0

Compared to all other tested carbon farming techniques B.4 Agroforestry is ranked 7 out of 7 according to the sum of mean criteria scores of 8,0.

2.6 REDUCING TILLAGE (C.1)

The carbon farming technique of reducing tillage (C.1) was chosen by seven partners for testing:

Tab. 11: Overview over all trials of C.1, including scoring on a scale from 1 (very low) to 5 (very high) of the three main criteria *Impact* (Estimation of the positive impact on carbon sequestration), *Feasibility* (incl. costs and labor demand), and *Acceptance* (of farmers, consumers, public)

Appendix Number	Institute (country)	Trial location	Key data	Impact	Feasi-bility	Accep-tance
C.1.1	KIS (Slovenia)	Infrastructure Centre Jablje, Agricultural institute of Slovenia, Grajska cesta 1, 1234 Mengeš, Slovenia. Organic experimental field	Two-factorial design (soil tillage and preceding legume species) In total 30 plots, 30 m^2 each Conventional tillage with spring ploughing to 25 cm was compared to strip-till approach to test the cultivation of maize Different soil tillage was done on previously established plots with 13 different legumes species (included both overwintering and non-overwintering species) and 2 commercial mixtures for green manuring in late summer of 2023, after the harvest of winter wheat	3	2	3
C.1.2	GAK (Hungary)	farm 01: MATE University educational and demonstration farm, Szárítópuszta	▪ Basic tillage with cultivator is used in half of the experiment, while ploughing is used in the other part. ▪ Main crop: corn	4	3	3
C.1.3	RI.NOVA (Italy)	RI.NOVA experimental farm “Martorano 5” in Cesena (FC)	2 types of soil tillage at a depth of 25 cm with ploughing (T3) or without ploughing (T2) were compared with an un-tilled plot (T1). The trial was developed in a field that had not been ploughed for at least 2 years before starting the trial. A superficial tillage was then carried out with a rotary harrow just before the transplanting of lettuce (cv. Gentilina) on 21 June.	3	3	2
C.1.4	IUNG-PIB (Poland)	Agricultural Experimental Station of IUNG-PIB	A field experiment, without repetition, is being conducted in fields of all crops simultaneously as part of the crop rotation: winter rapeseed - winter wheat - winter wheat. The	4	2	3

		in Kępa-Puławy (Lubelskie Voivodeship) 51°25'34.5"N 21°59'07.1"E, Poland	experiment compares two tillage systems: the plow tillage system (TT) and the no-tillage system (TB). The experimental area for research is 6 ha, a single field is 1 ha, which results from the adopted 3-field plant rotation and 2 farming systems. All straw is left on the field after grain harvesting; in a plow cultivation it is plowed, in a no-tillage system - mixed with the soil to a depth of 12-15 cm.			
C.1.5	BFA (Austria)	Field trial located in Falkenstein at a site of organic farmer Franz Stadler	3 variants of tillage are compared in 3 repetitions in a randomized block field trial before soybean after a freeze-killed cover crop mixture, 2 of the variants are strip tillage techniques at different times Variant 1 "early striptill" was stripped on 29th of April 2024. Variant 2 "late striptill" was stripped two weeks later. Variant 3 "no striptill" was not stripped. All 3 variants were tilled shallowly (soil depth of 5-7 cm) before implementation. Each plot was sized 12 m x20 m due to usual farm machine width.	4	4	3
C.1.6.	No Gravity (Slovakia)	Trial on the Blue Berry Farm: 919 04 Smolenice/Lošonec, Trnava district (western Slovakia)	test and assess the reduced tillage techniques if cultivating the garden blue berries with the conventional and reduced (no till) soil tillage in the organic cultivation; During the experiment, the conventional tillage was used at the control field (area of 1200 m^2) and was compared with the field (1200 m^2), where no-till technique had been applied.	4	2	3
C.1.9	ART (Czech Republic)	DVP, Bratčice, 664 67 Bratčice, Czech Republic	2 plots: 300 m^2 each (30x10m), three replications per variant, 2 variants: -control variant (conventional tillage) -Reducing tillage variant (no till), along with the cover crop mixture main crop: Sugar Beet (Beta vulgaris subsp. vulgaris var. altissima)	5	5	2

2.6.1 Joint conclusions

The partners testing carbon farming technique C.1 reduced tillage came to the following conclusions. Most frequently denoted conclusions are mentioned first (App. C.1.1 - C.1.9).

- Reduced tillage emerges as an attractive option for sustainable soil management practices, particularly in the context of maintaining soil fertility, reducing erosion, and enhancing carbon sequestration.
- By minimizing soil disturbance and preserving organic matter, reduced tillage may promote improved soil structure, enhance microbial activity, and support more stable nutrient cycling processes.
- Annual changes in SOC are challenging to analyze accurately. Drawing meaningful conclusions from the gathered data is difficult due to various environmental and management factors affecting soil carbon pools. Typically, SOC changes are better estimated from samples collected over a longer period, reducing the reliance on conclusions based on fluctuations in the labile SOC pool.
- Results of soil chemical parameters highlight the potential of reduced tillage systems to foster nutrient dynamics compared to conventional ploughing.
- Further long-term studies will be essential to fully understand the scope of these benefits and to optimize reduced tillage techniques for various agricultural systems.
- The limited duration of some experiments prevented the drawing of definitive conclusions. However, results indicate that switching from no-tillage to tillage and then ploughing leads to a slight reduction in organic carbon content (%) and SOM (%). This is in line with existing literature.
- Conversely, the agronomic performance of the subsequent crop (lettuce), both in term of vegetative development and yield, was lower in the no-tillage plot. Overall, these results suggest that maintaining high production and quality standards, particularly for high-yielding crops such as vegetables grown in clay soils, requires some form of tillage. However, whenever possible, tillage techniques that cause soil breakdown without turning clods, such as subsoiling, should be preferred to ploughing.
- When correctly applying agricultural technology, using simplified tillage can achieve relatively high yields of agricultural plants, including wheat, rapeseed, corn, legumes and others.
- The unfavorable impact of a bad pre-crop may cause greater yield drops in some years than simplified tillage.
- The wider application of the proposed technical and technological solutions in broad agricultural practice will translate into a reduction in the pressure of agricultural plant production on the natural environment and mitigating climate change.

- Within a long-term no-tillage experiment, the humus content increased from 2,37 % to 5,17 % within the observed time period.
- A 2024 organic trial with conventional and strip-till techniques and different cover crop species shows significant differences in grain maize yields, weed suppression, and soil organic carbon (Corg) content.
- Conventional tillage consistently resulted in higher grain yields, with the most significant differences observed for Persian clover and alfalfa.
- Mechanical weed control was unable to destroy over-wintering legumes, which became competitors for resources under strip tillage.
- Strip tillage on plots with cover crops showed advantages in weed suppression, particularly with overwintering legumes, like white clover and vetch, where dense soil cover reduced weed emergence.
- Conventional tillage initially led to a decline in Corg due to accelerated decomposition caused by soil disturbance, followed by significant recovery in autumn 2024, likely due to increased root biomass and crop residue inputs. Strip tillage, on the other hand, showed a slight increase in Corg from autumn 2023 to spring 2024, indicating that reduced soil disturbance helps retain organic carbon, though the overall recovery by autumn 2024 was lower than in conventional tillage. However, these changes are likely to represent changes only in the labile soil organic carbon (SOC) pool, while the effect on more permanent SOC increases is likely smaller than indicated here.
- Legumes like sweet clover and Serradella showed strong recovery in Corg under conventional tillage, while Alsike clover and Hungarian vetch performed well under strip tillage. However, certain species, such as Serradella, consistently underperformed in maize yield across both tillage systems, suggesting their unsuitability for the tested conditions.
- Results clearly demonstrate the positive effects of minimal tillage practices, combined with a diverse mix of cover crops, on soil carbon dynamics. These practices led to measurable improvements in total organic carbon (TOC) content.
- Results suggest that while minimal tillage can support carbon sequestration, its effect is not as pronounced as in the conventional tillage treatment.
- The quality of humus, indicated by the HA/FA ratio, also showed a slight improvement. While these changes are modest, they point to a potential for improved humus formation.

2.6.2 SWOT analysis

SWOT analyses were carried out in focus groups with different stakeholders (such as farmers, advisors, scientists, agroeconomic and educational experts and representatives of legal authorities) in each country which conducted a trial of the carbon farming technique reduced tillage (C.1) with regard to the trials' results and experiences. The outcomes of these SWOT analyses are gathered and summarized in this chapter.

Strengths:

- **Reduced fuel costs**: Fewer passes over the field with machinery significantly lower fuel consumption and operational expenses.
- **Reducing soil compaction**: Minimum tillage or no-tillage techniques facilitate the transit of machinery through the field and consequently reduce soil compaction because the bearing capacity of the soil is better than that of tilled soil.
- **Soil health improvement and preservation:** The practice improves conservation of organic matter, enhancing soil structure, encourages biodiversity, and prevents erosion and associated nutrient losses, including carbon.
- **Moisture conservation:** By minimizing soil disturbance, reduced tillage helps retain soil moisture, which is critical during periods of drought. Improved water infiltration due to reduced tillage enhances water availability.
- **Promoting soil microorganisms:** Reduced soil disturbance and increased organic matter promote the diversity and abundance of soil microorganisms.
- **Shorter cultivation time**: Reduced tillage processes save time compared to conventional plowing methods, enhancing overall efficiency.
- **Climate resilience:** Healthier soils under reduced tillage are better equipped to handle extreme weather events, such as heavy rains or prolonged droughts.
- **Simplifying logistics:** Reduced tillage may simplify logistics for cultivation and sowing on larger plots, streamlining farm management.
- **Synergies with other techniques: The** combination of minimal tillage practices with a diverse range of cover crops has shown promise in enhancing soil carbon sequestration.

Weaknesses:

- **Potential weed and pest pressure:** Reduced soil disturbance may lead to increased weed growth and harboring of pests, necessitating greater reliance on herbicides and pest management, which could have environmental or economic implications.
- **Special equipment needs**: The adoption of reduced tillage often requires the purchase of specialized machinery, such as no-till drills, which are costly.
- **Cost of technical adaptation:** Transitioning to reduced tillage involves expenses related to training, equipment, and changes in farming practices.

- **Learning curve:** Farmers may need time and guidance to master the new techniques and adapt them effectively to their specific conditions.
- **Decrease in yield:** In the initial years of reduced tillage, crop yields may decline as the soil adjusts to the new farming method. During the early stages of adopting reduced tillage, colder soil conditions may increase the need for nitrogen fertilizers and result in slower germination and early growth often causing yield depressions.
- **Different specific needs of subsequent crops:** Reduced tillage techniques are not always in line with specific needs of subsequent crops, especially for those, which need a well-prepared seedbed, like sunflower, rapeseed or sugar beet. If operations are not correctly planned, delays can accumulate, making subsequent activities like sowing and transplanting difficult to manage.
- **Unclear long-term effects:** The long-term effects of minimal tillage and cover crops on soil fertility and carbon dynamics are still unclear, highlighting the need for further research to assess the sustainability of these practices over the long term.
- **Modification of management**: For farmers, adopting minimal tillage and cover crop practices could require modifications to current management strategies, which is complex in terms of multiple effects onto soil and management strategies. This might involve changes in agronomic practices, which could present challenges for broad implementation.
- **Time management of external services:** The use of cover crops combined with minimum tillage or no-till practices requires timely and technical management of agronomic operations. This is often difficult to combine with the involvement of agricultural subcontractors, who may not be able to follow such a precise schedule.
- **Dependency on specific soil types**: Reduced-tillage methods may not be suitable for all soil types or climates. They are easier to implement on lighter, sandy soils, where reduced tillage also achieves more and different beneficial results than on heavy clay soils. Therefore, it is important to adapt no-till practices to specific local conditions.

Opportunities:

- **Farmers are engineers:** Many farmers are very interested in machines: they often provide certain technical on-farm innovations, or are at least open for such.
- **Farmers' favourite topic**: Farmer like to talk about their machines and tillage philosophies, which leads to wide-spread bottom-up dissemination of awareness or at least start a discourse about reduced tillage techniques
- **Combination of practices:** According to seasonal circumstances and micro-location, armers can customize reduced-tillage practices to suit specific seasons and local environmental conditions in combination with other carbon farming techniques, maximizing effectiveness.
- **Increasing economic efficiency:** Reduced tillage can improve the economic efficiency of farming by optimizing resources and reducing input costs. This approach could reduce the need for a diverse range of agricultural machinery, simplifying farm operations.
- **Farmers' cooperations:** Many new tillage machines have high investment costs. Still, they are time efficient. Farmers' cooperations may reduce costs and risks for multiple farmers sharing usage of machines.

- **Increase of soil productivity:** Over the long term, healthier soil ecosystems can lead to increased productivity and better crop yields, which may motivate farmers to adept this technique.
- **Climate-smart branding:** Farmers practicing reduced tillage can market their products as environmentally friendly, tapping into the growing demand for sustainable food.
- **Government financial incentives:** Many governments offer subsidies and financial support for adopting climate-smart and sustainable farming practices.
- **More climate resilience:** Reduced tillage improves the soil's ability to withstand climate stresses, making it especially beneficial in drought-prone areas.
- **Research and innovation**: Effective knowledge transfer plays a crucial role in maximizing the benefits of reduced tillage. Identifying crop varieties better suited to the specific conditions of reduced tillage is an opportunity.

Threats:

- **Lack of awareness and experience**: Among farmers missing awareness or missing best practices about the benefits of using reduced tillage techniques may lead to limited adoption of this carbon farming practice. Local soil cultivation traditions as part of a "farmer's culture" may inhibit beneficial innovation.
- **Local particularities**: The success of reduced tillage and cover crop systems may be influenced by local soil conditions, climate fluctuations, and regional farming practices. This could limit the effectiveness of these methods in certain areas, particularly where soil types or environmental conditions differ considerably.
- **Climate change risks:** Unpredictable weather patterns could reduce the reliability of many reduced-tillage practices. Extreme weather events, such as droughts or heavy rainfall, could negatively affect seed germination and crop growth, especially when seeded over cover crop residues.
- **Farmers' attitude against new methods:** Resistance to change among some farmers may slow the adoption of reduced tillage, especially in communities rooted in traditional practices. Additionally, many farmers have their own, site-adapted tillage philosophy without reduced tillage, which may still be reasonable.
- **Pest resistance**: The reliance on herbicides in reduced tillage systems can contribute to the development of herbicide-resistant weed and pest species.
- **Chemical residues:** Increased herbicide usage may lead to the accumulation of chemical residues in the soil, raising environmental and health concerns.
- **Short-term economic returns**: The adoption of reduced tillage may encounter resistance due to concerns about potential risks, such as lower short-term crop yields, uncertainty around financial returns
- **Insufficient data**: Further research is needed to better understand the broader implications of reduced tillage on other agronomic factors, including pest management, nutrient cycling, and long-term soil health. Without sufficient data on these potential risks, farmers and agricultural advisors may be cautious about fully adopting these practices.

- **Price fluctuations:** Fluctuations in raw material prices and costs associated with managing agronomic operations, such as purchasing specialized equipment or investing in resources for implementing direct seeding techniques, could increase.

2.6.3 Farmer's viewpoint

As farmers were a main group of stakeholders in all SWOT analyses their opinion and point of view was considered strongly and is described there. For further details of regional aspects see appendices C.1.1 – C.1.9).

2.6.4 Environmental impacts, CO_2 and biodiversity

Global climate change increases the extremes, with prolonged dry spells and sudden localised high rainfall events. The characteristics of each season cannot be counted on, for example, winter precipitation does not recharge our soils, frost does not complete the dusting and drought periods no longer occur only in summer. It is therefore important to ensure that as much of the rainfall as possible reaches the soil's entire structure and that the stored moisture is retained in the root zone of each crop, thus ensuring soil stability and increasing humus content through reduced oxidation processes. In parallel with this process, soil microbial life is revitalised year after year, significantly increasing the adaptability (drought tolerance) of the crop sown in the soil.

In addition to creating and maintaining a favourable physical and biological condition, reduced tillage farming practices has a positive impact on the development of economic indicators (number of passes, time and fuel requirements). The econometric assessment can show the positive impact of these farming systems in terms of yields, which in turn determines the profitability of the farming system used. On the other hand, the specific tractive effort, fuel consumption and time requirements can be taken into account, so that environmental and economic aspects can be considered in parallel with soil protection. In conclusion, frequent soil disturbance, high time, energy and fuel-intensive cultivation systems can lead to additional expenditure, soil degradation and environmental damage in the long term.

Reduced tillage helps mitigate climate change by lowering CO_2 emissions, leaving crop residues on the soil surface, preventing the breakdown of organic matter to release carbon into the atmosphere and sequestering carbon in the soil, increasing soil organic carbon (SOC); better preserving soil structure with less soil disturbance, keep more carbon in the soil, and the reduced quantity of file needed for less tillage operation may also contribute to the positive effect.

Regarding its impact on biodiversity, because of the improved soil structure and soil health, the environment will be better for soil organisms, such as earthworms, microbes, fungi, and insects. Leaving crop residues on the soil surface provides food and shelter for a variety of wildlife, including insects, small mammals, and birds. The presence of stubble and plant residues also supports pollinators and beneficial insects, which can support natural pest control and less use of pesticides. The biodiverse soil ecosystem is better equipped to resist diseases, pests, and environmental stresses like drought or flooding (App. C.1.2)

2.6.5 Economic analysis

For an economic analysis, a site-specific overview of all costs and labor is indispensable and can be found in all referring appendices (C.1.1 – C.1.9).

2.6.6 Ranking of Technique

Tab. 12: Joint mean scoring of the present technique on a scale from 1 (very low) to 5(very high), x indicates one partner scoring

Criteria / Score	1	2	3	4	5	Mean score
Estimation of the positive impact on carbon sequestration			xx	xxxx	x	3,9
Feasibility (incl. costs and labor demand)		xxx	xx	x	x	3,0
Acceptance (of farmers, consumers, public)		xx	xxxxx			2,7
Sum						9,6

Compared to all other tested carbon farming techniques C.1 reduced tillage is ranked 5 out of 7 according to the sum of mean criteria scores of 9,6.

2.7 LIMING EFFECT (C.4)

The carbon farming technique of applying external organic fertilizers (A.1) was chosen by three partners for testing:

Tab. 13: Overview over all trials of C.4, including scoring on a scale from 1 (very low) to 5 (very high) of the three main criteria *Impact* (Estimation of the positive impact on carbon sequestration), *Feasibility* (incl. costs and labor demand), and *Acceptance* (of farmers, consumers, public)

Appendix Number	Institute (country)	Trial location	Key data	Impact	Feasi-bility	Accep-tance
C.1.6	No Gravity (Slovakia)	Trial on cadastral district 856771: Trnava region, 919 04 Smolenice, Slovak Republic	Treatment: $CaCO_3$ + S; $CaSO_4$- + $CaCO_3$, before that alfalfa, after that sowing of winter wheat, Plots: 3x 200 m^2,	3	3	3
C.1.7	AIO (Croatia)	Trial at the Agricultural institute Osijek, Južno Predgrađe 17, 31000 Osijek, Croatia	Plots: 4 treatments and 3 repetitions (plot size 10 x 10 = 100 m^2, total experiment size 400 m^2. Treatments: 1. Control – no liming 2. Filter dust – 50 kg/ha (byproduct from cement factory) 3. Filter dust – 70 kg/ha, 4. Filter dust – 80 kg/ha Pre-crop was corn, sowing of winter wheat occured in October, 2023.	3	2	3
C.1.8	OBG (Germany)	Trial on farm Johannes Wagner, Müßighof 3, 91720 Absberg, Germany	Plots: 3 variants, three replicates each, randomised design, plots size: 4.5 x 12m, 54 m^2 each; Variants: - Control: Only S, 20 kg S/ha - $CaCO_3$-Variant: 2.5 t $CaCO_3$/ha + 20 kg S/ha - $CaSO_4$- Variant: 1.4 t $CaSO_4$/ha + 1.5 t $CaCO_3$/ha Treatment: 14.10.2023, before that alfalfa, after that sowing of winter wheat.	3	4	4

2.7.1 Joint conclusions

The partners testing carbon farming technique C.4 liming effect came to the following conclusions. Most frequently denoted conclusions are mentioned first (App. C.4.6 - C.4.8).

- Long-lasting experiments should enhance the outcome. Therefore, further investigation of this technique within the running Carbon Farming project or within a new project with similar focus is highly recommended.
- Fertilization with gypsum did not show any negative effects. If any, the effects of gypsum fertilization were positive on the measured traits, even after only one year of treatment.
  - In TOC difference values of 2023 and 2024, both calcium-carbonate and gypsum, showed far higher increases (0.197 and 0.213 %) than control (0.057 %).
  - In CEC difference values, also gypsum exhibited the highest value (1.423 cmol/kg soil) vs. calcium-carbonate (0.350) and control (0.826)
  - Above shown BCSR difference even showed a statistical tendency to increase with gypsum within one year, far more than the other variants.
  - The yield of winter wheat showed over all variants a mean of 24,67 dt/ha, without any difference by variant, but the included moisture was with statistical tendency lower in the gypsum variant.
- Given the hypothesis that the highly available and water-soluble Ca^{2+} from gypsum will, rather than calcium carbonate and surely better than the control variant without additional Ca, bind negatively charged humic substances, the results adumbrate that this treatment could be a way of increasing carbon sequestration in soil.
- The BCSR, which increased by tendency, shows that more Ca is bound to soil exchange sites and thereby, even though gypsum is not increasing pH, will avoid H^+ ions on exchange sites on the one hand and on the other hand, will increase bound C of humic substances.
- Particularly in the present sandy soil, where there is not too little clay, the increase of BCSR shows a higher binding of C of humic particles and thereby a higher carbon sequestration potential.
- Supporting this hypothesis might be an increase of the mean specified Caeff CEC in gypsum plots by 1.92 cmol/kg (from 5.90 in 2023 to 7.81 in 2024), whereas the total mean increase overall variants was only 0.94 cmol/kg. This shows that the gypsum fertilization derived increase of BCSR really depended on the increased Ca-share.
- Missing statistical significances within Germany's trial may be due to a small number of samples. Still, high differences of mean values of treatment groups and p-values < 0,1 (e.g. for base cation-saturation ratio) show a strong tendency of influence of gypsum treatments on carbon stocks.
- The greatest significance in the Croatian experiment was found between the amounts of applied filter dust, and in order to observe the effect on the carbon content in the soil

before and after the application of filter dust, the experiment should be monitored for several years. The positive effect of liming can be observed in the increase in soil pH in the FD 50 kg treatment.

- In the treatments FD 70 kg and FD 80 kg, where the soil pH was high, there was a slightly higher value of humus content in the soil, which is not statistically significant. Due to the high pH reaction of the soil, significant decomposition of organic matter could not occur. Similar to humus, mean TOC values were higher in the FD 70 kg and FD 80 kg treatments.
- The number of bacteria was lower in all treatments compared to 2023, which is possible because at that time of soil sampling, more cellulose, lignocellulose and chitin remained, which are degraded by fungi. In the FD 70 kg treatment, a higher number of fungi was found in the soil (21,718.00 cfu/1 g of dry soil) compared to 2023, while a lower number of fungi was recorded in the FD 80 kg treatment. This is probably related to the slightly lower pH reaction of the soil in the FD 70 kg treatment than in the FD 80 kg treatment.
- This technique is particularly beneficial in areas with highly acidic soil, and it is advisable to combine it with organic fertilization. In soils with an appropriate pH level, the decomposition of humus occurs, making it essential to replace any lost organic matter. After liming, it is important to maintain soil health through optimal organic fertilization to prevent future acidification.
- By liming the overall impact of pH shifts on carbon sequestration may likely be positive, as they may lead to a slower decomposition rate, enhanced humus stability, and thus greater long-term carbon storage in the soil. However, this would depend on other factors such as microbial activity, soil texture, and overall soil management practices.

2.7.2 SWOT analysis

SWOT analyses were carried out in focus groups with different stakeholders (such as farmers, advisors, scientists, agroeconomic and educational experts and representatives of legal authorities) in each country which conducted a trial of the carbon farming technique liming effect (C.4) with regard to the trials' results and experiences. The outcomes of these SWOT analyses are gathered and summarized in this chapter.

Strenghts

- **Increased soil structure:** Easily available Ca2+ is always good for the formation of an optimal soil structure and helps to build up permanent humus. Calcium from both $CaCO_3$ and gypsum aids in soil structure by flocculating clay particles, increasing pore space, water infiltration, and reducing compaction. The improvement in soil structure, including increased aggregation from both lime and gypsum, helps reduce erosion, preserving organic matter and preventing the loss of sequestered carbon.

- **Soil pH regulation:** $CaCO_3$ (Lime) raises soil pH, neutralizing acidic soils, which improves plant growth and enhances microbial activity in acidic soils that contributes to carbon sequestration.
- **Independence of soil pH:** Gypsum provides calcium and sulfur, improving soil structure and promoting plant growth without making the soil overly alkaline, which makes it a reasonable technique also for neutral an alkaline soil.
- **Higher yields in acidic soils:** Due to an increased soil pH, higher yields are common in acidic soils making this technique very attractive to be implemented under these conditions.
- **Increased microbiological activity**: The number of microorganisms increased by applying the liming agent carbocalc which is a by-product of sugar production. Carbocalc is very cheap when compared to some granular liming agents, which increases its scalability.
- **Flexible Effects:** $CaCO_3$ and gypsum address different aspects of soil health, with lime neutralizing acidity and gypsum improving soil texture and nutrient availability, creating an overall flexible approach for Carbon Farming by choosing site-specific reasonable lime agents.

Weaknesses

- **pH limited effectiveness**: $CaCO_3$ is most effective on acidic soils, so it's less useful for alkaline soils, and over-application can lead to soil alkalinity, which could harm plant growth and reduce carbon sequestration. Gypsum may have less benefit on soils that already have adequate calcium levels.
- **Way of application of different lime agents**: As far less $CaSO4$ than $CaCO3$ is needed per ha (recommendation of 50-60kg S/ha), the better way of application can be reached with granulated gypsum in a centrifugal spreader. With an average of 60 kg S/ha and a 20% content of S in granulated gypsum, you would apply about 300 kg per ha. In the powdery original form of gypsum the application will not work evenly, as a minimum of 1000 kg is necessary to receive a good scattering. This can be far better reached with lime ($CaCO3$) fertilization with a broad acre spreader, as you need a far higher amount of it. Liming agent carbocalc is fine dust, so in the case of humid air during application, the product may clump, which makes it extremely difficult to distribute the product evenly on the soil surface. In addition, farmers do not have adequate machinery for applying the liming agent. In the case of the application of some granulated agent for liming effect, the application itself becomes easier, but this raises the cost of liming.
- **Carbon effect needs time**: The full effects of lime and gypsum on carbon sequestration may take years to manifest, making short-term carbon farming goals harder to achieve.
- **High initial costs:** both lime and gypsum can be costly to apply, especially on large-scale farms, with transportation and application costs adding to the financial burden.
- **Periodicity**: Liming and gypsum applications may need to be repeated periodically, adding to the long-term cost and maintenance.
- **Nutrient Balance**: Gypsum, while safer, can lead to excessive calcium in the soil if used incorrectly, potentially imbalancing other essential nutrients like magnesium. Excessive application of lime could result in soil becoming too alkaline, which can harm plant roots, reduce nutrient uptake, and limit plant growth.

Opportunities

- **Increased research and innovation:** there is growing research on optimizing lime and gypsum use for carbon farming, leading to potentially more efficient, cost-effective practices and formulations. Innovations in application techniques (e.g., precision farming) could lower costs and improve results.
- **Increased information transfer** about liming and/or gypsum application, particularly to the farmers with appropriate training materials.
- **Co-benefits for soil health:** in addition to carbon sequestration, lime and gypsum can enhance other soil qualities, such as reducing soil salinity (with gypsum) and promoting better nutrient cycling, leading to overall soil health improvement.
- **Minimizing sulphur leaching:** Rising awareness of a minimum risk of leaching S into the groundwater, if applied in a recommended range, should be highlighted.
- **Service opportunity:** Farmers see an opportunity in providing liming services for local farmers who do not possess appropriate machinery.

Threats

- **Environmental impact of lime production:** the mining and transportation of lime can have significant environmental impacts, such as energy consumption, carbon emissions, and habitat disruption, reducing the sustainability of its use.
- **Regular soil assessment**: Farmers are used to only fertilizing with lime (or gypsum) if the soil turns to acidic conditions. Recognizable values, being an incentive to start gypsum fertilizing, are missing. Without developing such and without creating awareness of possible benefits for the farmers there will be no increase of gypsum application.
- **High upfront costs of lime and gypsum applications**, along with the time needed for measurable improvements in carbon sequestration, may deter farmers, especially if the return on investment is uncertain or takes too long to materialize.
- **Varying effectiveness based on climate:** the effectiveness of lime and gypsum in promoting carbon sequestration can be influenced by local climate conditions. For instance, heavy rainfall or drought could negate some of the benefits of improved soil structure and pH regulation.
- **Lack of scientific data:** Creating reliable data of effects to support knowledge about agricultural and environmental benefits.
- **Complexity of verification**: As carbon farming programs develop, there may be regulatory challenges around verification, reporting, and validation of carbon sequestration through lime and gypsum applications, potentially creating bureaucratic hurdles for farmers.

2.7.3 Farmer's viewpoint

As farmers were a main group of stakeholders in all SWOT analyses their opinion and point of view was considered strongly and described there. For further details of regional aspects see appendices C.4.6 – C.4.8).

2.7.4 Environmental impacts, CO2 and biodiversity

Since agricultural management lowers soil pH, liming can compensate for this negative effect and thus ensure sustainable soil fertility. By helping to aggregate soil particles, liming prevents erosion and maintains moisture in the soil. Overall, liming can ensure stable soil structure and functionality. A stable soil structure can prevent the accumulation of CO2 (produced by soil respiration) in soil air, which would damage microbial activity and plant roots and, again through the formation of carbonic acid, increase soil acidity. In addition, phosphate, an important nutrient for plants, is usually bound to iron and aluminium in acidic soils. Liming converts these phosphates into calcium phosphates, which can be taken up by plant roots after contact with protonic root exudates.

Liming is an established agronomic practice; the amount of liming to be done will depend on the soil acidity of the site. Liming in acidic soils will always increase pH and will help to increase above- and below-ground plant growth. The soil organic carbon input can certainly be increased by this measure. However, liming also can promote stable carbon stocks and form permanent humus through the binding ability of the double positively charged calcium (Ca2+) to the negatively charged humic acids. It is known that the amount of mobile humic acids in soil will decrease, and the amount of stabilized humic acids will increase, with an increased intensity of liming. Though the total amount of soil organic carbon might not change at once, the share of carbon in permanent humus will increase and thus form a stable resource of soil fertility and at the same time relieve atmospheric carbon dioxide content, which will contribute to efforts for climate neutrality.

Application of gypsum (calcium sulphate) will work in a similar way as calcium-carbonate lime but will not increase pH of soil. Nevertheless, the valuable Ca will also be dissolved in neutral soil conditions, independent of acidic conditions. Ca then will help to bind humic carbon, and the intrinsic sulphur will be a nutrient for plants, particularly for legumes. Moreover, the readily available Ca can exchange Mg-ions bound to soil particles, which will improve soil structure in heavy soils (App. C.4.8)

2.7.5 Economic analysis

For an economic analysis, a site-specific overview of all costs and labor is indispensable and can be found in all referring appendices (C.4.6 – C.4.8).

2.7.6 Ranking of Technique

Tab. 14: Joint mean scoring of the present technique on a scale from 1 (very low) to 5(very high), x indicates one partner scoring

Criteria / Score	1	2	3	4	5	Mean score
Estimation of the positive impact on carbon sequestration			xxx			3,0
Feasibility (incl. costs and labor demand)		x	x	x		3,0
Acceptance (of farmers, consumers, public)			xx	x		3,3
Sum						9,3

Compared to all other tested carbon farming techniques C.4 liming effect is ranked 6 out of 7 according to the sum of mean criteria scores of 9,3.

TOTAL RANKING OF TECHNIQUES

By gathering the scores of each tested carbon farming technique presented in this report, a total ranking based on the cumulative mean scores of the three evaluation criteria can be established. It is important to note that the scores are mean scores voted by each partner based on their single national field trial. Although investigating the same technique, these trials were conducted on different sites with different focuses and different hypotheses. Their comparability with each other is limited. Still, a total ranking may show a quick overview about possible strengths and weaknesses of each technique, which were summarized for each technique separately in the very chapter in this report and can be found in detail for each national field trial in appendices (App. A.1.1 – C.4.8).

The results of this total ranking will be incorporated in the CE Guide for Carbon Farming techniques.

Diversification in crop rotation (B.2) has the highest total score with 10,5 followed closely by Additional cover crops (B.1) with a total score of 10,4 (Fig. 1). Relocation of harvest residues (A.2) is ranked third with a total score of 10,0. External organic fertilizers is ranked fourth with a total score of 9,8, followed by Reduced tillage with a total score of 9,6. Liming effect ranked sixth with a total score of 9,3, while Agroforestry has the lowest total score of 8,0.

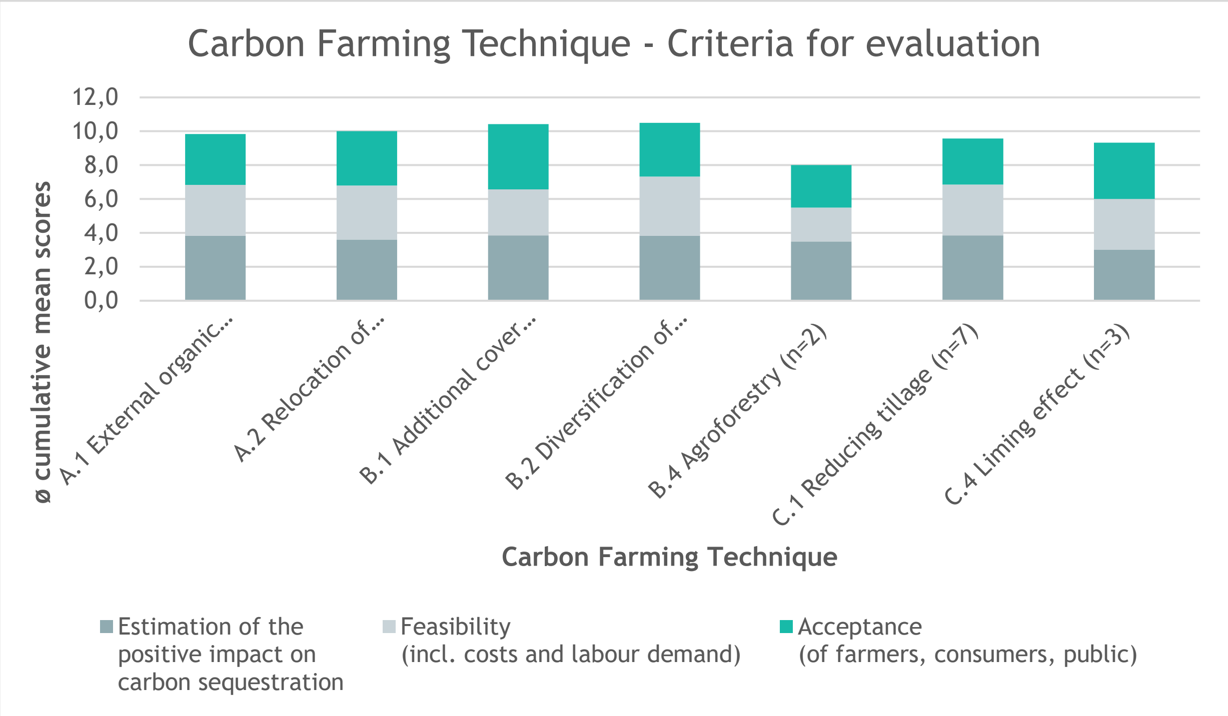

Figure 1: Criteria for evaluation of Carbon Farming Technique – ø cumulative mean score

Fig. 2 shows single bars for each evaluation criteria. The included bars of standard deviation underline, that the tested techniques are limited comparable. The results show that strengths and weaknesses differ by each technique and further weighting of them could be interesting for further guidance.

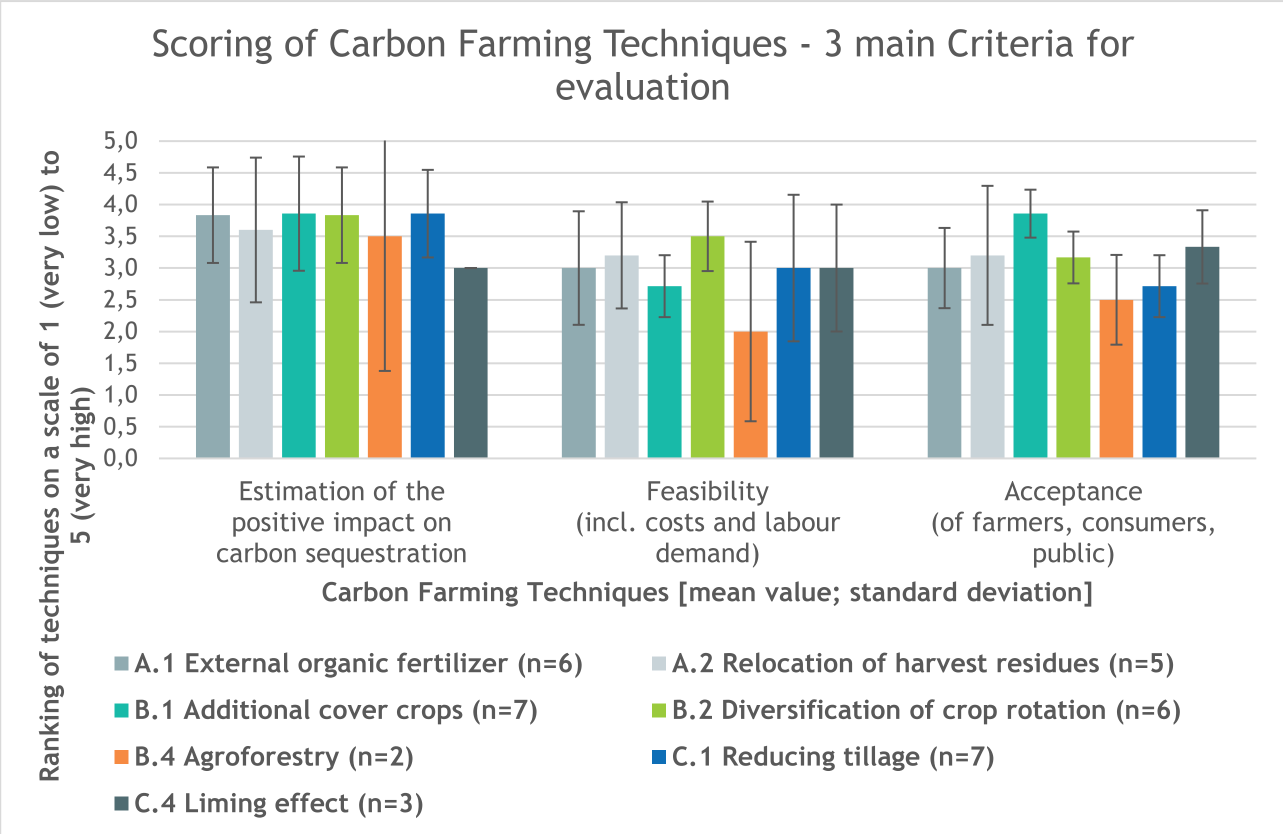

Figure 2: Scoring of Carbon Farming Techniques of the 3 main criteria for evaluation on a scale of 1 (very low) to 5 (very high)