CARBON FARMING SCHEME

LIFE Preparatory Project

Action A1 Science-based mechanisms for farmers and foresters to capture carbon from the atmosphere

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

LIFE CarbonFarmingScheme

Expanding carbon sequestration activities by providing best practices and guidance for future farming schemes

The goal of the project is to identify and accelerate the development and adoption of novel incentives for carbon sequestration and the increase and maintenance of the organic carbon stock in soil and biomass in Europe. With the aim of promoting a well-functioning voluntary carbon market the project will uncover the key factors in supply and demand measures to invite the private sector to accelerate climate action. The results of the project will be fed into the development of the EU agricultural and climate policies.

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Science-based mechanisms for farmers and foresters to capture carbon from the atmosphere

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Definitions

Carbon farming and carbon forestry

Nature-based practices performed in agriculture or forestry in order to sequester greenhouse gases from the atmosphere.

Compliance carbon market

System where a company can use carbon credits as mechanism that contributes to reaching legally binding climate targets

CRC

Carbon removal credit. A credit covering one ton of CO_2e removed from the atmosphere and stored.

Voluntary carbon market

Market where parties such as companies and private persons can voluntarily offset their emissions by buying carbon credits. In a voluntary market carbon credits cannot be used to fulfil legally binding climate targets.

1. Introduction

The LIFE Carbon Farming Scheme project aims to test and develop an incentive scheme for farmers and forest owners to sequester carbon (C) in fields and forests. The project seeks to identify factors that could increase private sector involvement and interest in carbon capture.

Carbon farming measures enhance the carbon sequestration in the soil, support vegetation and strengthen C stock in agriculture and forestry. Research on carbon cultivation methods is constantly developing and the need to share intelligence between actors is important to enable its leveraging, as well as to come forth with cost-effective and efficient emissions removal solutions. Implementing climate-friendly actions in a land sector and developing incentive schemes thereof is vital to achieve local and international emissions targets.

This report addresses practical research examining the case farms in the EU, comparing the current cultivation methods with carbon-smart techniques. The data has been scientifically studied and concluded in the form of practical outcomes. The project assesses how changes in farming practices can affect soil C stocks on the EU farms and forests. Calculations that have been done for the case farms focused on the estimation of the amount of carbon inputs (C inputs) used and a change in the carbon sequestration levels.

2. Methodology for estimating the additionality of soil organic carbon stock through carbon farming practices implementation

Carbon farming is a way of farming to sequestrate carbon in the agricultural soil. Carbon that otherwise ends up as carbon dioxide (CO2) in our atmosphere, causing climate change. There are multiple ways to conduct carbon farming, from minor adjustments on the farm level by applying fertilizers rich in carbon or planting cover crops, to changes in the entire farming system like crop rotation.

In this study, we estimated the potential of different carbon farming practices to sequester carbon in the soil at the farm level. The calculations have been done on crop and livestock farms in different parts of Europe. In this approach, we assess the impact of carbon farming practices on Soil Organic Carbon (SOC) stock, compared to the conventional farming practices.

We applied the Yasso07 soil model in this study, which describes the decomposition of organic matter for mineral agricultural soils based on information on climate and C input quality (Tuomi et al 2008, Tuomi et al. 2011). The Yasso07 model is widely applied to assess carbon balances of both forest and agricultural soils. It is used in the greenhouse gas inventory of Finland to assess changes in soil C stocks (UNFCCC 2020).

Figure 1 presents the whole study process from data acquisition to the carbon additionality estimation results. The study included practical data collection via case farm interviews that was evaluated with scientific measures.

The estimation of the additionality of SOC stock through carbon farming includes:

1. Assessment of above and below ground C inputs from crop and manure when using a) current management practices and b) carbon farming practices.
2. Assessment of the additionality in SOC stock when carbon farming practices are implemented.

The calculations leveraged data collected from the case farms, complemented by literature and climate measurements.

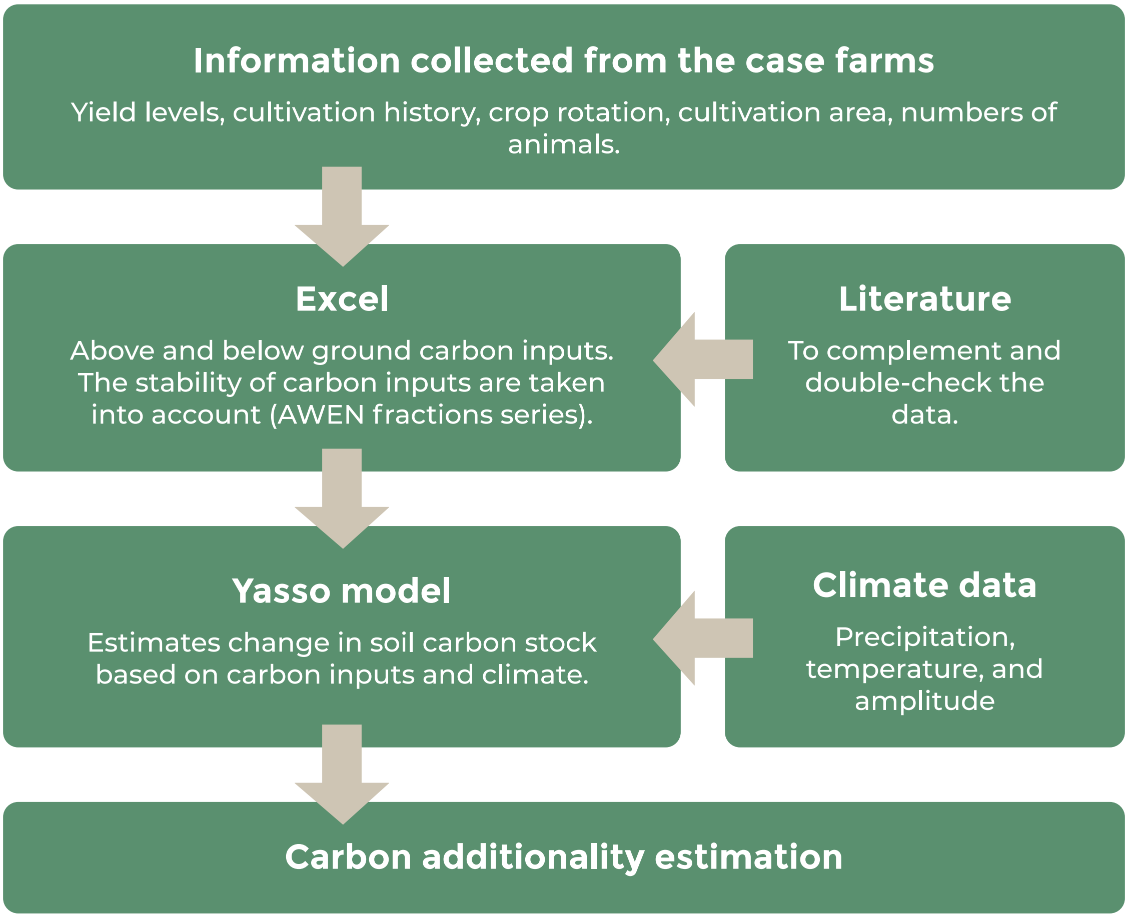

Figure 1. Description of the carbon calculation process from data acquisition to the carbon additionality estimation results.

2.1. Assessment of above and below ground carbon inputs

At agricultural farms, C inputs involve all organic matter allocated to the soil, including aboveground and belowground crop residues, manure, and organic soil amendments. In this study, the determination of C inputs followed an approach by Bolinder et al. (2007). To estimate the C inputs from crops, we collected information from farms regarding crop rotation, crop yields, and cultivation area. For detailed estimations concerning above- and below-ground C inputs and for double-checking our calculations we complemented them with data from the literature (Table 1).

Table 1. Values used for calculating C inputs from plants to the soil.

Crops	DM	Ref.	HI	Ref.	S:R	Ref.
Barley	0.86	MTT 2013	0.53	Peltonen-Sainio et al. 2008, Rajala et al. 2003, Rajala et al. 2007	5.6	Hansson et al. 1987, Ilola et al. 1988, Paustian et al. 1990, Johansson, G. 1992, Kätter-er et al. 1993, Maljanen et al. 2001, Rajala and Pelto-nen-Sainio 2001, Pietola and Alakukku 2005
Hay	0.86	MTT 2013	0.84	Expert assumption	0.27	Poeplau 2016
Oats	0.86	MTT 2013	0.46	Peltonen-Sainio et al. 2008, Rajala et al. 2003	5.6	Hansson et al. 1987, Ilola et al. 1988, Paustian et al. 1990, Johansson, G. 1992, Kätter-er et al. 1993, Maljanen et al. 2001, Rajala and Pelto-nen-Sainio 2001, Pietola and Alakukku 2005
Pea	0.87	IPCC 2000	0.50	Pahkala 2009	5.0	IPCC 2000
Rapeseed	0.92	MTT 2013	0.35	Pahkala 2009	5.1	Ilola et al. 1988, Pietola and Alakukku 2005, Zagal 1994
Rye	0.86	MTT 2013	0.40	Peltonen-Sainio et al. 2008, Hakala et al. 2003, Pahkala et al. 2004	5.6	Hansson et al. 1987, Ilola et al. 1988, Paustian et al. 1990, Johansson, G. 1992, Kätter-er et al. 1993, Maljanen et al. 2001, Rajala and Pelto-nen-Sainio 2001, Pietola and Alakukku 2005
Silage	0.34	Peltonen-Sainio et al. 2008, Rajala 2003	0.84	Expert assumption	0.27	Poeplau 2016
Sugar beet	0.21	Pahkala 2009	0.66	Pahkala 2009	5.0	IPCC 2000
Wheat	0.86	MTT 2013	0.42	Peltonen-Sainio et al. 2008, Rajala et al. 2003	5.6	Hansson et al. 1987, Ilola et al. 1988, Paustian et al. 1990, Johansson, G. 1992, Kätter-er et al. 1993, Maljanen et al. 2001, Rajala and Pelto-nen-Sainio 2001, Pietola and Alakukku 2005.

The C input from the crop residues is calculated and divided into C inputs from above-ground biomass, including C inputs from straw, leaves, and stubble, and below-ground biomass, including C inputs from roots, and rhizodeposition. The C input from above-ground biomass (CI_{ab}) was calculated as:

$$CI_{ab,i} = C_{yield,i} \, x \, \frac{1 - HI_i}{HI_i}$$

where $C_{yield,i}$ is the carbon content of harvest product of crop *I*, and HI is the harvest index, which is the ratio of harvest product to total above-ground biomass. The carbon content of the harvested product was calculated by multiplying the annual yield (kg ha^{-1}) estimated by the farmer through a dry matter (DM*i*), and carbon contents (CCi) of the product that was assumed 0.45 according to Jensen et al. 2005.

C input from the root biomass (CI_{rb}) of crops was assumed to be proportional to the above-ground biomass. For annual crops CI_{rb} was assumed to be equal to their annual root biomass C and was calculated as:

$$CI_{rb,i} = C_{yield} \, x \, \frac{1}{HI_i \, x SR_i}$$

where SR_i is the ratio of the shoot and root biomass of crop *i*.

For perennial crops, the root biomass was estimated as for annual crops (above) and the annual CI_{rb} was estimated as:

$$CI_{rb} = \frac{RootDM}{L} \, x \, CC$$

where L is the average length of continuous cultivation of the crop before renewal.

Rhizodeposition (CI_{rhizo}) was estimated as:

$$CI_{rhizo,i} = TR_i \, x \, C_{rb,i}$$

where TR is the turnover rate (1/year) and CI_{rb} is root biomass. For annual crops, we used 0.41 (Kuzyakov and Domanski 2000, Whipps 2000, Gill 2000, Kuzyakov and Schneckenberger 2004, Gill et al. 2002, Nguyen 2003) and for perennial grasses, we used 0.65 (Bolinder et al 2012) for TR.

Figure 2 shows mean C inputs from plants to soil. Crop residues are assumed to be left in the soil, which is a standard practice in Finland. To estimate C input from manure, we used data from farms regarding field area per animal and a number of animals.

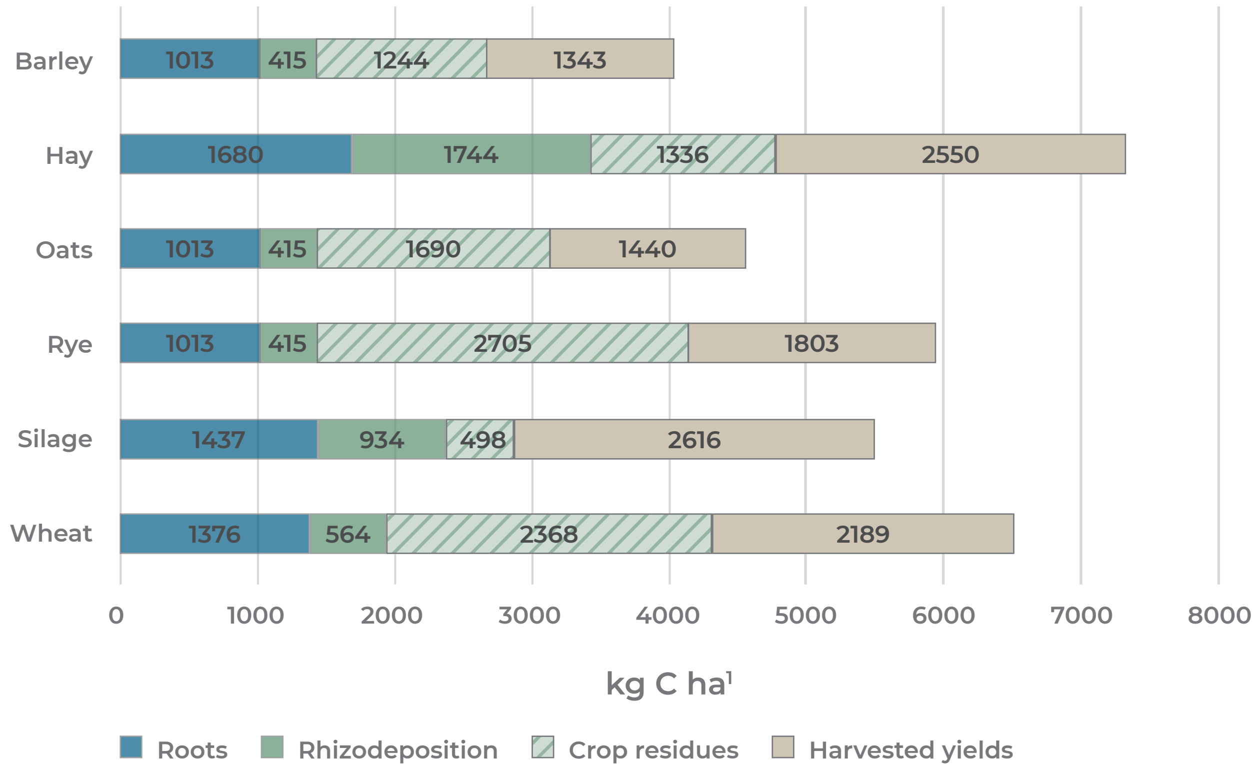

Figure 2. Average C inputs from cereal crops and grasses currently produced at case farms (kg C ha1). The basis for calculations of C inputs are yields estimated by farmers and literature values.

Manure-derived C input (CI_{manure}) was calculated as:

$$CI_{manure} = \sum_i Ni \times VS_i \times CC_{manure}$$

where N_i is the number of head of livestock species *i* and VS*i* is the average annual excretion of volatile solids in manure per head of species *i*. The carbon content of manure (CC_{manure}) was assumed to be 50% of VS (Pettygrove et al. 2009). For cattle, the amount of VS was calculated using the IPCC equation (Equation 4.16 in IPCC 2000), and for other animals (swine and sheep) IPCC default values were used.

Based on the information concerning production areas and C inputs from cropping and livestock, both at present and in different carbon farming scenarios, we calculated hectare based total C inputs which were used as input for Yasso07 model.

2.2. Carbon input quality

Yasso07 requires information on the C input quality in AWENs fractions which describe the chemical composition of decomposing materials as acid (A), water (W) and ethanol (E) soluble, non-soluble (Ns) fractions. They roughly represent the content of cellulose (A), sugars (W), waxes (E) and lignin (N) in the residues. Table 2 presents the fractions used in the calculation.

Table 2. Litter quality in AWENs fractions of different crops and manure. A: Acid-hydrolysable compounds; W: Water soluble; E: Ethanol soluble; Ns: Non-soluble, non-hydrolysable compounds.

Crop residue	A	W	E	Ns	Ref.
Cereals (barley, oats, maize, and wheat)	0.71	0.08	0.03	0.18	Karhu et al. 2012
Grasses, alfa-alfa	0.46	0.32	0.04	0.18	Jensen et al. 2005, Liski et al. 2013
Manure	0.65	0.12	0.07	0.16	Karhu et al. 2012
Oilseed,	0.87	IPCC 2000	0.50	5.0	IPCC 2000
rapeseed	0.40	0.34	0.04	0.22	Jensen et al. 2005, Liski et al. 2013
Pea, beans, and other vegetables	0.63	0.14	0.02	0.21	Jensen et al. 2005, Liski et al. 2013
Sugar beet	0.26	0.54	0.04	0.16	Jensen et al. 2005, Liski et al. 2013
Sugar beet	0.21	Pahkala 2009	0.66	5.0	IPCC 2000
Wheat	0.86	MTT 2013	0.42	5.6	Hansson et al. 1987, Ilola et al. 1988, Paustian et al. 1990, Johansson, G. 1992, Kätterer et al. 1993, Maljanen et al. 2001, Rajala and Peltonen-Sainio 2001, Pietola and Alakukku 2005.

2.3. Climate

The case farm climate data is presented in Figure 3. The data was provided by Lobelia – Past Climate Explorer site, using ERA5 (ECMWF) climate data sets, which was collected from 1981 to 2010, and modified with Copernicus climate change service information, based on Earth Observation satellite data (Lobelia 2020). The climate data included mean annual temperatures (°C), precipitation(mm), and temperature amplitudes (°C) between the warmest and coldest months (i.e., (Tmax-Tmin)/2).

Figure 3. Mean annual precipitation and temperature during 1981 – 2010 in countries where the case farms are located. The tan scatter bars represent the temperature range between the average warmest and coldest temperature (Source: ERA5 dataset, 1981-2010)

2.4. Yasso07 soil model

The Yasso07 soil model estimates decomposition of litter and changes in soil C stock based on chemical quality of litter inputs and climate. The model is based on wide empirical litter decomposition data from different ecosystem types, including the Bayesian calibration method applied in the model development. The model requires only a limited number of easily available input information and omits the impact of soil management and texture. Yasso07 model utilizes information on C input as acid (A), water (W) and ethanol (E) soluble, non-soluble (N) and humus (H) fractions. They roughly represent the content of cellulose (A), sugars (W), waxes (E) and lignin (N) in the residues. The model consists of these four litter compartments (AWENs). Organic litter is broken down into these compartments based on its chemical quality. Each compartment has a specific decomposition rate, affected by temperature and precipitation. We used the original parameterization of the model in this study. The simulated estimates represented soil layers down to a depth of 1 m (Palosuo et al. 2015).

The initialization data sheet is a platform where the user can use the steady state-assumption or start with some predefined soil C stock. The calculations were done assuming the soil to be in a steady state with the average agricultural litter input currently produced at each case farm. The parameter set from Tuomi et al 2009 was used due to suitability for EU wide examination (Tuomi et al. 2009, Karhu et al. 2012).

2.5. Assessment of the additionality in soil organic carbon stock

In our approach, the theoretical baseline for the calculation is the current state of the soil C stock, being a result of current farming practices and more precisely C inputs allocated to soil in each climate. We did not empirically estimate the soil C stocks in each farm. Instead, the calculation in this study was based on a comparison of the modeled impact of current practices and carbon farming practices on soil C stock.

First, we ran the Yasso07 model to an equilibrium state with the information of the C inputs allocated to soil based on current farming practices and simulated their effect on soil C stock change, corresponding to a zero effect. Second, we simulated the change in soil C stock as a result of implementing proposed carbon farming practices. Third, we calculated the difference between the SOC stocks of current and carbon farming cases. This represented the additionality in the SOC stocks. We used mean values for a 10 and 25-year simulation periods. This approach enabled us to assess the impacts of different practices in a situation where empirical estimations were not possible.

3. Carbon farming practices at agricultural and forestry farms and their calculation protocols

3.1. Case farms

Case farms are located in four different bio-geographical regions in Europe (Figure 4). Regional similarities were found in weather conditions, yields and farming practices. The climatic conditions and especially rainfall intensity largely affect the cultivation cycle in the continental and Mediterranean regions. In the Mediterranean, cultivation is directly linked to rainfall and therefore the use of cover crops or collector plants is more difficult due to the limited water supplies. The autumn cereals are much more common in southern Europe than in the north. Importantly, concerning results of the case farm, the cultivation in the Boreal region is more diverse in terms of crop rotation and plant varieties. This may be due to the fact that the case farms participating in this study have already been influenced by carbon management methods. The carbon-smart case farms interviewed in this study were expected to have higher baselines when compared with the average farms.

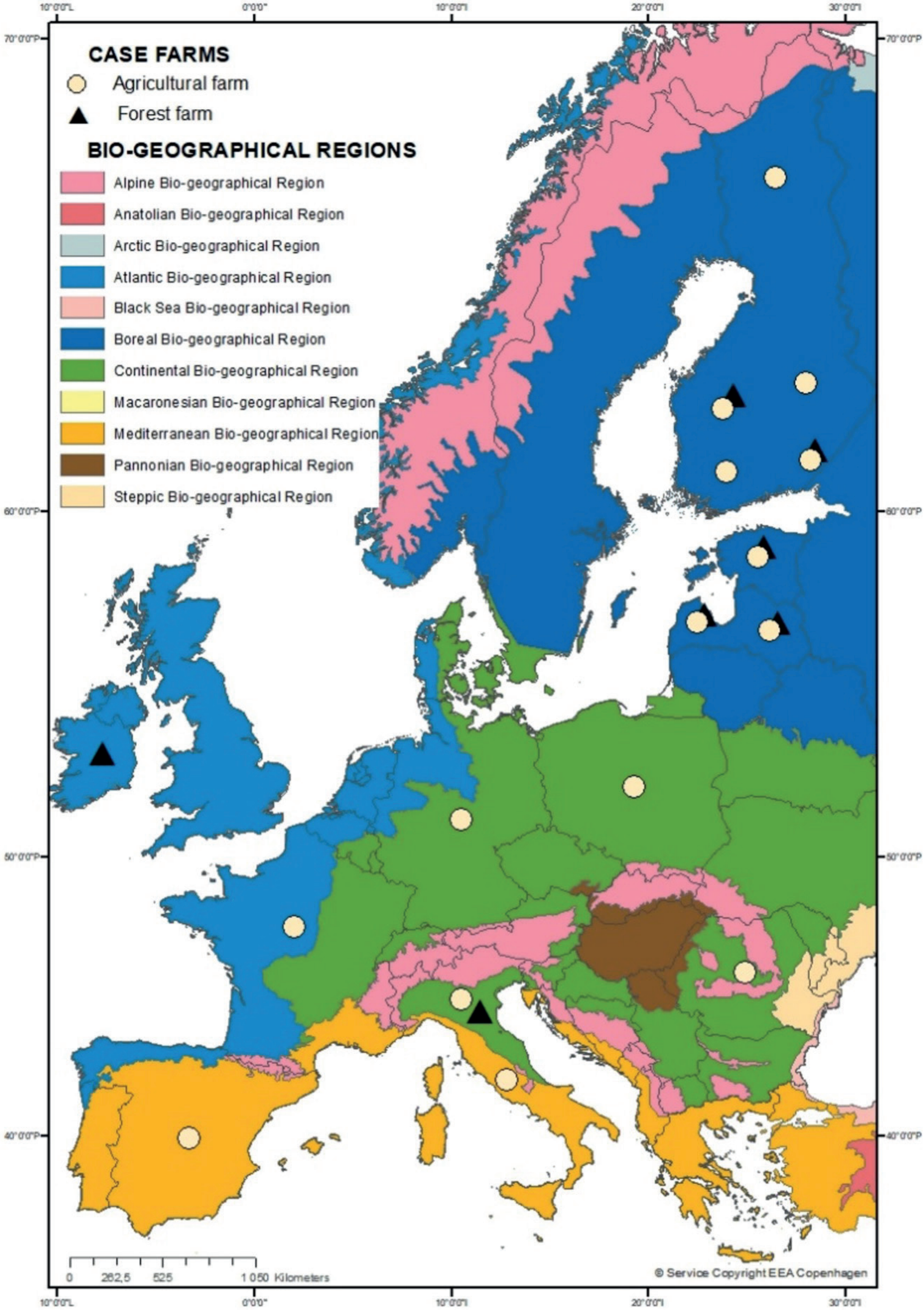

Figure 4. Case farms disposition in the EU based on the bio-geographical region.

The biogeographical regions in Europe were identified based on intelligence obtained from the European Environmental Agency (EEA), covering EU Member States and the Emerald Network countries, namely data used in the Habitats Directive of the European Community and the Emerald Network under the Bern Convention (EEA 2020). The map presents areas across Europe that are defined based on their ecological and natural resources, as well as animal and plant distribution similarities.

3.2. Practices in agricultural farms

Based on the literature, we identified various carbon farming practices with potential to increase C inputs allocated to soil and thus potential to increase soil C stocks (Text box 1). Additionally, while interviewed, the farmers were also suggesting methods that could be beneficial for increasing soil C stock at their farms. In some instances, for example at the farms in Italy, these ideas would indeed increase soil C stocks. The final selection of practices to be used for calculation was eventually done based on expert assessment and outcomes of the interviews:

- Land arrangement and ditches to manage the drainage of rainwater and avoid water stagnation in the plains;
- Increased usage of bees-friendly plants to increase biodiversity and create an area that could provide bees with food during the whole season;
- Organic farming application not only as a procedure to reduce chemicals and sprays but also as a preservation of soil and its biodiversity, as in case of biodynamic production;
- Great attention paid to crop rotation;
- Cooperation with livestock farms in the area of organic fertilization;
- Inclusion of cruciferous crops and green manure into crop rotation.

Table 3 displays the different carbon farming practices included in the carbon calculations. These practices were selected based on practical applicability, needs and starting point in different farms, considering for example adequate fodder production for farm animals and practical constraints for crop rotations.

Calculations were carried out for 15 agricultural farms. Yield increases by 10% and 15% were expected to be achieved through improving soil growing conditions resulting from potential improved farmer competence. Extension of grassland area and changes in the cutting height of grasses were applied to farms having grass as a product. Green fallow was applied to farms having no grasslands beforehand. The resulting reduction in the production area of other crops was distributed evenly.

Text box. 1. Carbon farming practices included in the farm calculations.

- Sustainable intensification by improving soil growing conditions, resulting in hypothetical yield increase by 10% and 15%
- Changed harvest index of grasses by 20%, 30%, 40%, 50% and 60%
- Introduction of green fallow in the production by 10% and 20% of the production area
- Increased grassland area to 50% of the total production area
- Introduction of cover crops with cultivation of spring cereals

Table 3. Application of carbon farming practices in the project case farms.

	Yield increase	Change in cutting height of grasses	Introduction of green fallow	Introduction of cover crops	Introduction of pulp mill and fiber sludge
ESTONIA	X	X			X
FINLAND I	X	X	X		X
FINLAND II	X	X		X	X
FINLAND III	X	X			X
FINLAND IV	X	X		X	X
FINLAND V	X		X	X	X
FRANCE	X	X		X	X
GERMANY	X		X		X
ITALY	X		X		X
LATVIA I	X	X			X
LATVIA II	X		X	X	X
POLAND	X	X	X		X
ROMANIA	X	X			X
SPAIN	X	X		X	X

Cover crops

Cover crops (or catch crops) are utilized to benefit soil health and productivity. They increase vegetation cover and soil organic matter, prevent erosion and nutrient losses, increase infiltration of water, fix nitrogen, can break infections with soil borne diseases, and increase agrobiodiversity, thus building the overall resilience of farming systems. Cover crops can be sown together with the main production crop and allow to continue growing after the harvesting of the main crop in the fall or they can be sown immediately after the harvest of the main crop, to prevent the land to be fallow. Cover crops fix additional carbon from the atmosphere by photosynthesis and supplement soil with additional plant biomass. Cultivation of range of catch crops creates a more diverse agroecosystem, supporting diverse soil organisms, roots, and improving soil structure. Such soils have a greater ability to store carbon.

In the calculation protocol the harvested yields for the cover crops were estimated for Finnish farms from to be 700 kg DM ha^{-1} and 1500 kg DM ha^{-1} for the other European farms based on Munkholm and Hansen 2012. The root biomass was estimated by multiplying the yield by 1.7 while rhizodeposition was calculated as in section 2.1.

Green fallow

Green fallow enables keeping the soil green year-round. Green fallow can increase organic matter and nutrient content in the soil, and improve soil microbiological activity, soil structure and biodiversity.

In our calculation, the area allocated to green fallow was evenly taken from the currently cultivated land. In the simulations the applied shares were 10% and 20% of the total cultivation area. The yield was estimated to be 6000 kg DM ha^{1}, an average value for grasses in the case farms. All the above-ground biomass was assumed to be allocated in the soil.

Increased grassland area and changed cutting height of grasses

Grasslands under crop rotation improve soil's growing condition and have a positive effect on biodiversity. In the calculation, adding grassland areas and changing the cutting height of harvested grasses would increase C inputs allocated to soil, compared to current management, and thus increase soil C stock. The additional land area for grasses was taken from cereals. In the case of changed cutting height of grasses, the cutting height reflected in the calculations has changed harvest index as follows:

Harvest index 0.6 equals 40% of above-ground biomass allocated to soil. The change of grass cutting height was calculated with HI values of 0.2, 0.3, 0.4, 0.5, and 0.6.

Soil improvement fibers

Applying soil improvement fibers in the fields adds direct C inputs to soil. Their use improves soil nutrient and carbon balance, through enhancing soil biological activity. The addition of organic matter to the soil feeds the soil's micro-organisms, increasing their activity and quantity in the soil. MAHTAVA project has produced empirical and modelled information on decomposition of carbon from different organic fertilizers and soil improvement fibers (Heinonsalo 2020).

The values for soil improvement fibers applied in our calculations are presented in table 4. In the calculation we estimated the application rate for the soil improvement fiber at 40 000 kg ha^{-1} (fresh weight). The total C input for the cultivation area is calculated by multiplying the fresh weight with dry matter content of 38% and carbon content. We assumed the addition of the fiber to the fields in the cycle of 6 years. For farms having also animals, the manure applied as fertilizer was replaced with soil improvement fibers.

Table 4. Values for soil improvement fibers that were used in the calculation. The quality of litter (AWENs fraction) is based on Heikkinen et al. 2021.

	C%	C inputs total (kg C ha^{-1})	A	W	E	Ns
Nutrient Fiber 1	32.5	4987	0.63	0.05	0.02	0.31
Composted Nutrient Fiber 2	39.4	6044	0.60	0.04	0.03	0.33
Zero Fiber	33.3	5103	0.83	0.03	0.01	0.13

Estimation of the decomposition of soil enrichment materials in mineral soil

The decomposition of the soil enrichment materials and the share of carbon that remained in the mineral agricultural soil was assessed for a 100-year time span. The share of permanent carbon in the soil was estimated using the Yasso07. The decomposition of SOC depends on the chemical quality of litter inputs and on climatic conditions. The soil enrichment materials under assessment were 1) Nutrient Fiber 1 (Figure 5: Pulp mill sludge lime-stabilized), 2) Composted Nutrient Fiber 2 (Pulp mill sludge *Composted) and 3) Zero Fiber (Fiber sludge *Side stream of the wood industry). We estimated the decomposition of 1 kg of soil enrichment materials over a 100-year time span. We used average values of mean annual temperature, precipitation, and temperature amplitude (the difference between the average temperatures of the warmest and the coldest month) in the simulations. We used the actual annual values for years from 1990 to 2004 for Southern Finland, the annual temperature being 3.8°C, annual precipitation 628 mm and amplitude 13.1°C.

The share of carbon originating from soil enrichment materials in mineral agricultural soil during the simulation period is presented in Figure 5. The amount of carbon that remained in the soil during the simulation period is presented in detail in Appendix 1.

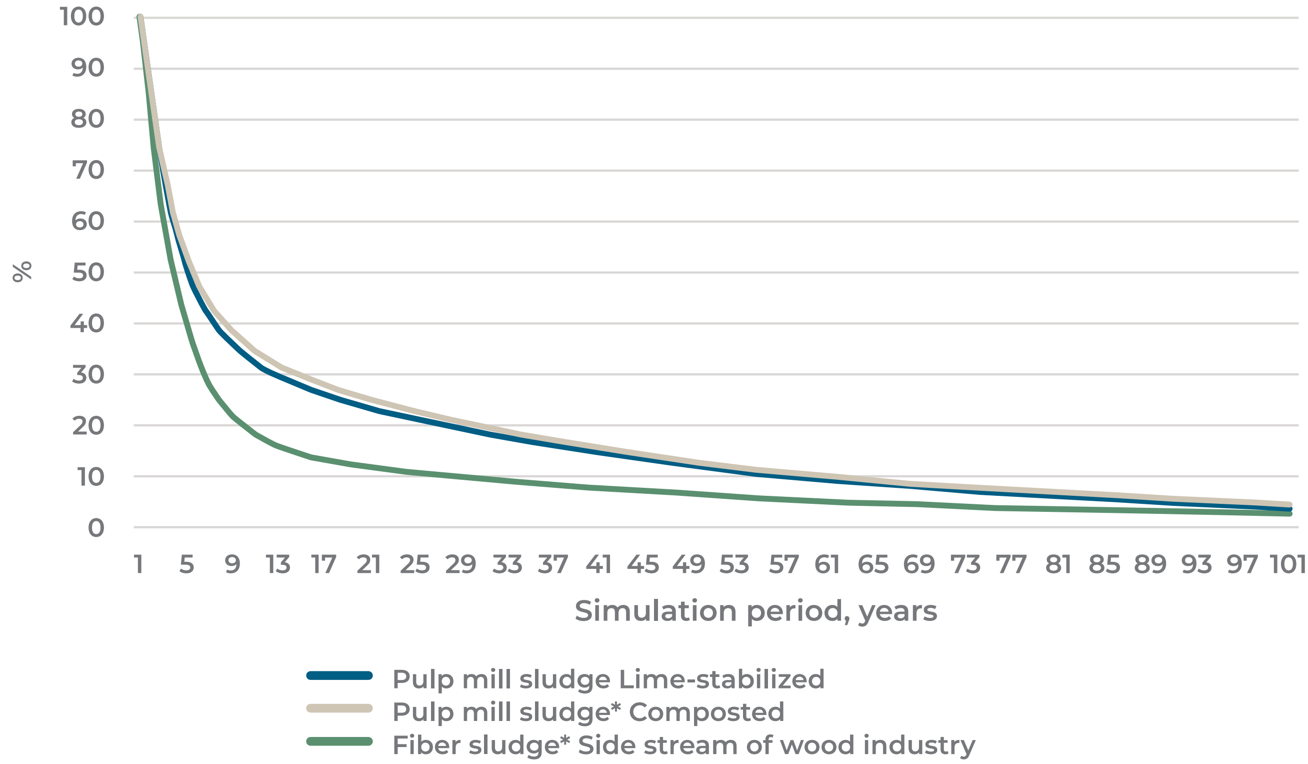

Figure 5. The share of carbon originating from soil enrichment materials remained in the soil after 100-year simulation period

Yield increase by 10% and 15%

The hypothetical yield increase is considered to be a result of improved farmer know-how and resulting actions benefitting soil growing conditions and fertility. In the calculation, the increase in yield directly increased the size of above-ground and below-ground C inputs.

Carbon inputs of carbon farming practices

Figure 6 confronts C inputs from current and carbon farming practices. The topmost bar presents C inputs produced by cultivation of winter wheat. The following bars below present the additionality of C inputs resulting from different carbon farming practices. Cover crops and soil improvement fibers would be possible to combine with production of winter wheat resulting in notably higher total C inputs compared to current methods.

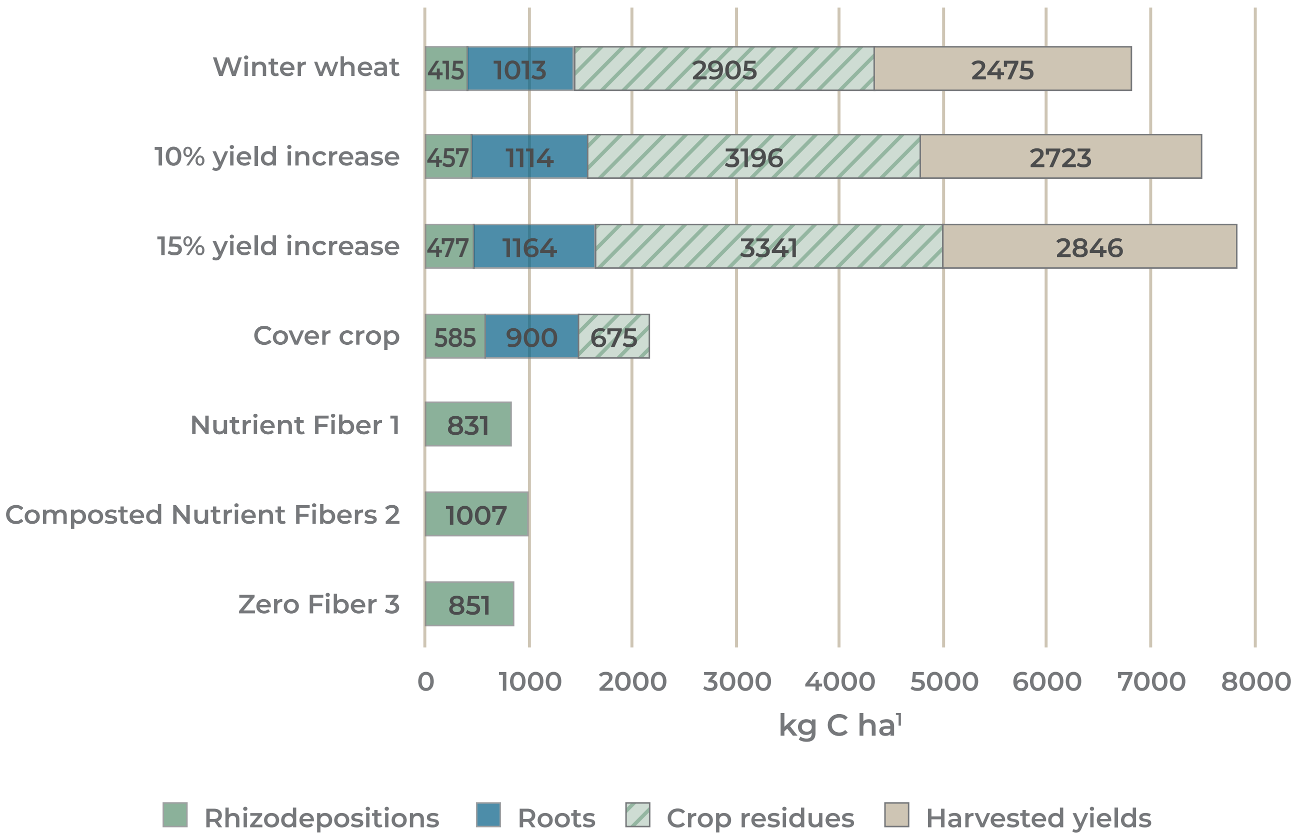

Figure 6. Above- and below ground C inputs of current winter wheat production and different carbon farming practices which could be implemented together with wheat production.

3.2. Practices in forestry

Carbon sequestration in forests

The new EU forest strategy was raised in the Commission communication on the European Green Deal (COM (2019) 0640). Forests are one of the most important areas when it comes to tackling climate change.

In the EU-27+UK, the forest area has been expanding since 1990 from 147.9 million hectares to 161.4 million hectares in 2020. Only 4% of forested area has not been modified by human intervention, 8% is constituted by plantations, while the remainder falls into the category of 'semi-natural' forests, i.e., ones that are modified by a man.

In Finland, forests (following the international forest definition, FAO) cover 22.8 million hectares (73.7% of land area), representing 13.8% of the forest area in the EU-27+UK. Finland's forest area has grown by more than 500 000 hectares over the last 30 years.

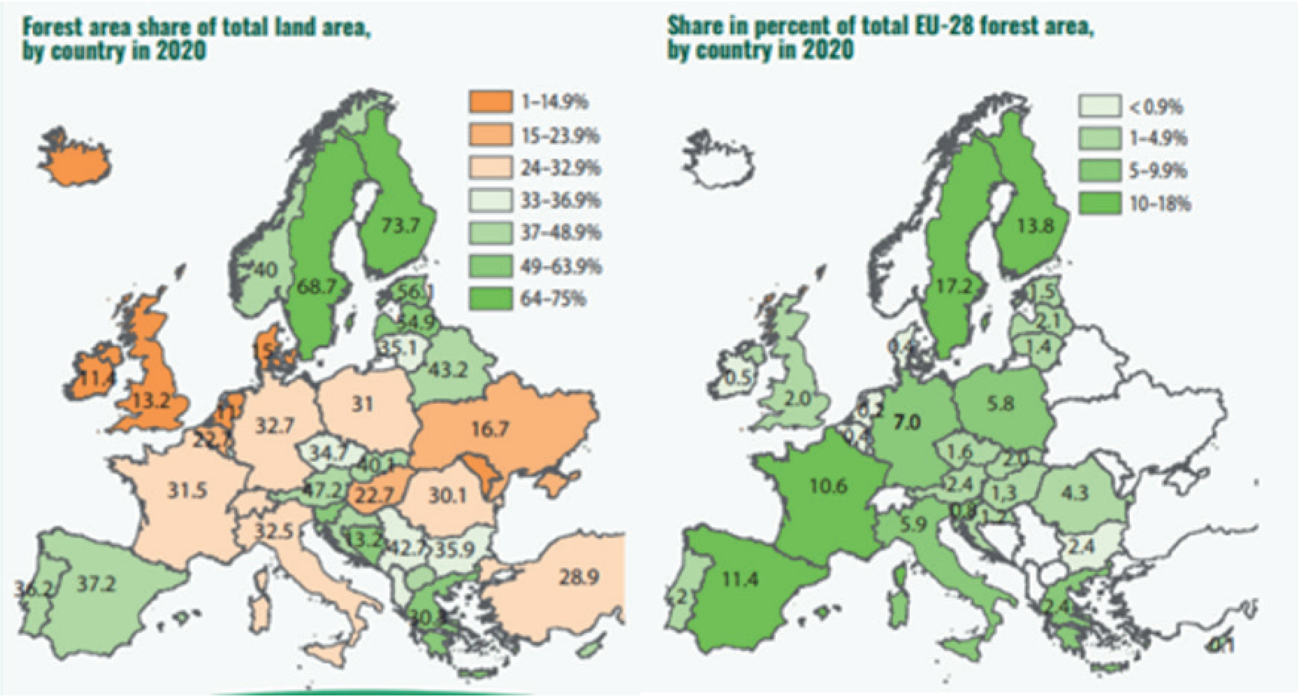

Figure 7. Forest areas share of total land area, by country in 2020 (left) and share in percent of total EU-27+UK forest area (right), by country in 2020 (Lier and Korhonen 2020).

In the 46 European countries, the FOREST EUROPE forest area has expanded since 1990 by approximately 11 million hectares and accounts in 2020 to 227.4 million hectares – a result of afforestation and natural forest expansion. Nowadays 34.8% of FOREST EUROPE's land area is forested.

The total C stock of forest biomass (above- and below-ground) accounts in 2020 to 13 240 million tons which equals 64 t/ha. In the EU 28, the total C stock of forest biomass accounts in 2020 to 9 802 million t, which is equal to 67.4 t/ha. In Finland, the total C stock of forest biomass (above- and below-ground) increased over the last 30 years from 633 million t in 1990 to 863.6 million t in 2020. The annual net sink of Finnish forests varies annually mainly due to harvesting.

Fertilization

Fertilization is the most immediate way to increase the forest growth in nitrogen-limited stands and soils typical for northern Europe. In the more southern areas of Europe, where the soils are more fertile and the amount of nitrogen deposition is high, the growth response to additional nitrogen injection is limited. The best growth response is obtained in stands at their fastest growth period which is after the closure of the canopy and starts to decrease when the natural self-thinning starts. According to the results of experiments where successive fertilization has been carried out, the growth response has been repeatable. The fertilization frequency can be set at once in 8-10 years. The normal dose of fertilizer is 150 – 180 kg N/ha. The most common fertilizer type is ammonium nitrate, but on more fertile soils nitrogen, phosphorus, and potassium (NPK) is recommended.

Forest management

Prolonging the rotation period is one of the possibilities to increase the C storage in the forest, but not necessarily the rate of carbon accumulation (Liski et al. 2011). Reforestation and afforestation are means to increase the forested area instead of other land use categories. Also, the prevention of deforestation has a significant role in the changes in standing forest biomass.

The former land use was shown to be a major factor contributing to changes in SOC after afforestation. On former croplands, SOC change differed between soil layers and was vastly positive (20%) in the 0–10 cm layer. Afforestation of former grasslands had a small negative (nonsignificant) effect indicating limited SOC change following this land-use change (Bárcena et al. 2014). It can be concluded that significant SOC sequestration in Northern Europe occurs after afforestation of croplands but not grasslands, and changes are small within a 30-year perspective.

It has been estimated that 14.4% of Europe's land area would be suitable for reforestation, with particularly adequate areas in the U.K., Portugal, western and southern France, Italy, and Eastern Europe (Griscom 2017).

3.3. Procedure for collecting farm level data

The WP1 case farm pilot started in February 2021. The farms were reached out through the Baltic Sea Action Group (BSAG) and the following organizations: Azolla project, Boerenbond, Centre National de la Propriété Forestière (CNPF), Centre National de la Propriété Forestière (National Center for Private Forest Owners), Climate Farmers, Eubia, Fundación Global Nature, IDELE, JIN Climate, LANDMARC Horizon, Ministry of Agriculture, Fisheries and Food (MAPA), Miteco, Noi Compensi Amo, Oficina Española de Cambio Climático (OECC), Rural advisory and training center (LRATC), Southpole, Svensk Kolinlagring, Terraprima, The National Institute for Agricultural and Food Research and Technology (INIA), and Union Framers Parliament (ZSA). They were approached with the LIFE Carbon Farming Scheme introduction letters, describing all the key details of the project and main tasks that the farm needs to provide in order to participate. The farms included agricultural farms such as dairy farms, organic farms, mainstream food production farms, and animal feed production farms, as well as different types of forestry farms.

The individual farms and organizations were introduced to the project via virtual call. During the first video call, the idea was to evaluate if the farms or organizations could provide the necessary information. The project aimed to find farms representing different production sectors and practices. Outreach through the organizations streamlined the communication with farmers and allowed contacting also smaller projects. Additionally, the farmers could acquire a more in-depth knowledge about the LIFE Carbon Farming Scheme thanks to a native-speaking connection through the organization.

After the first virtual meeting with the farmer, the farm received a preliminary data collection form, different for the agricultural farms and for the forestry (Supplementary preliminary forms as appendix 2 and 3). The agricultural preliminary information form included questions related to the farm cultivation history, cropping, yields of each crop, crop rotation, fertilizing, and husbandry. The farm's location was very important due to the related climate conditions. Similar information was collected with the forestry preliminary form. The information form included questions on the forest age, tree species, forest growth index, average diameter and height of the trees, and other more specific questions.

The detailed interviews kicked off after the farmer or an organization representative had filed out the preliminary form. The interviews were supposed to acquire information following at least minimum requirements set out for the project as described in a paragraph above.

Every farm is unique and the process to collect and gather all the information varied between the virtual interviews. The goal was to get a better overview of a given farm. As observed during the interviews, farmers were more willing to share information orally rather than filling out the form.

Challenges
The project was trying to come forth with the definition of 'the ideal farm' to represent an ordinary farm in each climate region, but it faced difficulties since the farms known to the climate action organizations were already climate-smart, so in principle they are still not necessarily an accurate representation of an ordinary farm.

The support from the side of organizations, common language skills, and the willingness to share the farm information were all considered very good. There were however some minor problems with data availability e.g., regarding the yields and crop rotation. Moreover, cultivation and farm history before 1991 has been hard to collect in eastern countries due to the economic systems transformation and resultant lack of data continuation. In southern Europe, most of the farms are funded by bigger food production companies that were hesitant to be a part of the project, and therefore in some of the cases required data could not be collected. Certain farms were too large for the purpose of the programme and therefore, smaller sections of the farms were used in the calculations. In case of forest farms, the main obstacle was to find eligible forests in southern Europe as well as organizations or farms willing to share their information. Most of the forest owners faced difficulties providing the required information, mainly because the forests are naturally grown and not measured extensively. In northern Europe, the forests are cultivated to a greater extent and in some of the cases fertilized, which is not as widespread in southern Europe. This allowed us to do the more detailed calculations for the forestry farms located in North Europe.

Every farmer that we interviewed wishes to generate high quality and healthy products as well as to have a better soil biodiversity. The possible changes for the farm resulting from carbon farming such as improved soil health, increased yields thanks to better soil nutrition, as well as the thickness of the organic soil are all considered important for the farmers. Their main concern was obviously the expected yield being a source of their income. Farmers have also acknowledged extreme weather conditions and admitted they are already apparent in the yields. This affects the cultivation and crop rotation plans for the upcoming seasons, which is considered one of the obstacles in the project. For the sake of this study though, climate conditions are assumed to stay as they are.

Selected reasons restraining farmers from participation in the project:

- Lack of understanding towards the importance of carbon removals in the context of net-zero economy by 2050
- Lack of understanding towards the importance of carbon removals in the context of evolving agricultural subsidies
- Language barrier
- Workload and time expenditure
- Data consistency across individual parcels of land

4. Results

Soil type, climate conditions, cultivation history and agricultural management practices largely influence the amount of soil C stock, how it varies between farms and even within one farm. Figure 8 presents modelled values concerning baseline situation for each of the case farms. These values are based on C inputs currently produced in the farms and climate but do not present the real size of soil C stock due to complex feedback mechanism which is not yet captured in the modelling tool (for example tillage is omitted). The variations result from different cultivation methods and weather conditions across the case farms.

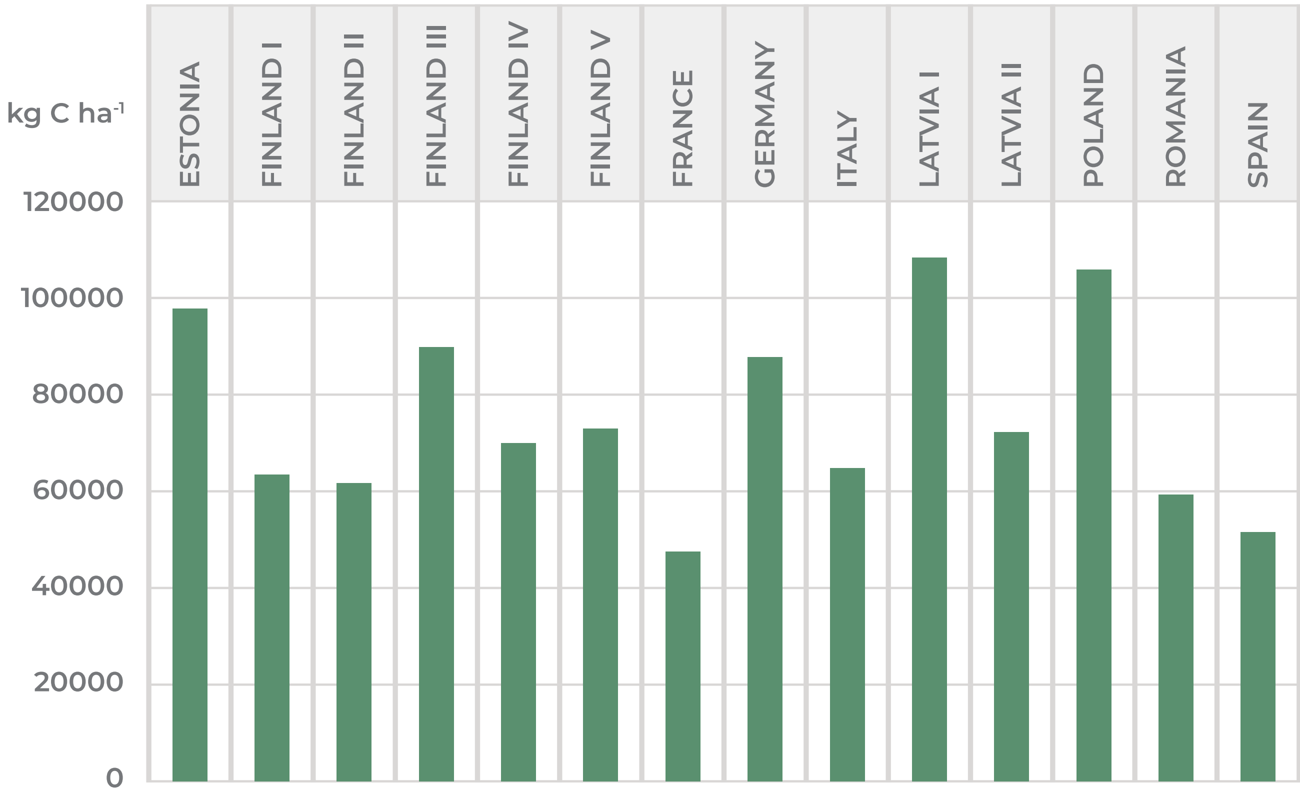

Figure 8. Modelled soil C stocks based on current management in the case farms. These values do not estimate real soil C stocks but are used in the calculation to assess the additionality of carbon farming practices in comparison to current practices on soil C stocks.

4.1. Carbon sequestration potential of carbon farming practices in the agricultural case farms

According to our modelling, the carbon farming practices altered soil C stocks by -3640 – 4440 kg C ha^{-1} during the 10-year simulation period (Figure 9). The annual carbon sequestration potential varied between -364 and 443 kg C ha^{-1} over 10 years. The results for each case farm are presented in appendix 4.

The highest carbon additionality was achieved with the use of soil improvement fibers (Figure 10). For composted nutrient fiber 2, the change in C stock was estimated at -3640 – 3130 kg C ha^{-1}. In some case farms, the C emission is a result of replacing the manure currently used as fertilizer with soil improvement fiber. In the case of Italian farm, the use of manure leads to better results than the use of nutrient fibers, because the use of manure adds more nutrients to soil than additional nutrient fibers. The calculated total C inputs at the farm are lower if nutrient fibers are used instead of manure. In Latvia and France, sole use of zero fibers causes negative results due to the lack of nutrients at all. The combination of nutrient fibers and manure could be implemented, but the usages and the amounts of the products are farm specific, hence such combination was not considered in the calculations.

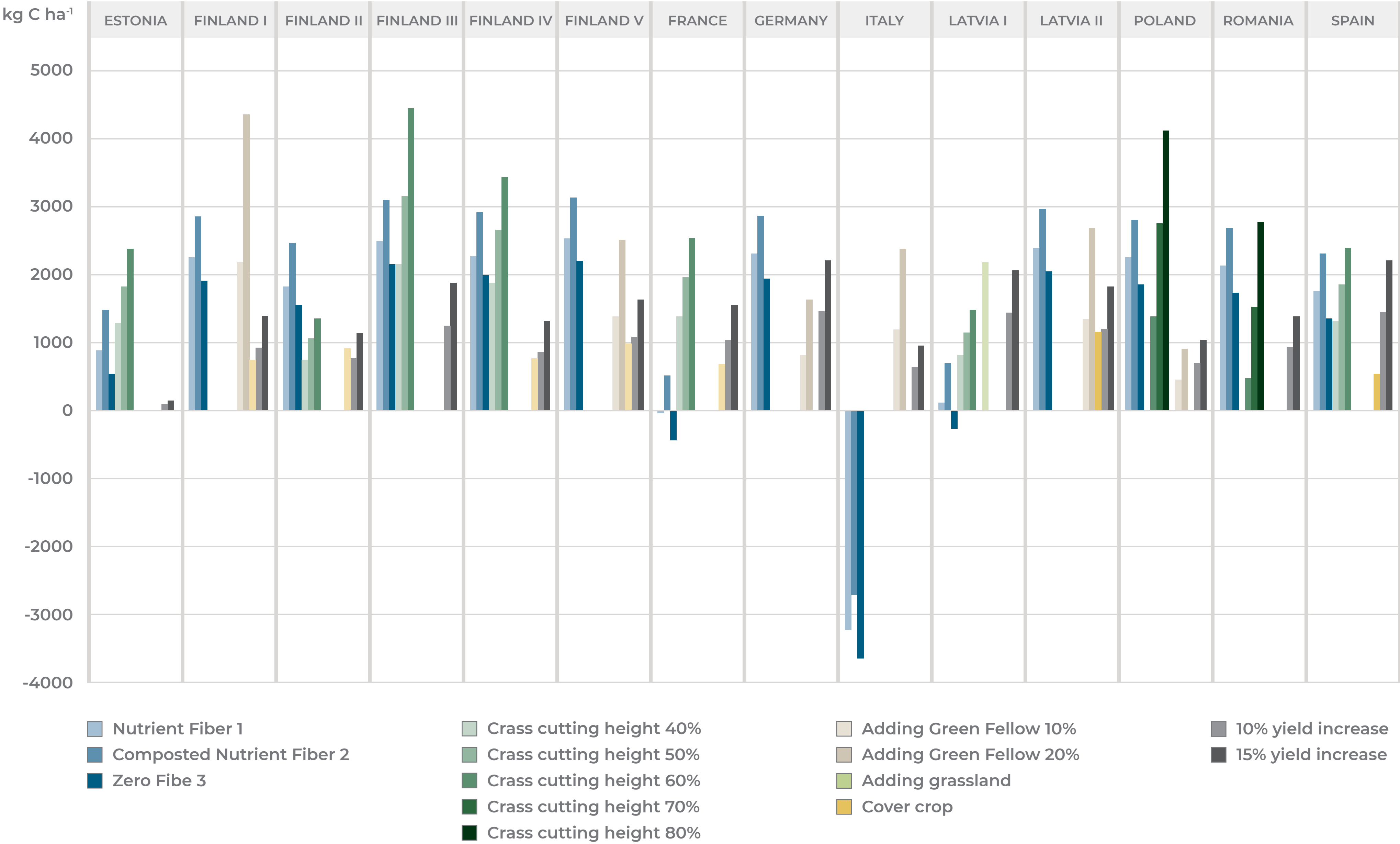

Figure 9. A summary of the carbon sequestration potentials of carbon farming practices in the case farms over 10-year simulation period.

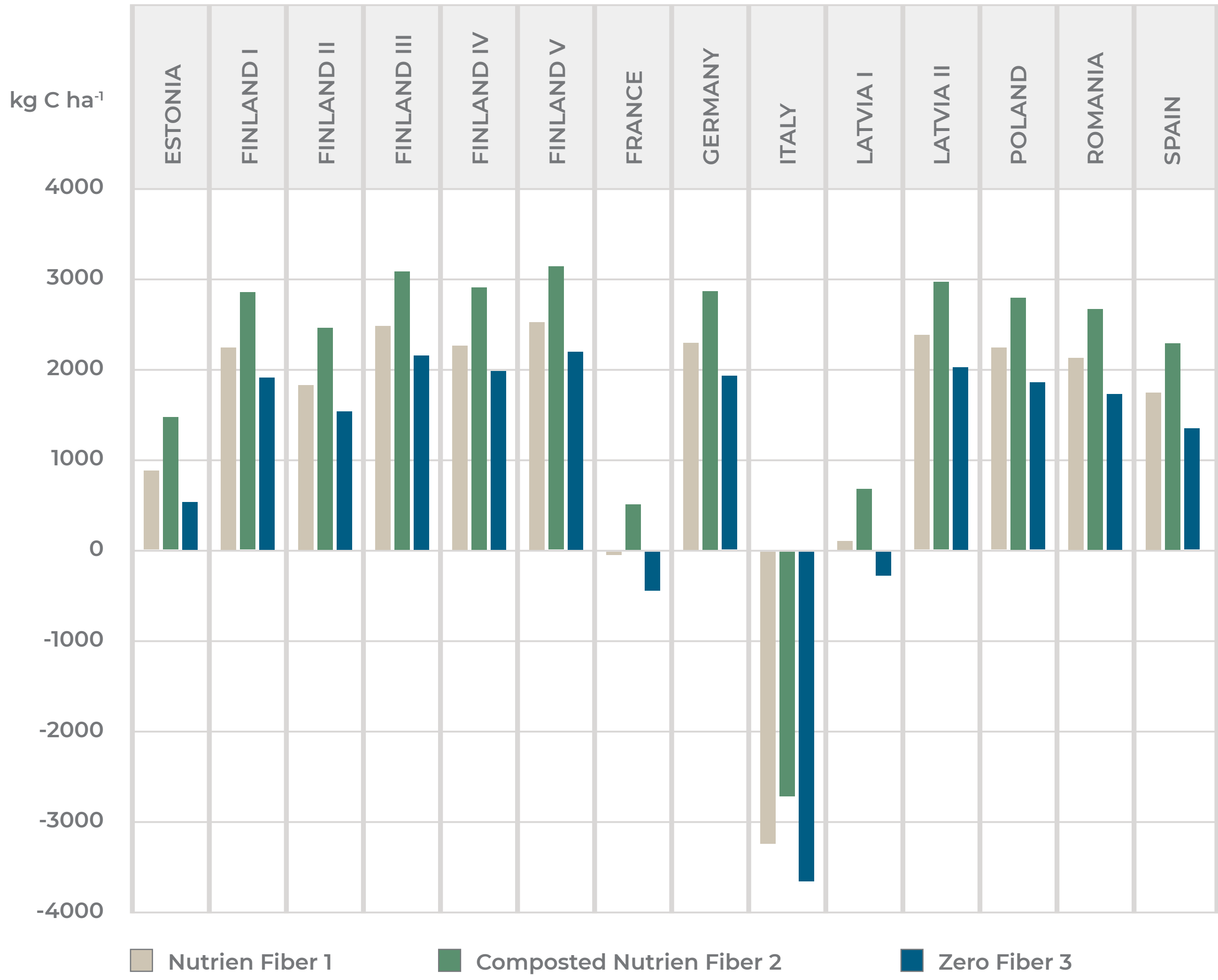

Figure 10. Potential soil C stocks surplus through the addition of soil improvement fibers in the case farms over 10-year simulation period.

The modified cutting height of grasses resulted in 460 – 4400 kg C ha^{-1} increase in soil C stocks (Figure 11). The cultivation routine modifications like a change in the grass cutting heigh, cause more machine use because the met yield needs to be harvested multiple times. Change in grass cutting height has shown a positive effect on the growth pace what in turn affects positively the soil's carbon content (e.g. farm in Finland). Based on the farmers' feedback on the results, related to grass cutting heights, less than 50% harvesting heights are the most realistic in a sense of sustainable and smart farming.

Figure 12. presents the addition of green fallow and cover crops to the cultivation. The addition of green fallow on 10% of the production area or integration of cover crops into crop rotation turn out to have almost the same results, between 500 – 2000 kg C ha^{-1}. Higher results are achieved through extending green fallow to 20% of the cultivation area. Comparing these results with other carbon farming practices, such as soil improvement fibers, annual carbon additions are lower but improvement in e.g., biodiversity (not assessed in this study) can be more beneficial than just adding fibers. Therefore, the combination of different methods would provide best outcomes for the agricultural farms.

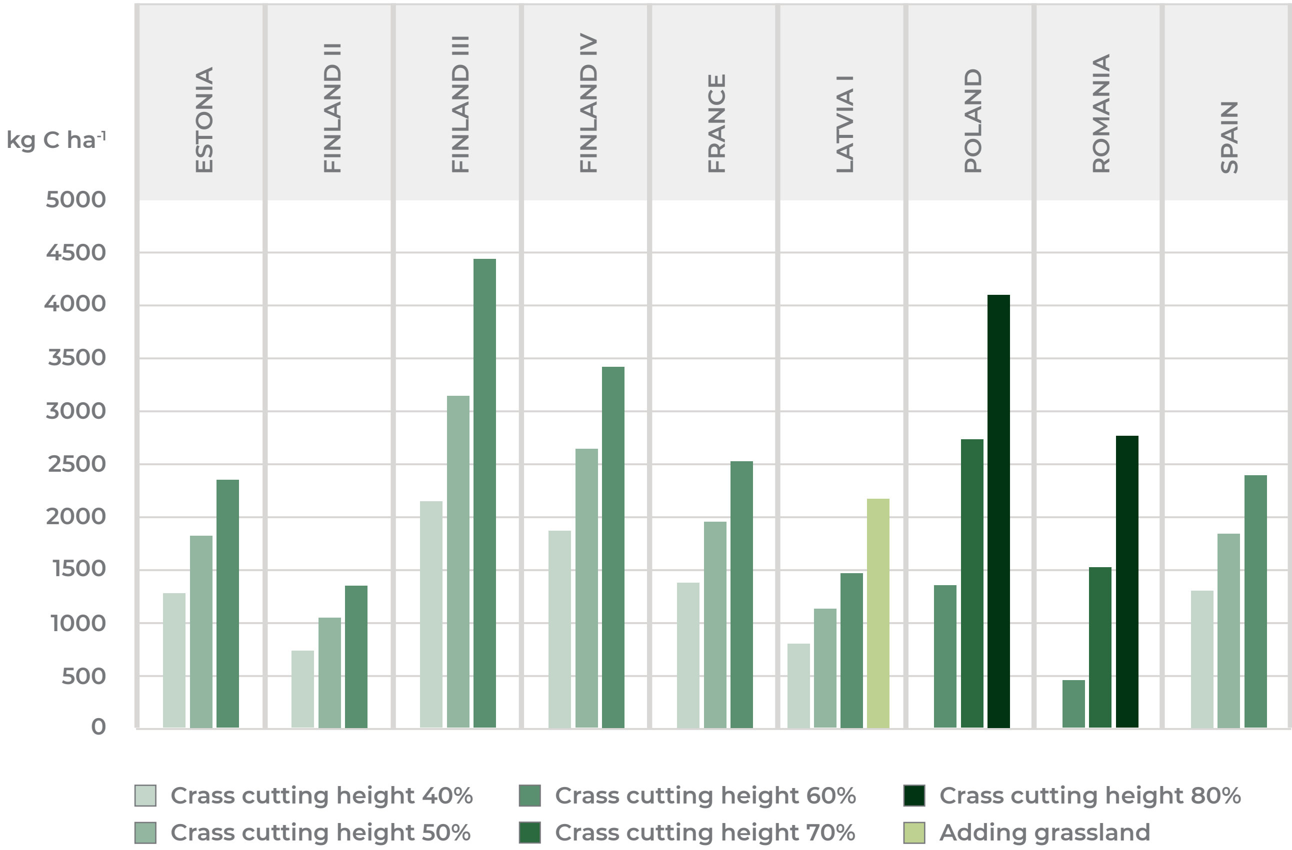

Figure 11. Potential soil C stocks surplus through modification of the cutting height of grasses and grassland area expansion in the case farms over 10-year simulation period.

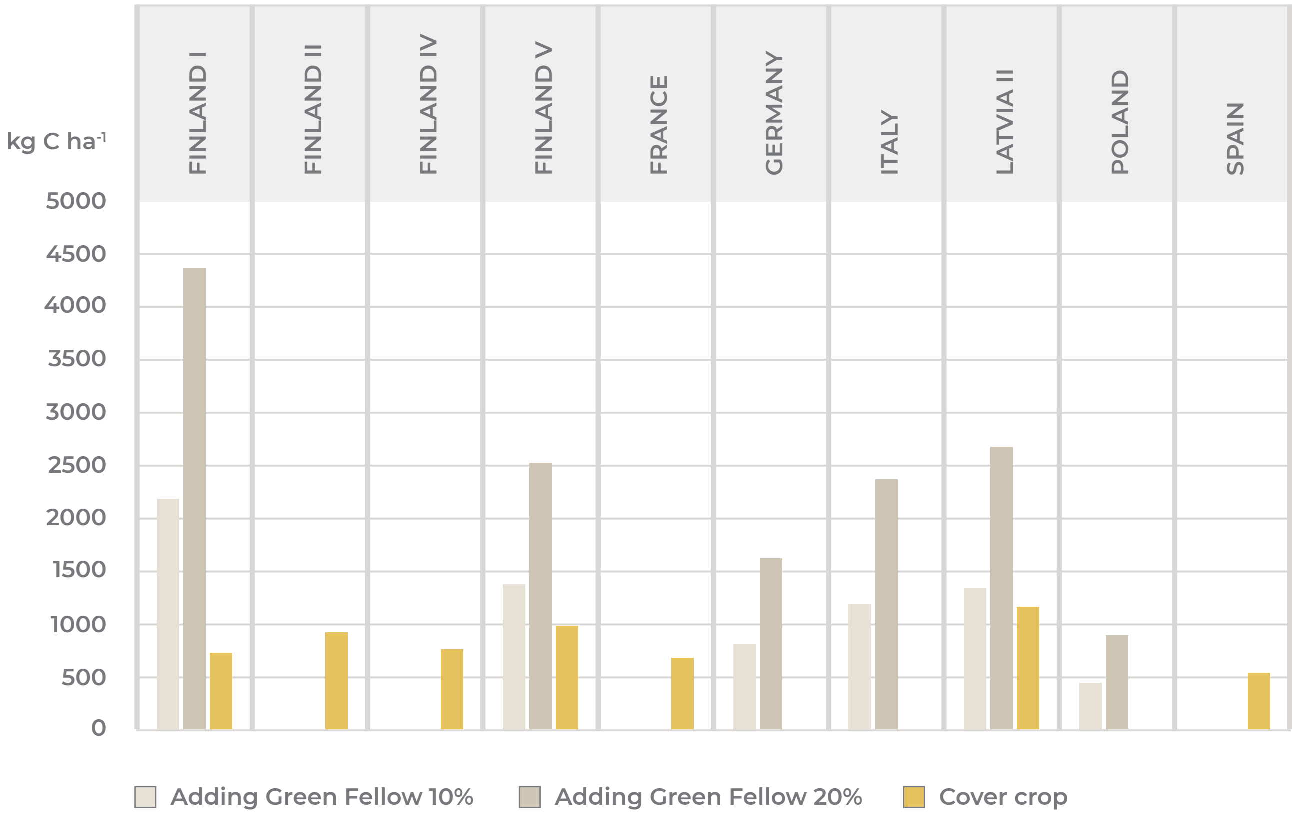

Figure 12. Presentation of average carbon sequestration increase achieved in the C stock over 10 years with addition of cover crops and green fallow, across the case farms.

4.1.1 Carbon additionality over time

Figure 13 presents the rate of carbon sequestration for each carbon farming practice over time. It was assumed that the new carbon farming practice starts in year 0 and is continuously implemented since then. All carbon farming practices have the highest additionality in the first 10 years upon their introduction. After this period, the sequestration evens out, as the new equilibrium point for the specific practice is approaching. Maintaining soil C stocks requires continuous implementation of carbon farming practices. If the practices change and e.g., C inputs reduce, the consequence is C emission from the soil.

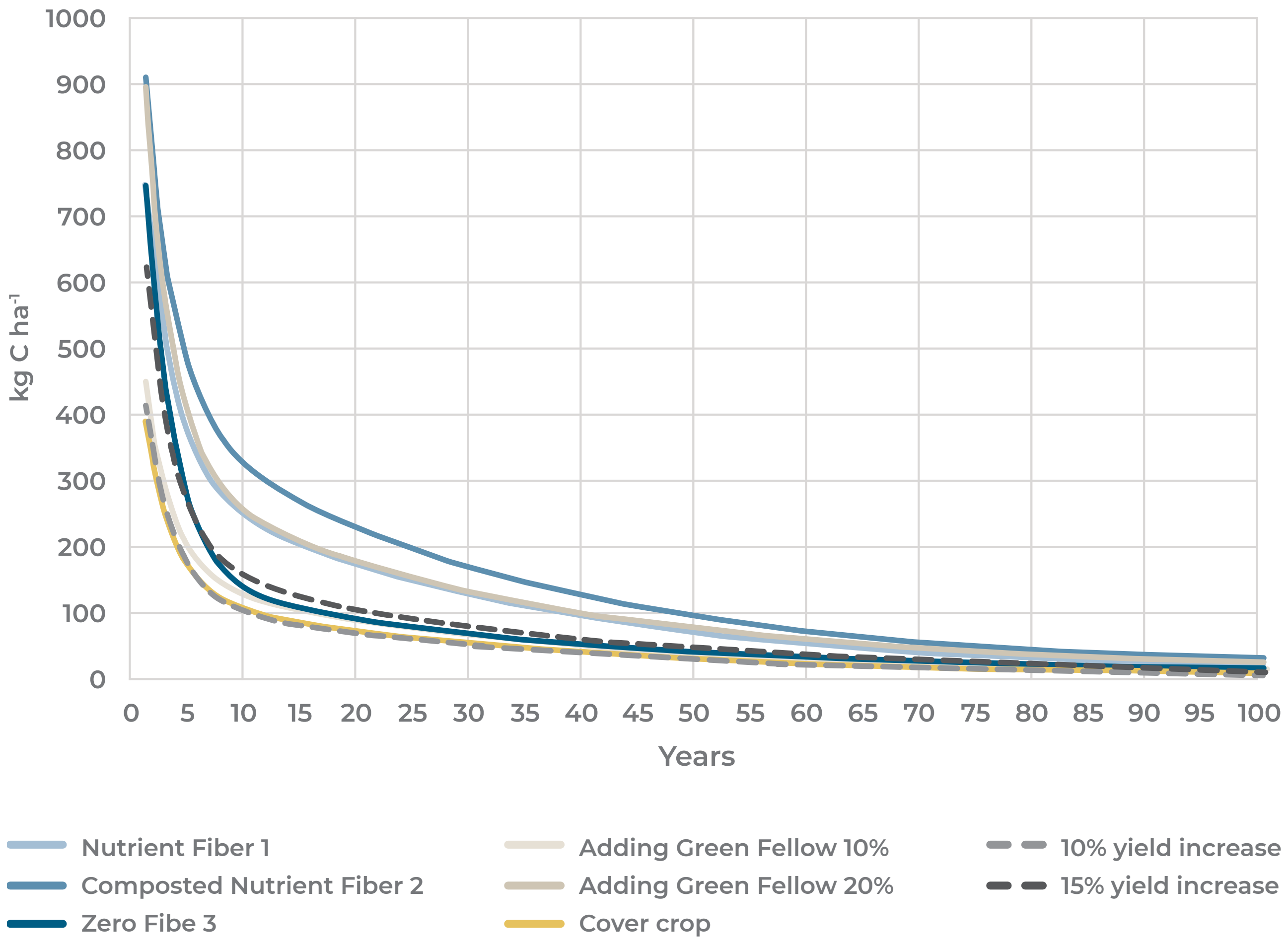

Figure 13. Addition of carbon through carbon farming practices after introduction of the new method.

4.1.2 Results from the case farms

Atlantic region

France

The farm is located along the Loire river. The average annual temperature between 1979 and 2018 is 12°C with an amplitude of 7.4. The precipitation average is 720mm a year.

The land has been in agricultural use for 100 years and under the same farming methods for at least 30 years. The main production type of the farm is dairy farming. The farm annually holds a total of 44 dairy cows, 8 calves, and 18 heifers. The total agricultural area of the farm is 62 hectares. The farm produces its feed for the animals, including cereals, permanent and temporary grass in various fields (Figure 14). The crop yields are estimated based on the husbandry feeding. The farm uses various non-organic and organic fertilizers.

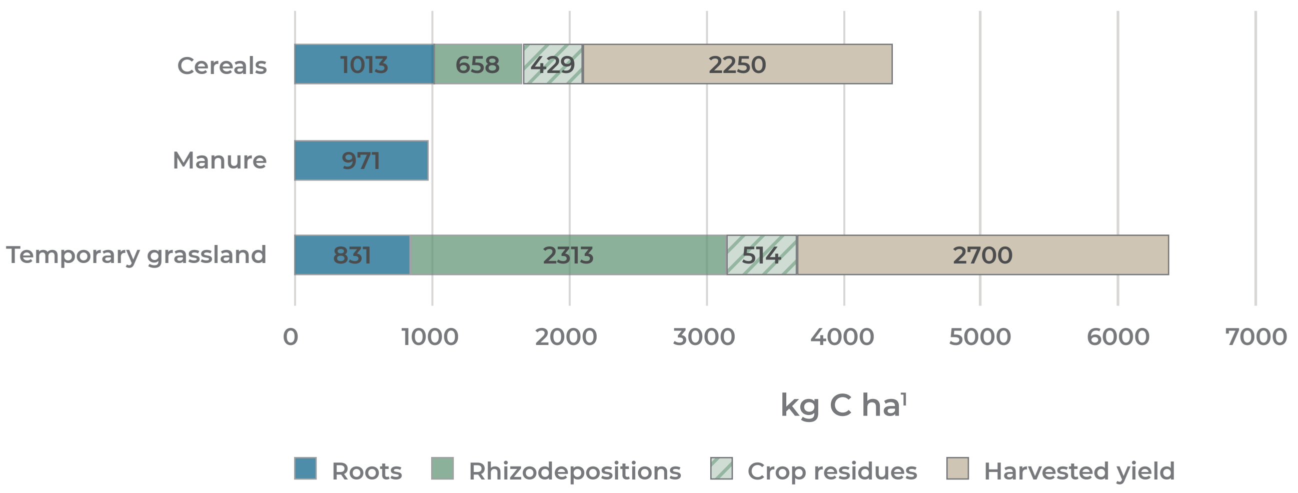

Figure 14. C inputs in current crop cultivation at case farm in France.

The annual carbon increment between different carbon farming methods (creating carbon additionality) varies across 10 years between 408 – -83 kg C ha^{-1}, and across 25 years the annual range is 261 – -65 kg C ha^{-1} (Figure 15). The emission is a result of replacing manure currently used on the farm with soil improvement fibers.

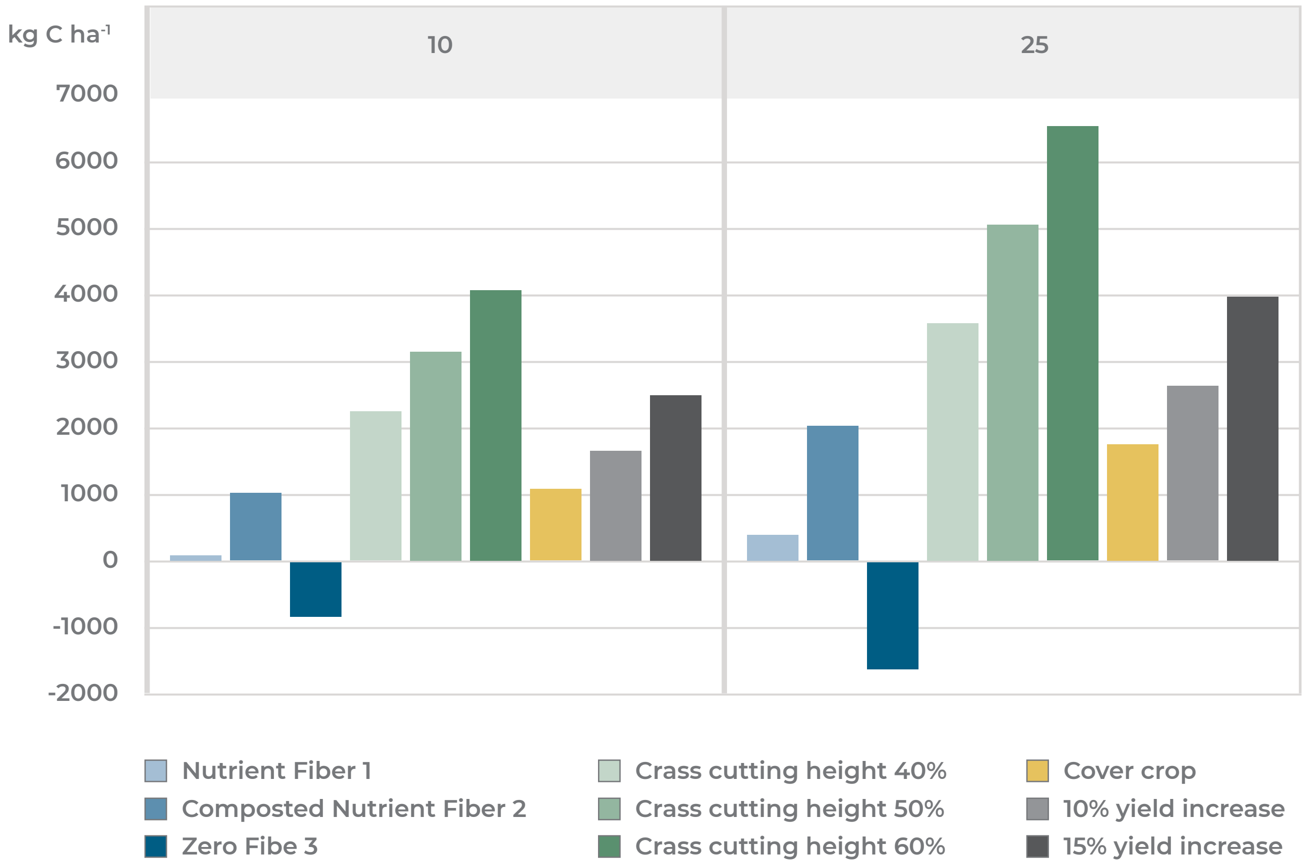

Figure 15. Carbon additionality of different carbon farming practices

Boreal

Estonia

The average annual temperature between 1979 and 2018 is 5.8°C with an amplitude of 11.35. The precipitation average is 718mm a year.

The total size of the farm is 33 hectares. The agricultural land includes permanent grassland and pasture that is used for animal feed (Figure 16). Farm animal husbandry has a total of 35 animals, including calves, heifers, and suckler cows. The agricultural land is at least 300-year-old. The orchards are up to 7 years old and formerly the area was used a grassland. Permanent grassland has remained in the same shape for 15 years while permanent pasture even for 70 years.

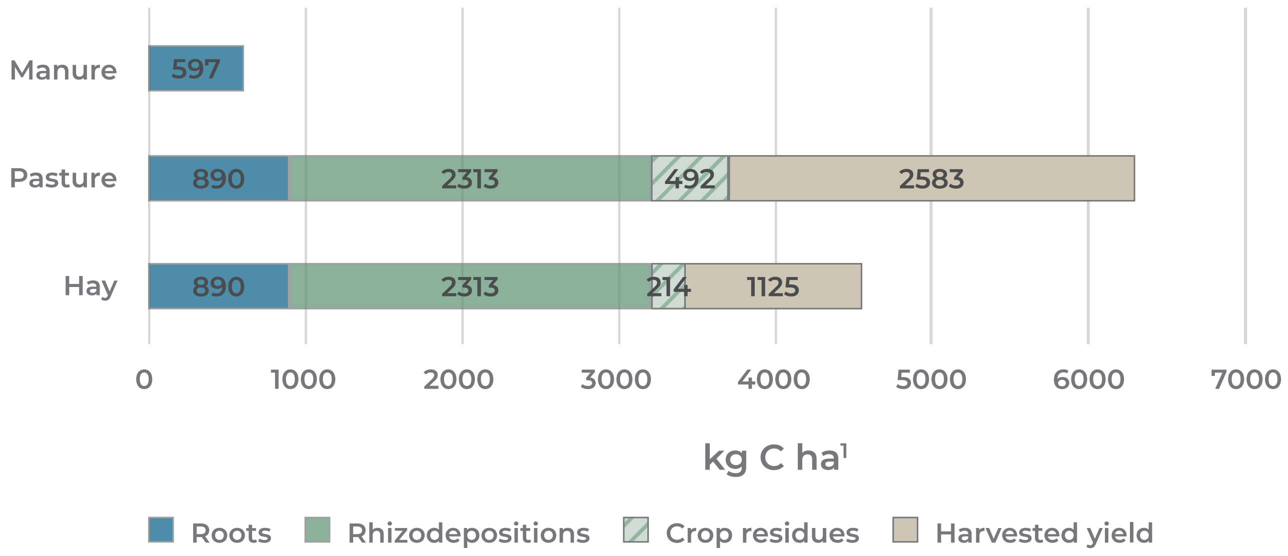

Figure 16. C inputs in current crop cultivation at case farm in Estonia.

The annual carbon increment between different carbon farming methods (creating carbon additionality) varies across 10 years between 386 – 71 kg C ha^{-1}, and across 25 years the annual range is 252 – 27 kg C ha^{-1} (Figure 17).

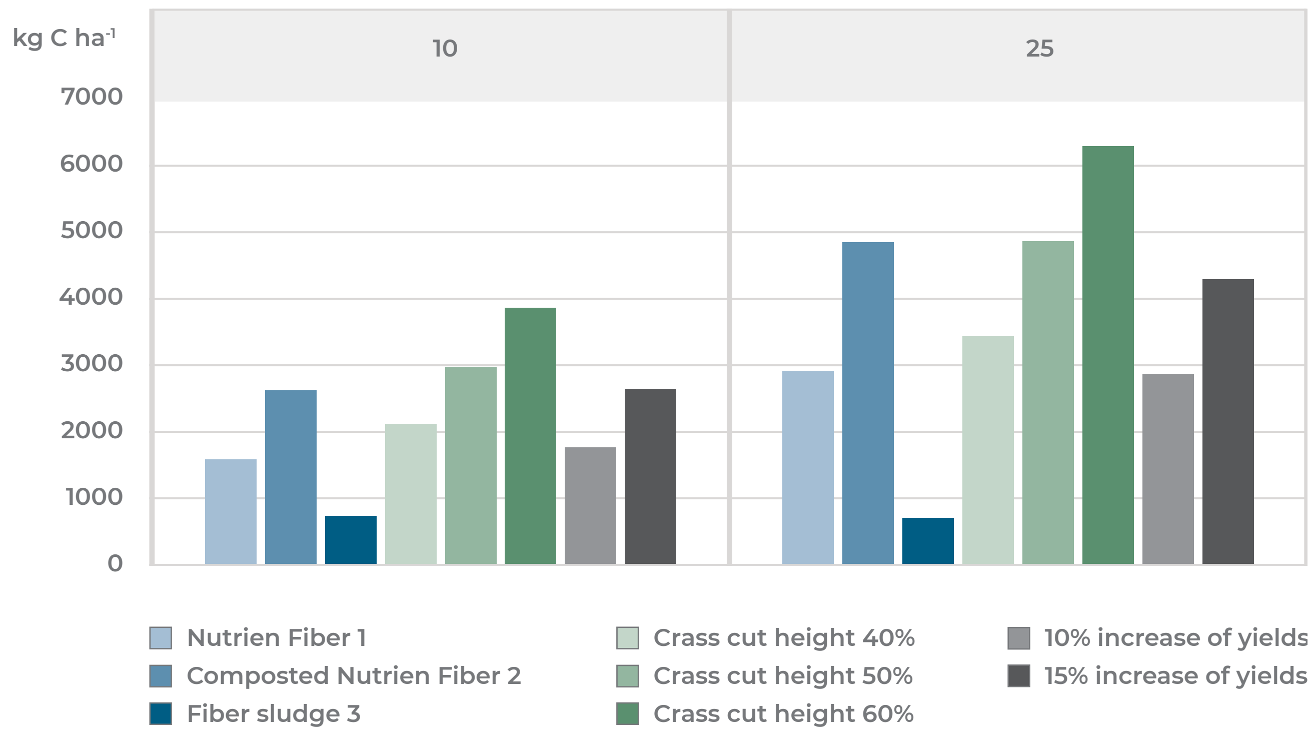

Figure 17. Carbon additionality of different carbon farming practices

Finland I

This family farm is in northern Europe. The average annual temperature between 1979 and 2018 is 5.1°C with an amplitude of 12.1. The precipitation average is 717mm a year.

Farm specializes in pig production with 200 sows in stock. Cultivated area covers 101 hectares of fields whereof 25 hectares are grasslands, and 76 hectares are oats, barley, and wheat (Figure 18).

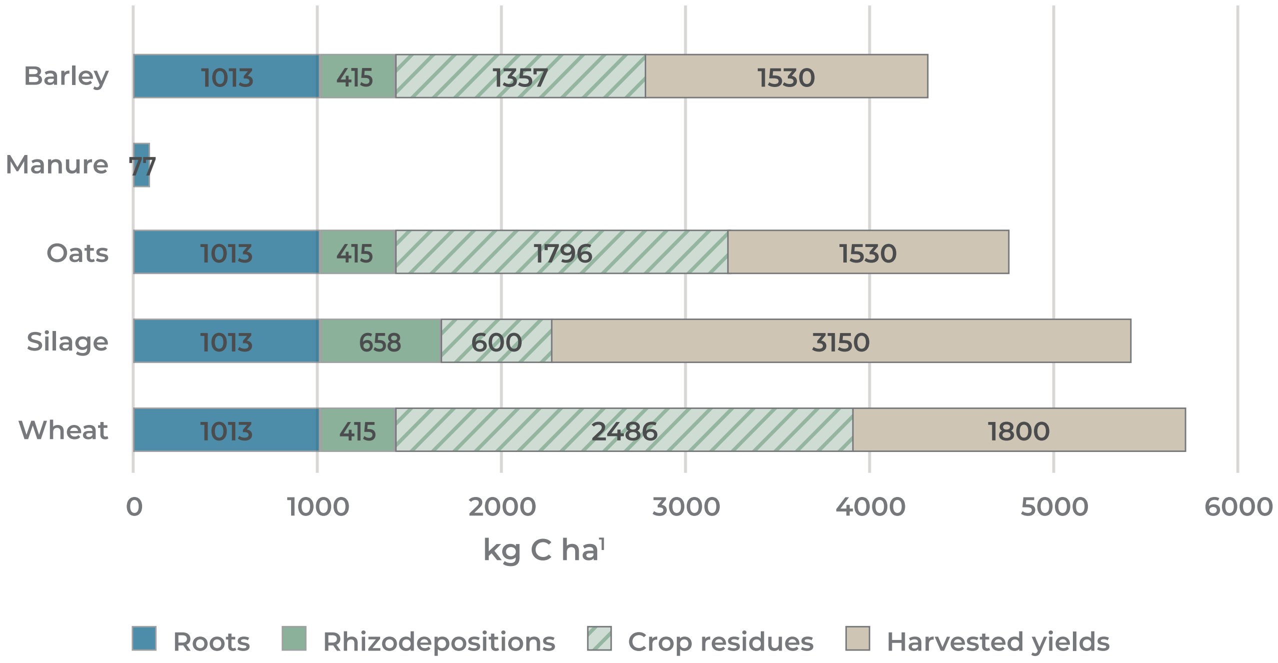

Figure 18. C inputs in current crop cultivation at case farm in Finland.

The annual carbon increment between different carbon farming methods (creating carbon additionality) varies across 10 years between 715 – 119 kg C ha^{-1}, and across 25 years the annual range is 468 – 78 kg C ha^{-1} (Figure 19).

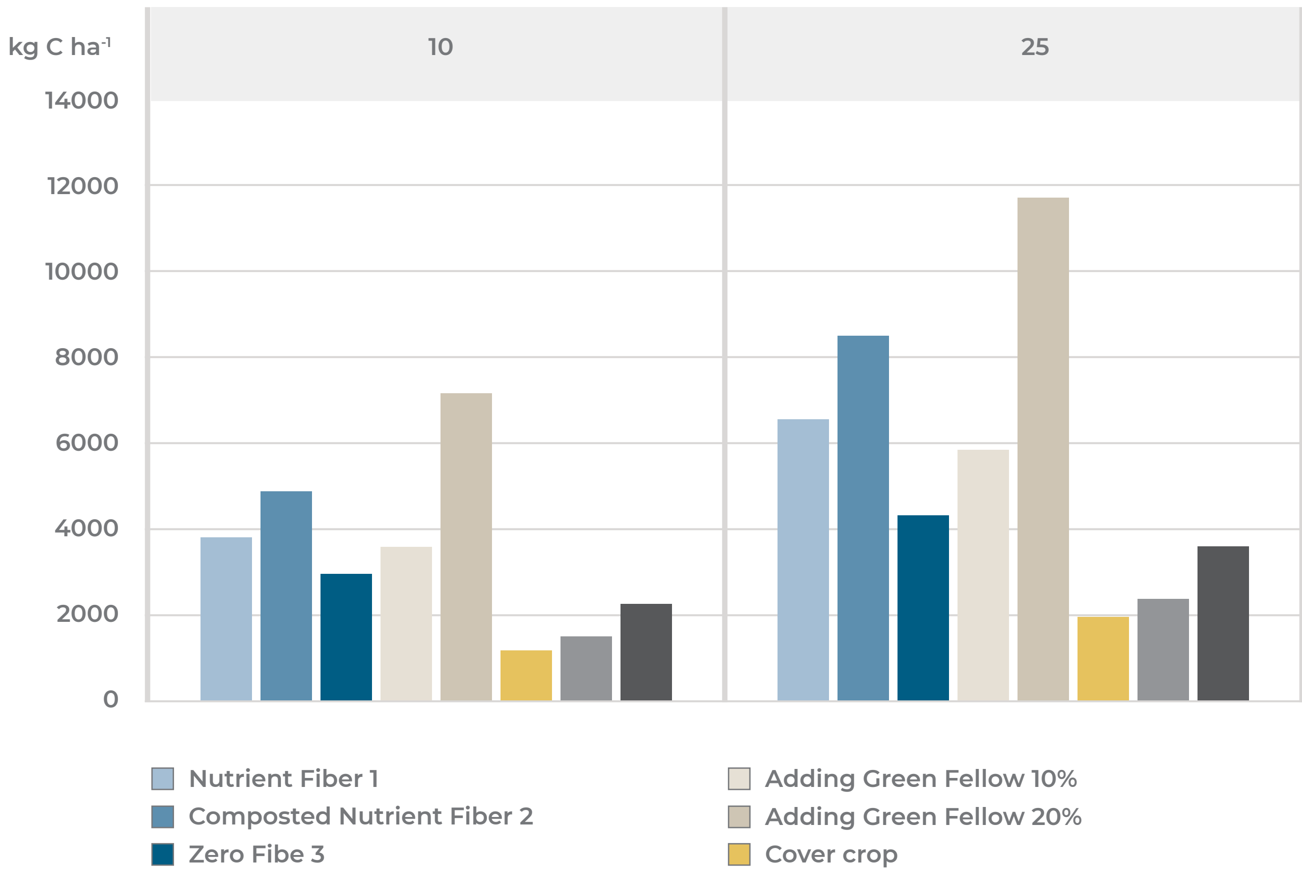

Figure 19. Carbon additionality of different carbon farming practices

Finland II

The average annual temperature between 1979 and 2018 is 1.8°C with an amplitude of 13. The precipitation average is 669mm a year.

The farm's work focuses on sheep husbandry and feed production. The land has been in an agricultural use for over 120 years. Currently, total area of the farm is 100 hectares, whereof 35 hectares is grassland, 20 hectares seasonally changing cereals, 15 hectares oats, 5 hectares barley, 15 hectares green hay mix, and 10 hectares grassland that is not used for production (Figure 20). Manure and potassium-biotite are used for fertilizing. Manure is first dried and then spread over 15-hectare area 3 times a year. Potassium-biotite is spread only once a year.

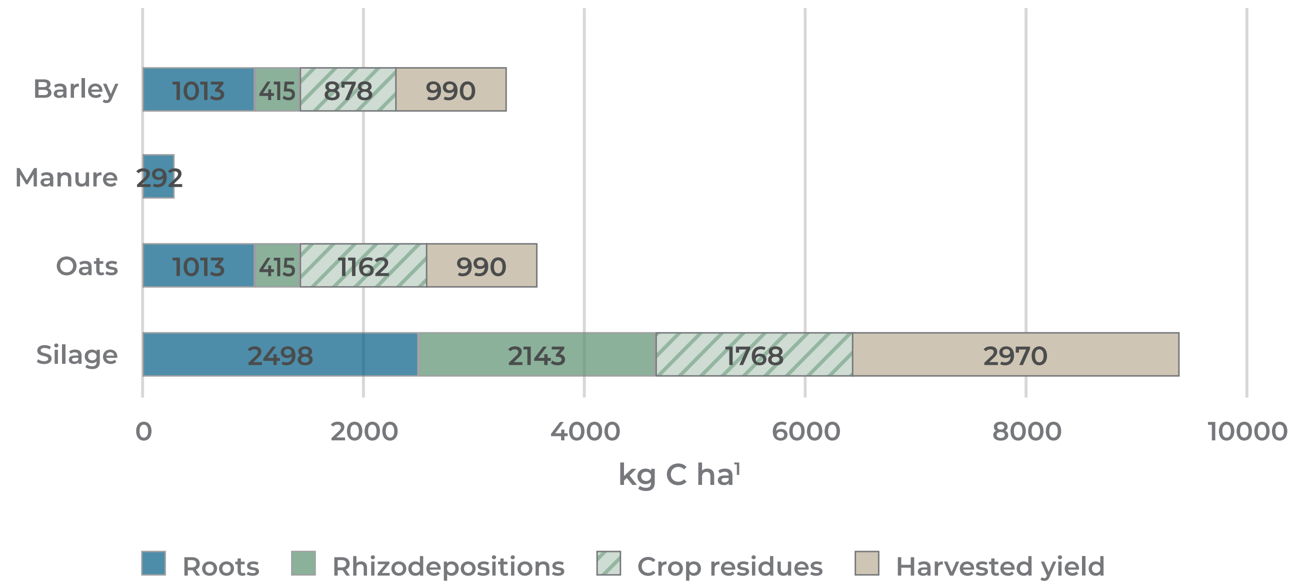

Figure 20. C inputs in current crop cultivation at case farm in Finland.

The annual carbon increment between different carbon farming methods (creating carbon additionality) varies across 10 years between 432 – 123 kg C ha^{-1}, and across 25 years the annual range is 312 – 81 kg C ha^{-1} (Figure 21).

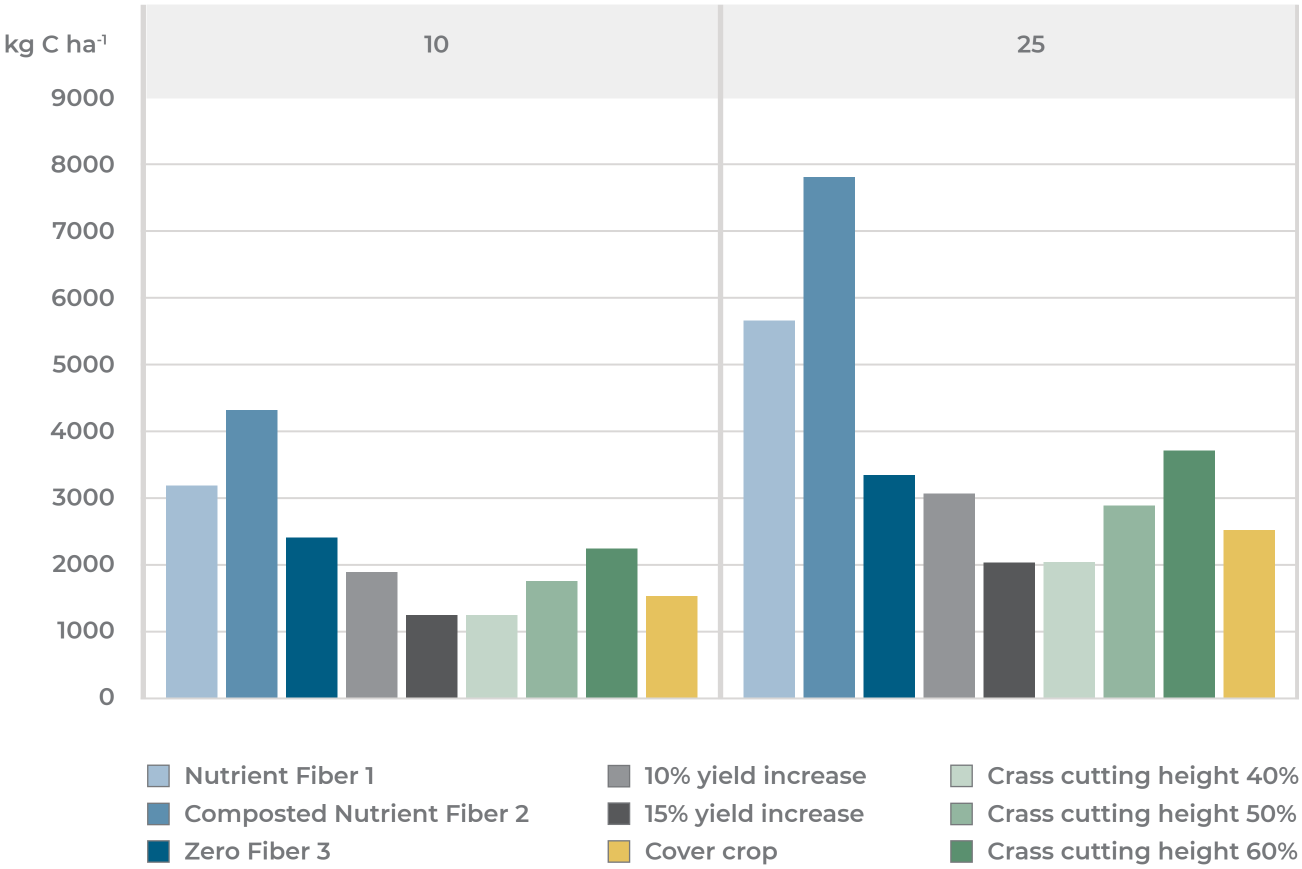

Figure 21. Carbon additionality of different carbon farming practices

Finland III

The average annual temperature between 1979 and 2018 is 4.5°C with an amplitude of 12.75. The precipitation average is 713mm a year.

Forest was converted to an agricultural land in mid-1900s, and the farm has been active since 1943. The total size of the organic seed and food production area is 120 hectares. The cultivation is based on ecological methods, such as diversified crop rotation, nutrient recycling, and mixed cultivation. The farm produces cereals, mainly for seed production, as well as the protein crops for seed, food, and fodder, while the oilseeds for oil pressing.

The calculations were carried out for 85-hectare area, with oats, peas, wheat, rye, autumn rapeseed, and grass crops (Figure 22). The farm's cultivation is rich, and diversity is wide, the crop rotation includes diverse green manure grasslands, nature conservation, and game fields. All crops have cover crops, such as ryegrass and clover. This improves the soil and helps the pest control. For the future, the aim is to increase soils growth conditions, diversity of plant production, product processing, and energy self-sufficiency (Tyynelän tila 2021). 5 to 10% of the soil is organic matter, which is planned to be increased in the coming years.

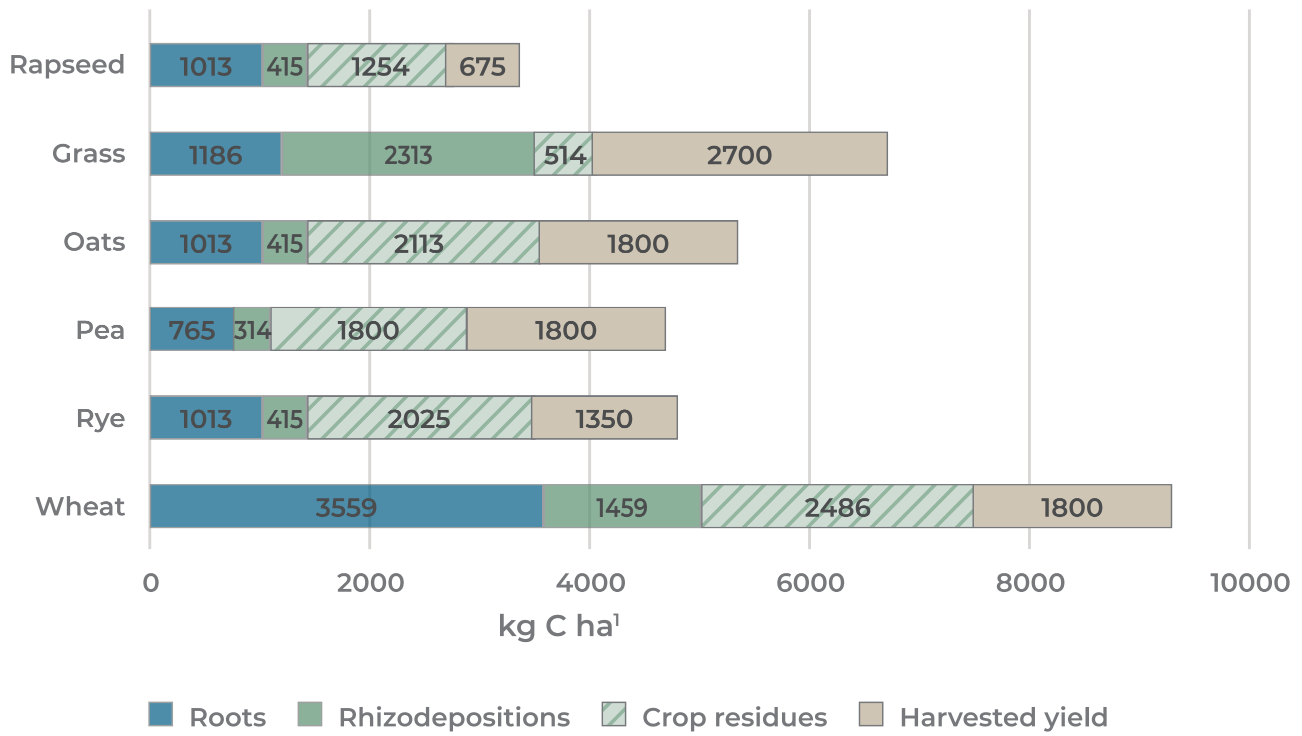

Figure 22. C inputs in current crop cultivation at case farm in Finland.

The annual carbon increment between different carbon farming methods (creating carbon additionality) varies across 10 years between 727 – 202 kg C ha^{-1}, and across 25 years the annual range is 470 – 130 kg C ha^{-1} (Figure 23).

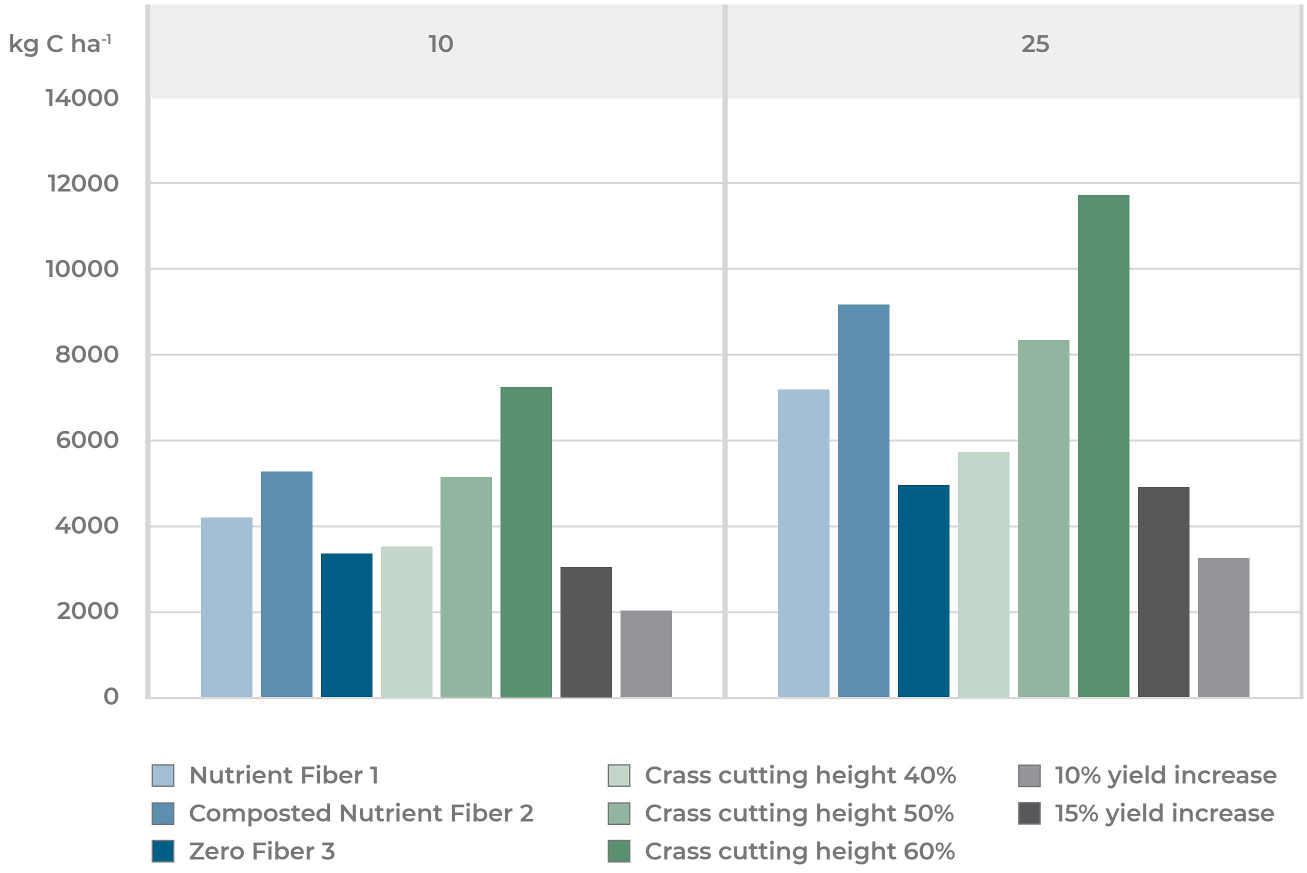

Figure 23. Carbon additionality of different carbon farming practices

Finland IV

The average annual temperature between 1979 and 2018 is 2/4°C with an amplitude of 11.9. The precipitation average is 614mm a year.

Farm has 430 hectares of cultivated land with 160 dairy cows and young cattle. The arable area covers 330 hectares of different types of grassland and 100 hectares of oats and barley (Figure 24).

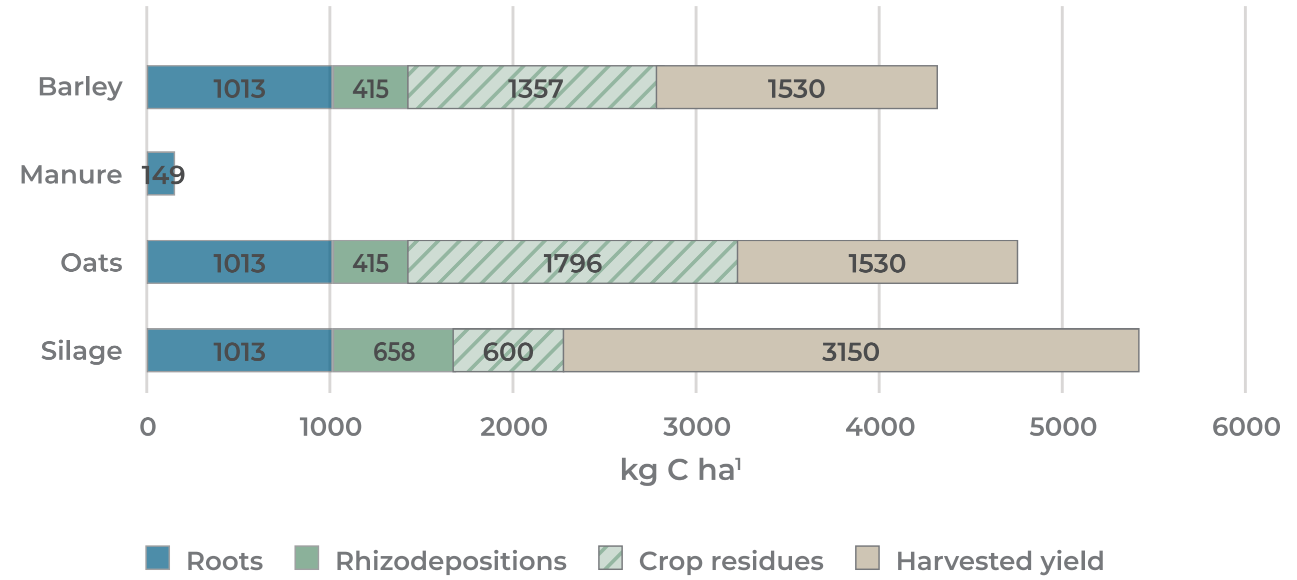

Figure 24. C inputs in current crop cultivation at case farm in Finland.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 575 – 126 kg C ha^{-1}, and across 25 years the annual range is 379 – 83 kg C ha^{-1} (Figure 25).

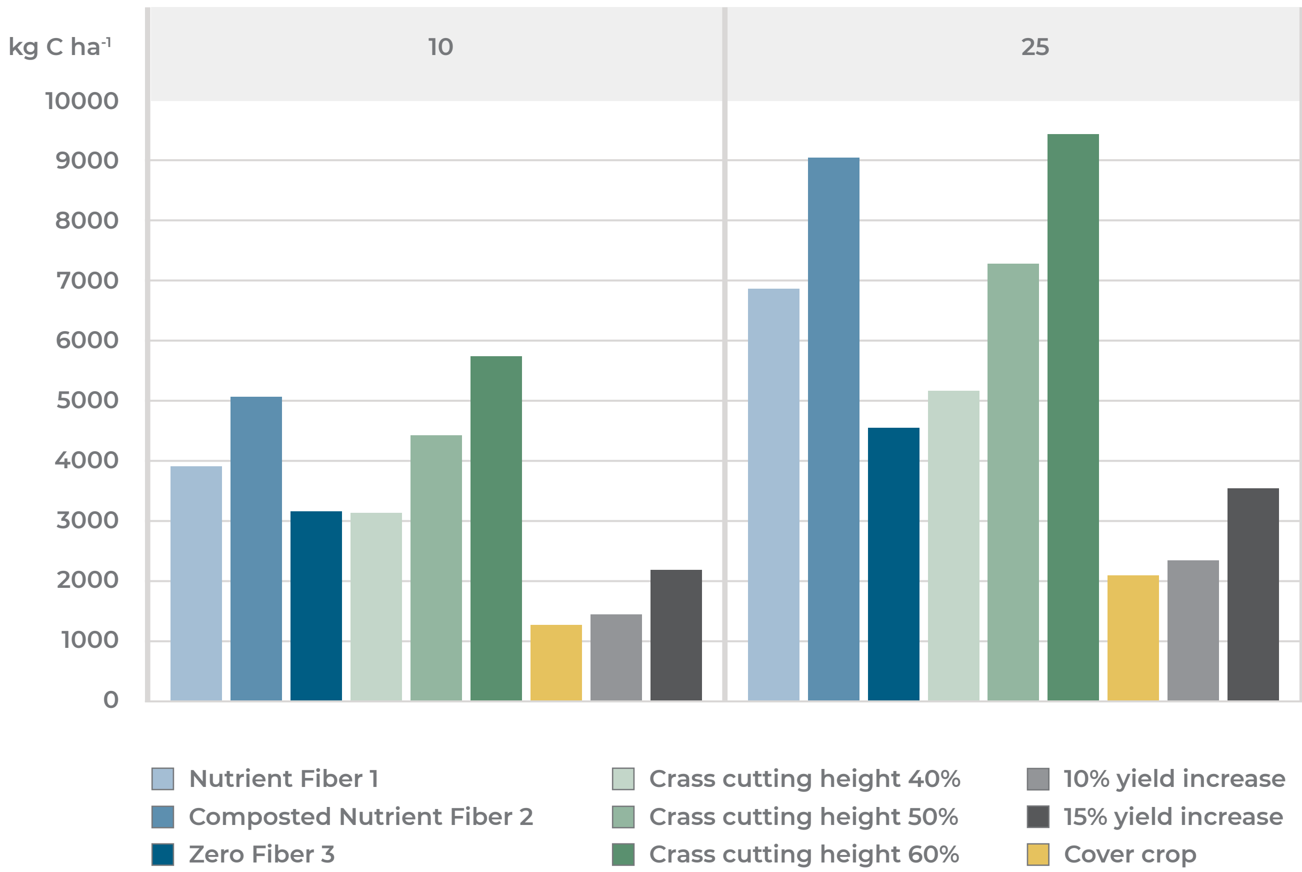

Figure 25. Carbon additionality of different carbon farming practices

Finland V

The average annual temperature between 1979 and 2018 is 3.7°C with an amplitude of 12.65. The precipitation average is 722mm a year.

This farm has been running as a conventional crop farm with cattle since 2002. Previously it was mainly a dairy farm. It has 75 hectares of agricultural land and the current cultivation includes barley, wheat-pea, kidney bean, autumn rye, autumn wheat, and rye (Figure 26). The cultivation cycle is 6 to 8 years.

Figure 26. C inputs in current crop cultivation at case farm in Finland.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 537 – 165 kg C ha^{-1}, and across 25 years the annual range is 375 – 108 kg C ha^{-1} (Figure 27).

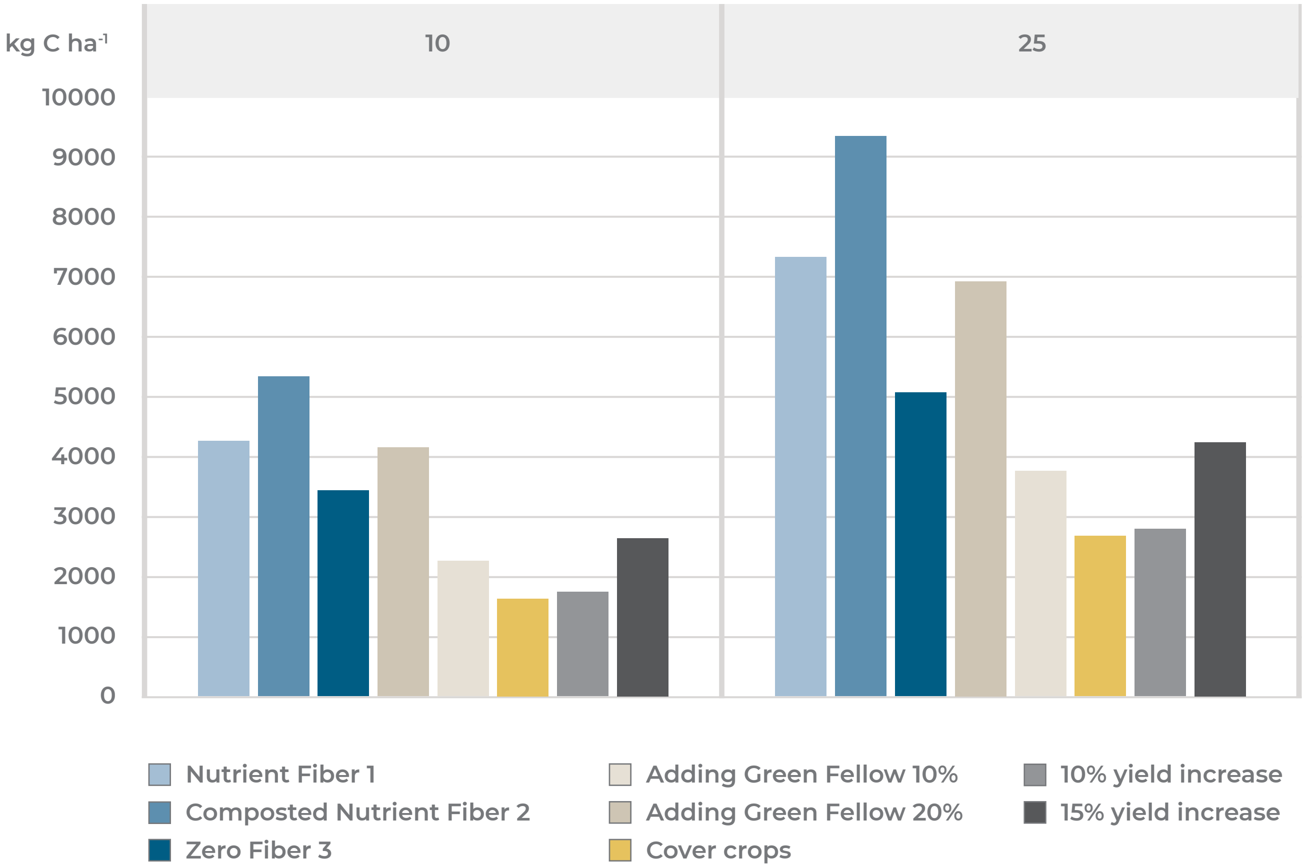

Figure 27. Carbon additionality of different carbon farming practices

Latvia I

This case farm covers over 1400 hectares of agricultural land, runs biogas facility, and carries out forestry. The average annual temperature between 1979 and 2018 is 6°C with an amplitude of 11.3. The precipitation average is 830mm a year.

50 years ago, most of the current agricultural land was peatlands and forests. The farm has been running intensive production since 2006. Before that, it was an extensive pasture for cows. The farm produces maize silage and corn cod silage, winter triticale, alfalfa, and grass mix (Figure 28). The farm has uncultivated overgrown grassland of over 55 hectares. The main type of production is animal feed. The total number of animals on the farm is over 1600 in a year: 380 cows, 480 calves, and 360 heifers.

The farm's biogas production is 500m^3 per hour, with 50 – 55 % of methane.

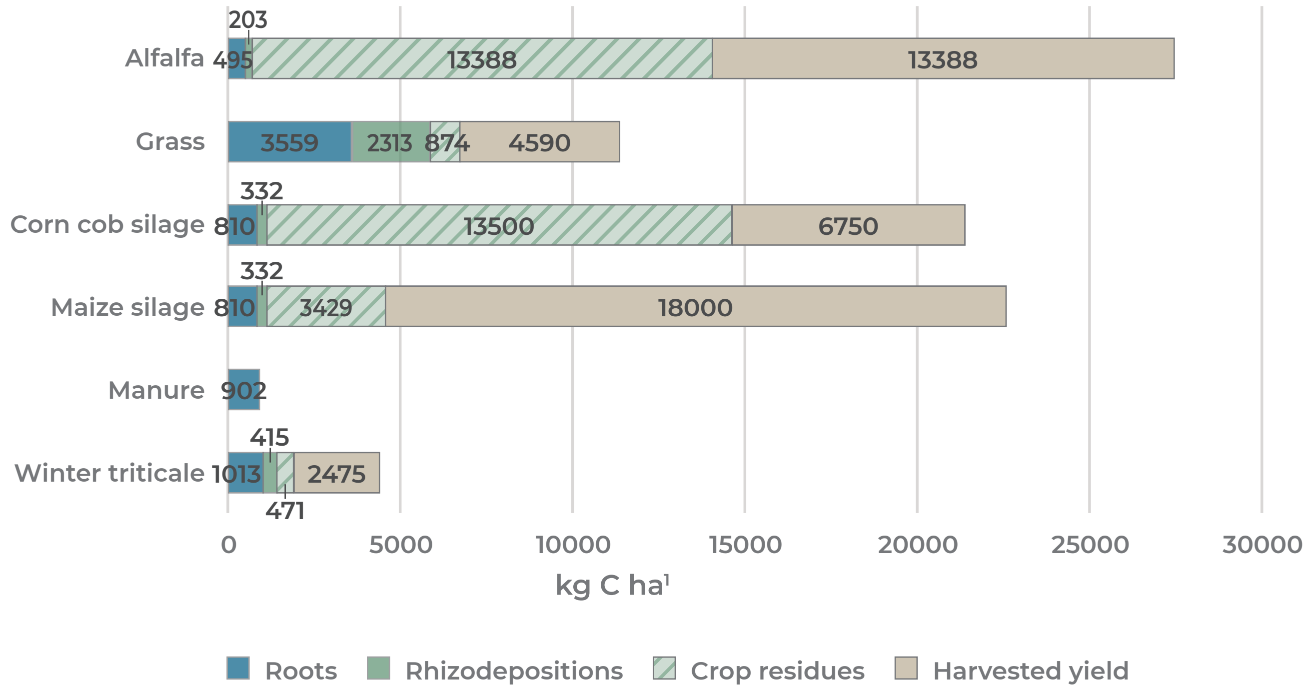

Figure 28. C inputs in current crop cultivation at case farm in Latvia.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 357 – -58 kg C ha^{-1}, and across 25 years the annual range is 235 – -54 kg C ha^{-1} (Figure 29).

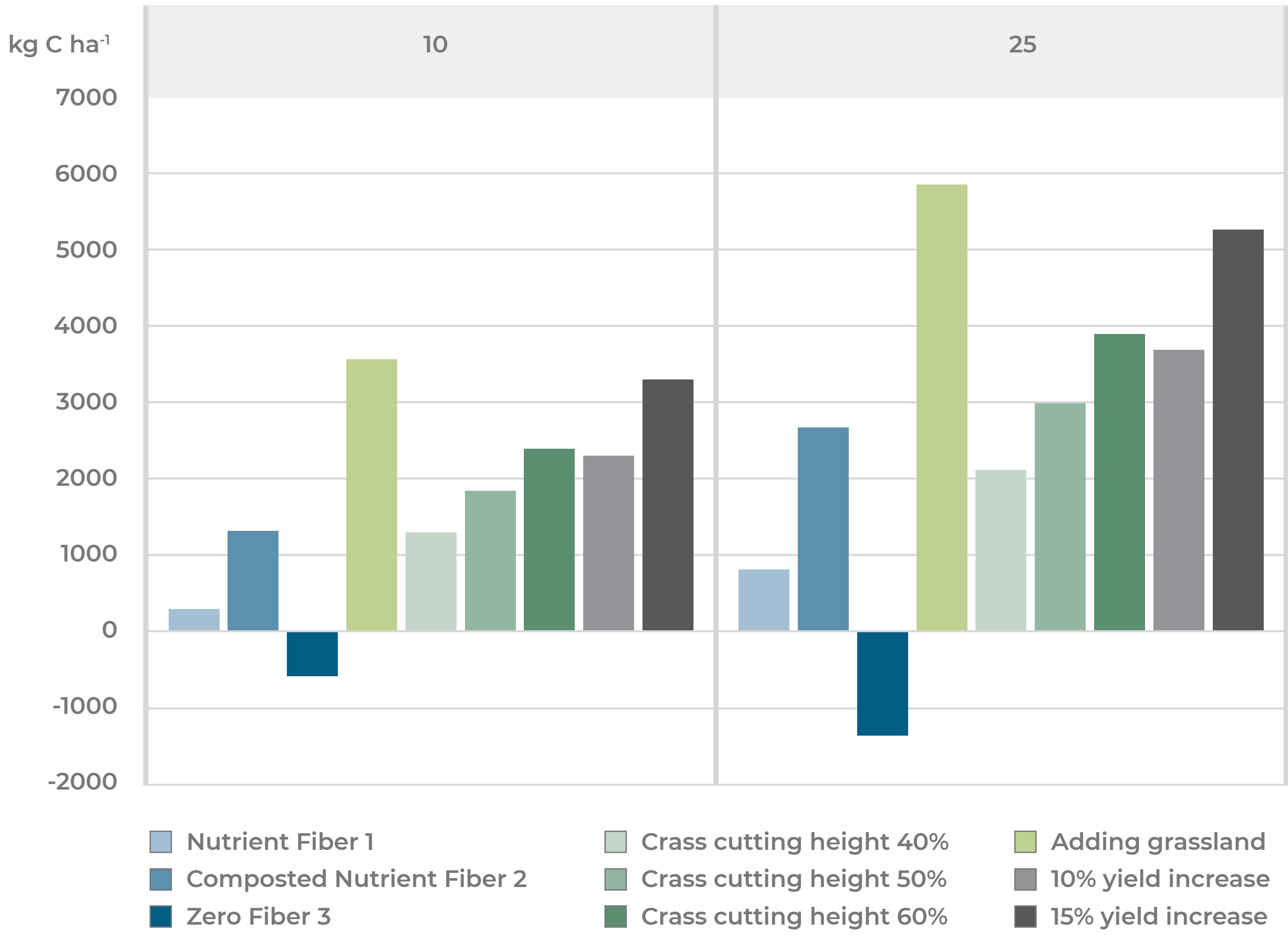

Figure 29. Carbon additionality of different carbon farming practices

Latvia II

Over 400-hectare agricultural farm produces crops for human consumption, animal feed, and biogas from winter rapeseed. The farm has also some 10 hectares of forest. The average yearly temperature between 1979 and 2018 is 6.7°C with an amplitude of 10.05. The precipitation average is 721mm a year.

The arable land has been in use for 100 years. The crop rotation has remained more or less the same during last 5 years with the addition of beans and peas in 2019. The main crops under rotation include winter weed, winter rapeseed, barley, beans, and peas (Figure 30). The wheat and rapeseed are fertilized with natrium, potassium phosphorus, and sulfur.

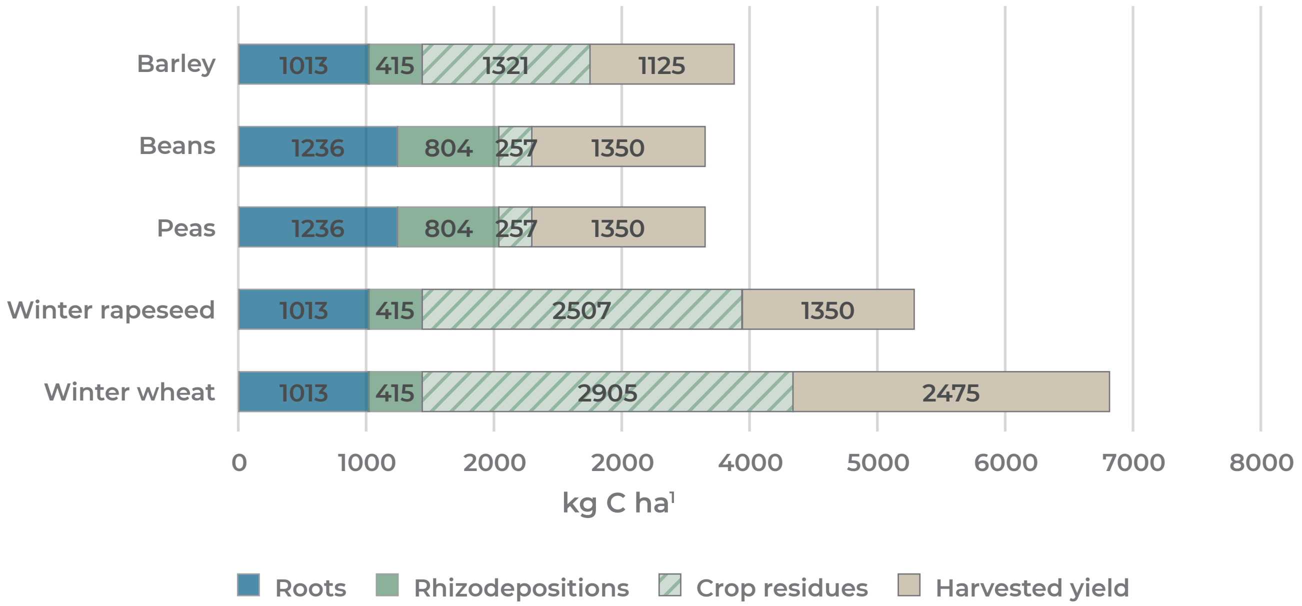

Figure 30. C inputs in current crop cultivation at case farm in Latvia.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 505 – 188 kg C ha^{-1}, and across 25 years the annual range is 349 – 123 kg C ha^{-1} (Figure 31).

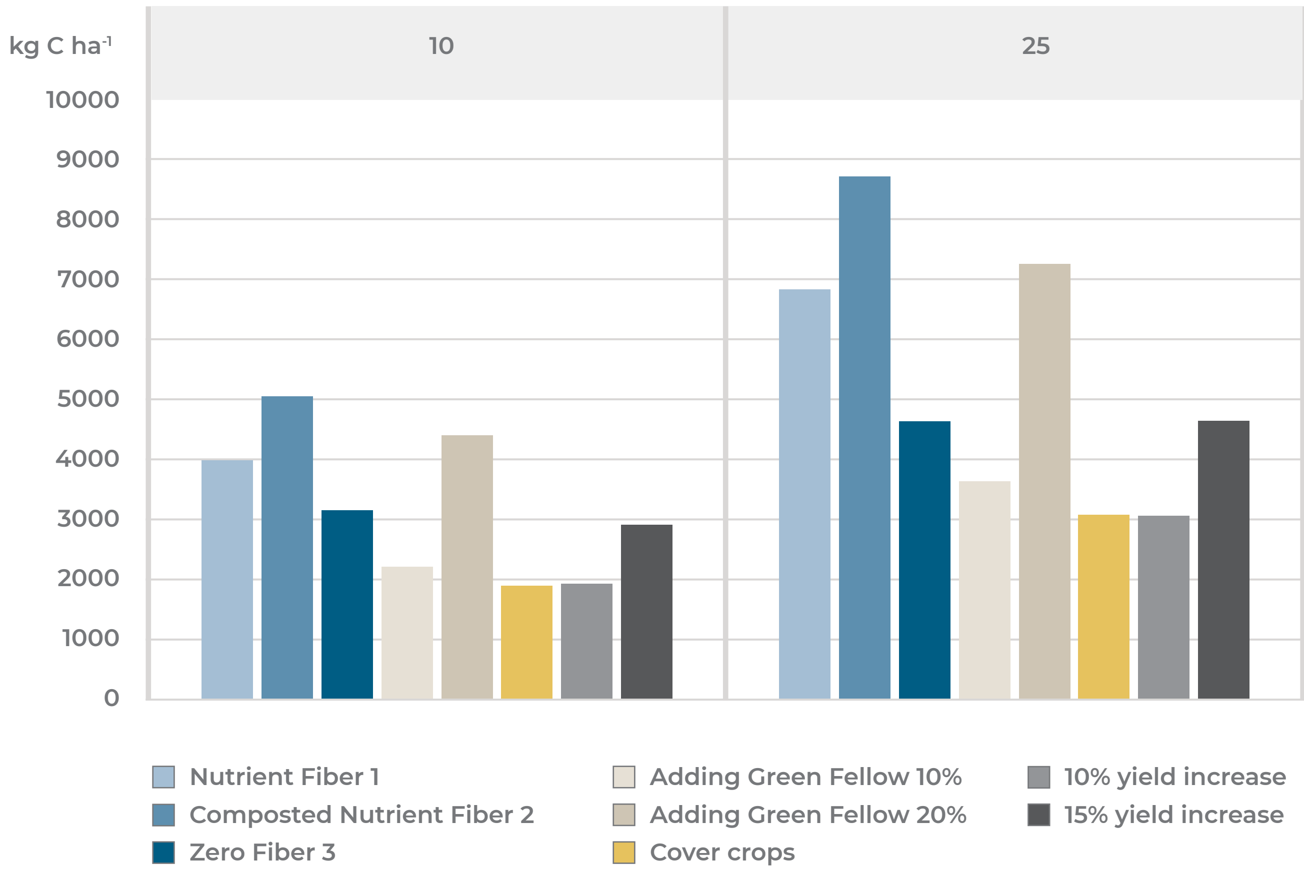

Figure 31. Carbon additionality of different carbon farming practices

Continental

Germany

The average annual temperature between 1979 and 2018 is 9.4°C with an amplitude of 9°05. The precipitation average is 653mm a year.

This conventional farm has 700 hectares of land, and produces 2.5Mw of biogas from corn, chicken manure, and grass silage. The biogas is produced together with 3 other farms in the area. 40% of the production is produced at this farm only from corn.

The area has been used for agriculture for over a thousand years. Crops include winter wheat, canola, corn, sugar beet, potato, and winter rye (Figure 32). The winter wheat, rye, barley, canola, and sugar beet production have been about the same for 20 years. In 2010 corn and in 2016 potatoes were added to the crop rotation. The farming uses various fertilizers depending on the crops rotated.

The area is rich in humus, which is very good for plants, but dry seasons tend to strongly affect the yields. It has been the case in 2018 when massive drought in the area negatively affected the yields (30-40% annual reduction).

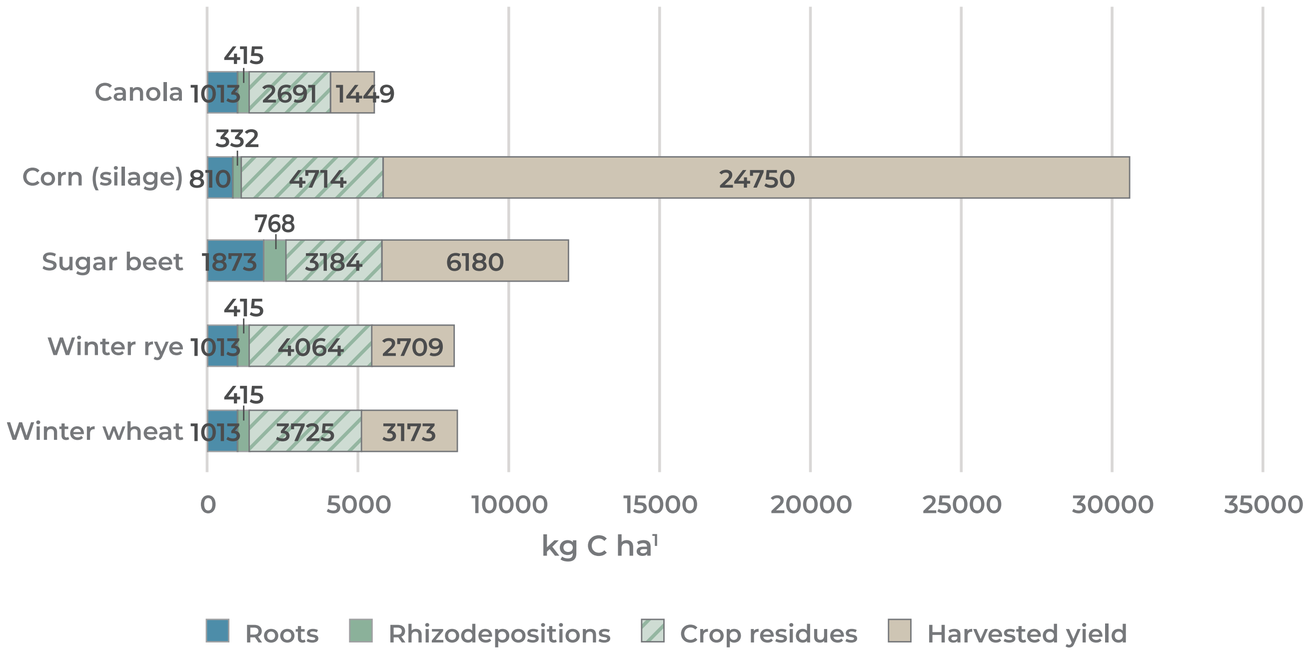

Figure 32. C inputs in current crop cultivation at case farm in Germany.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 485 – 134 kg C ha^{-1}, and across 25 years the annual range is 333 – 90 kg C ha^{-1} (Figure 33).

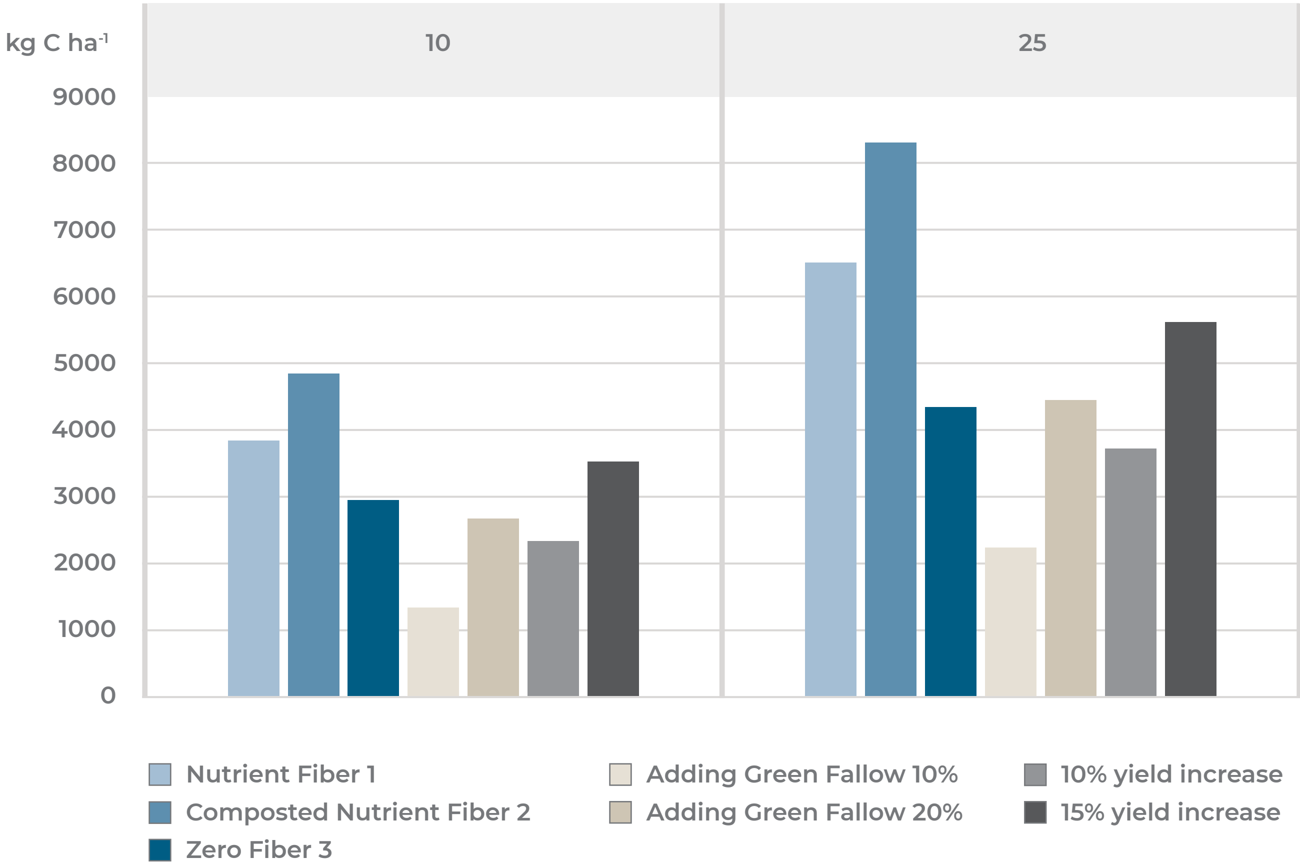

Figure 33. Carbon additionality of different carbon farming practices

Poland

This over 100 years old family farm is located in central Europe. The average annual temperature between 1979 and 2018 is 8.5°C with an amplitude of 9.03. The precipitation average is 809mm a year.

Before 2004 the farm was a conventional farm plowing all types of cereals such as winter crops, wheat, and rapeseed. Between 2004 and 2008, the land was managed with limited tillage, spring crops, and a cover crop of mustard, with shifting rotations of wheat, barley, mustard, lupins, and beans. Currently, the farm has 700 hectares of permanent grassland, exporting hay for animal feed and biomass to Poland and other European countries.

The current permanent grassland is covered by hybrid ryegrass, orchard grass, meadow fescue, and timothy (Figure 34). Half of the grassland is covered by hybrid ryegrass, and the remainder is divided evenly between orchard grass, meadow fescue, and timothy. The permanent grassland is cut at 6 – 10 cm height.

In the future, the farm is planning to cultivate beans, but the main goal is to keep exporting hay and improve the biodiversity. Farmer's own initiatives to improve the carbon sequestration at the farm will be to start using cover crops and raise the groundwater level.

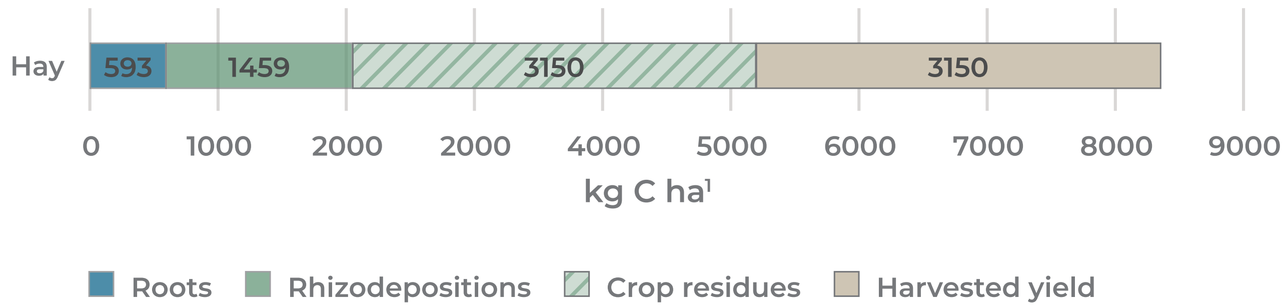

Figure 34. C inputs in current crop cultivation at case farm in Poland.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 666 – 72 kg C ha^{-1}, and across 25 years the annual range is 431 – 47 kg C ha^{-1} (Figure 35).

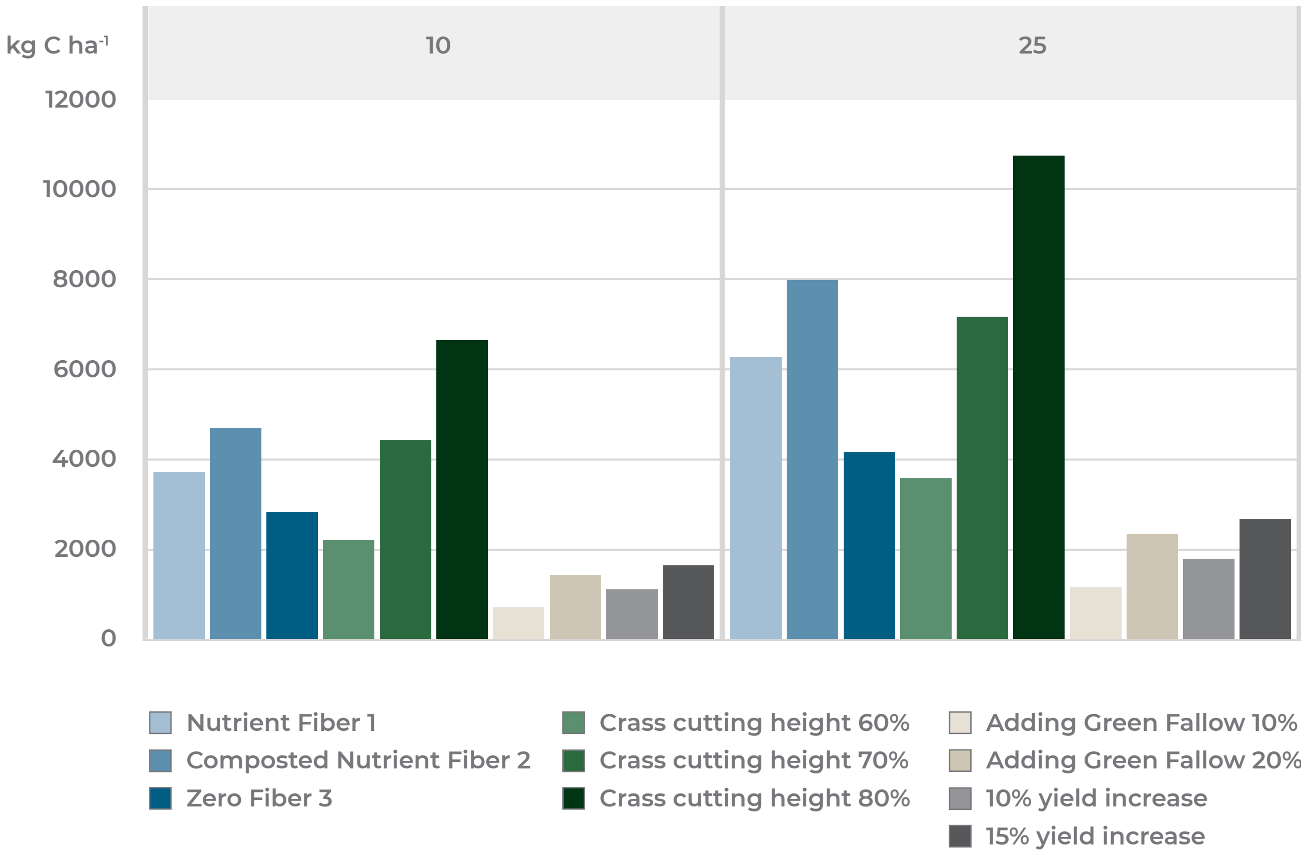

Figure 35. Carbon additionality of different carbon farming practices

Romania

The average annual temperature between 1979 and 2018 is 12 °C with an amplitude of 5.95. The precipitation average is 724 mm a year. Farm's cultivation history dates to 1700s, with various cultivation methods used. Currently the farm is producing hay, corn, wheat, rapeseed, soy, and sunflower seeds.

For the calculations the farm suggested to use 4500 hectares of hay, that includes evenly alfalfa, clover, and grass-clover mix (Figure 36). The hay is 85% dry. Only 50% of the hay has been cut, which has led to higher humus content. This helps the soil biodiversity to remain in a good state. The extreme weather conditions and occasionally mice plagues have been the mentioned as having the most detrimental effect for the yields.

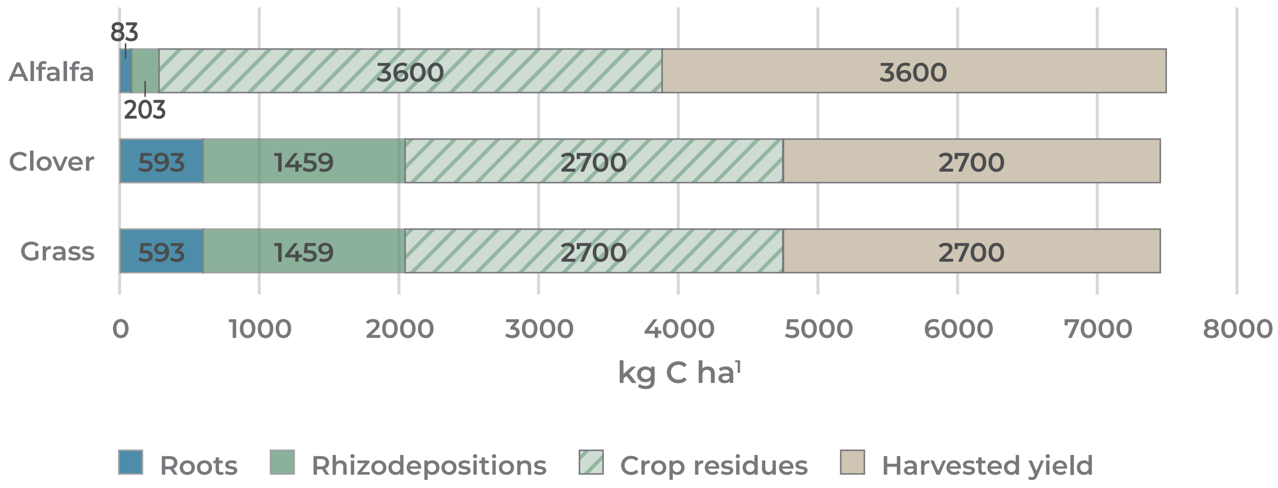

Figure 36. C inputs in current crop cultivation at case farm in Romania.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 448 – 75 kg C ha^{-1}, and across 25 years the annual range is 751 – 48 kg C ha^{-1} (Figure 37).

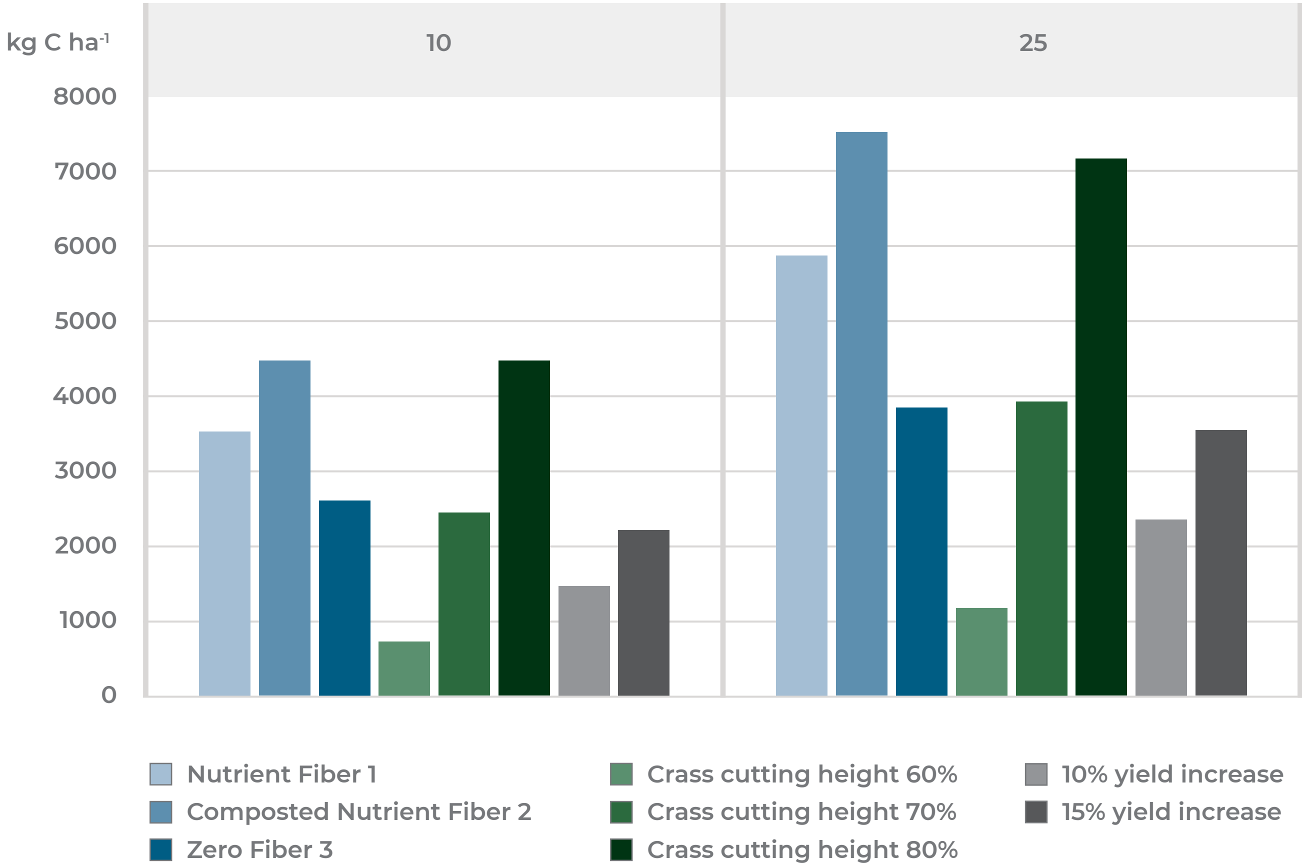

Figure 37. Carbon additionality of different carbon farming practices

Mediterranean

Italy

This organic farm producing vegetables is in northern Italy. The average annual temperature between 1979 and 2018 is 15°C with an amplitude of 10.55. The precipitation average is 675 mm a year.

The land has been always under cultivation. Over 20 years ago the land was used to cultivate fruits and sugar beets. Previously the farm was organic, cropping mainly wheat and forage. Currently the farm mainly produces alfalfa, wheat, and organic vegetables (Figure 38). The total area of cultivation is 500 hectares. Crop rotation involves various vegetables including cabbage, zucchini, pumpkin, green peas, beans, celery, and carrots. Only 20 hectares were used for the calculations, whereof cultivated crops are wheat and vegetables. Manure is used for fertilizing. There are about 2 hectares of land next to the fields that are left to preserve natural biodiversity. In 2020, the farm planted 200 trees there.

In 2015, the organic carbon content at the farm was 1%, with organic matter content of 1.8%. After the farm became organic and started crop rotation, the organic carbon content rised to 2.2%, with organic matter of 3.7% in 2020. The main cause of the increase of carbon content was the shift from conventional to organic and then to biodynamic farming, with a great attention to crop rotation. Use of pesticides and chemical fertilizers has been reduced thanks to increased use of organic fertilizers with manure from laying hens. Other measures included plowing the soil with the machine adjustable for a different soil condition (shoveling machine), secluding protected natural areas for biodiversity conservation, and setting up beehives as an environmental indicator.

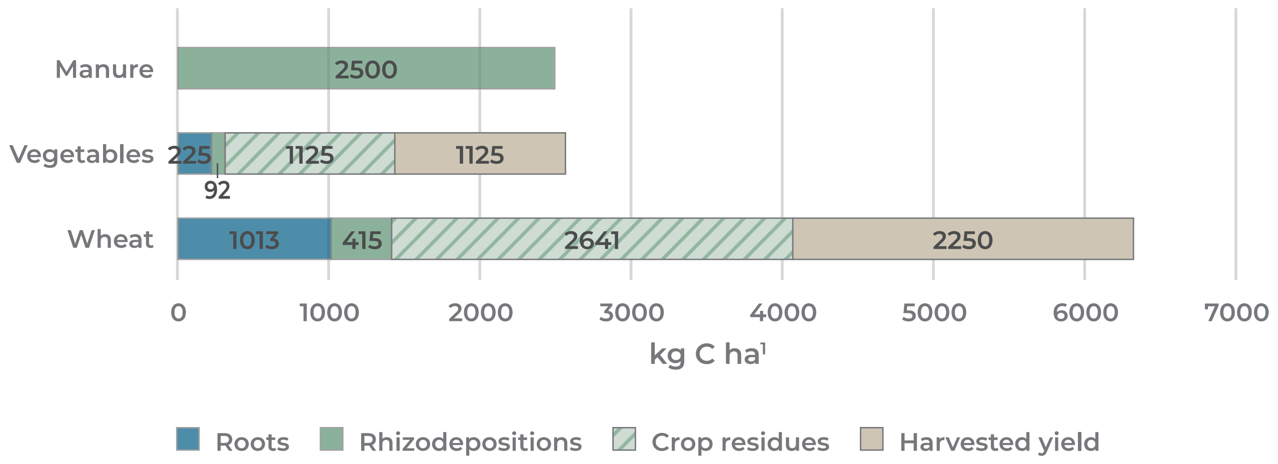

Figure 38. C inputs in current crop cultivation at case farm in Italy.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across 10 years between 383 – -595 kg C ha^{-1}, and across 25 years the annual range is 245 – -384 kg C ha^{-1} (Figure 39).

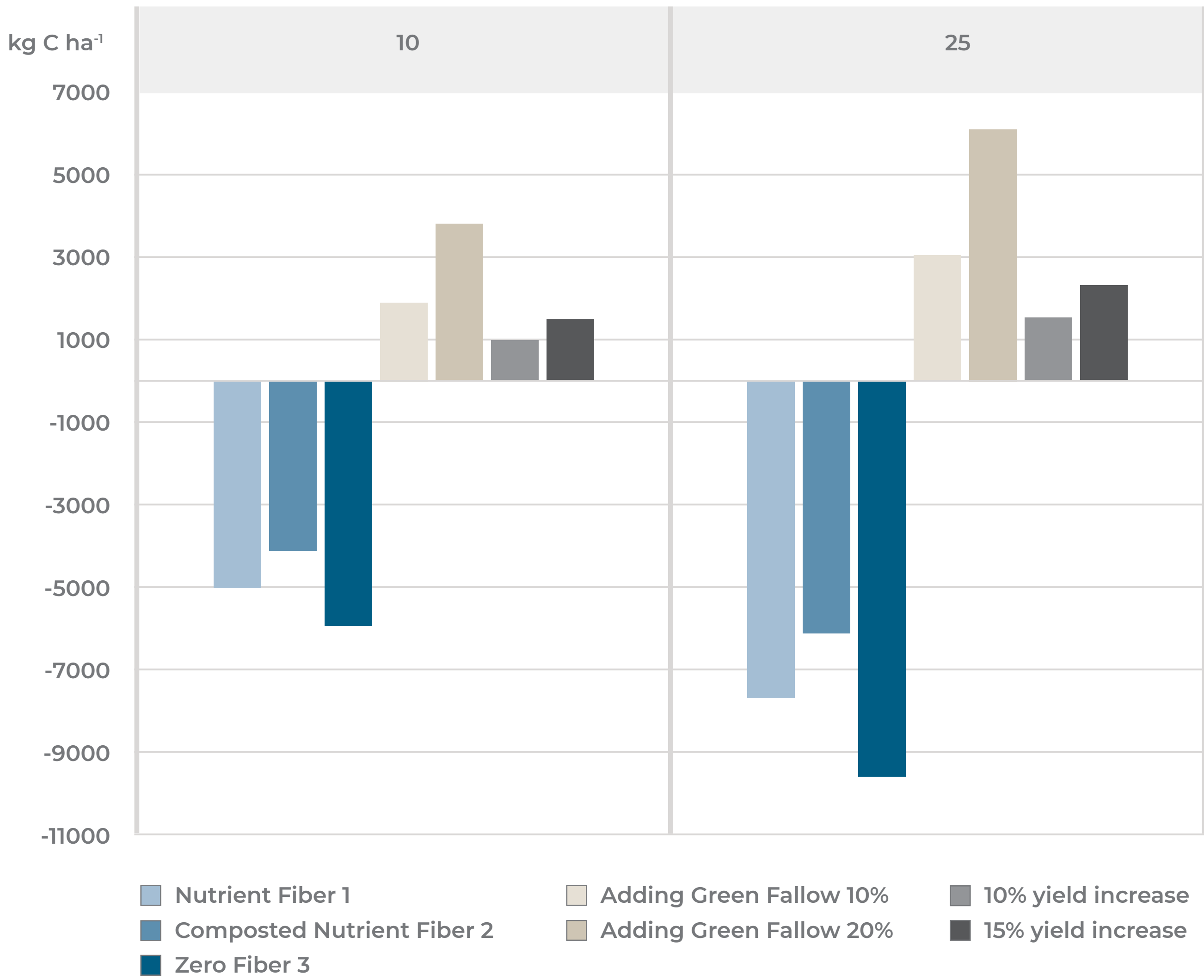

Figure 39. Carbon additionality of different carbon farming practices

Spain

This organic conventional family farm is in Spain. Farm has 99 hectares of land to cultivate hay, cereals for animal feed, and legume for human consumption. The average annual temperature is 15°C with an amplitude of 8.35. The annual precipitation average is 556mm.

The land has been used for agricultural purposes for over 40 years, and for 18 years it has been organic. The farm uses crop rotation and practices different methods to boost biodiversity such as mulching and cover crops. These methods are conducted on smaller areas (1-5 hectares) due to weather conditions that are making them difficult to expand. Yearly yields are heavily dependent on precipitation and can vary by +/-1000 kg/ha. The production contains chickpea, lentils, cereals, and hay (Figure 40). Farm's yearly average hold of cattle is 17 cows, 1 bull, and 15 calves. The cattle manure is used for fertilizing.

The farm wishes to improve soil health and biodiversity. The intention is not to solely capture CO^2.

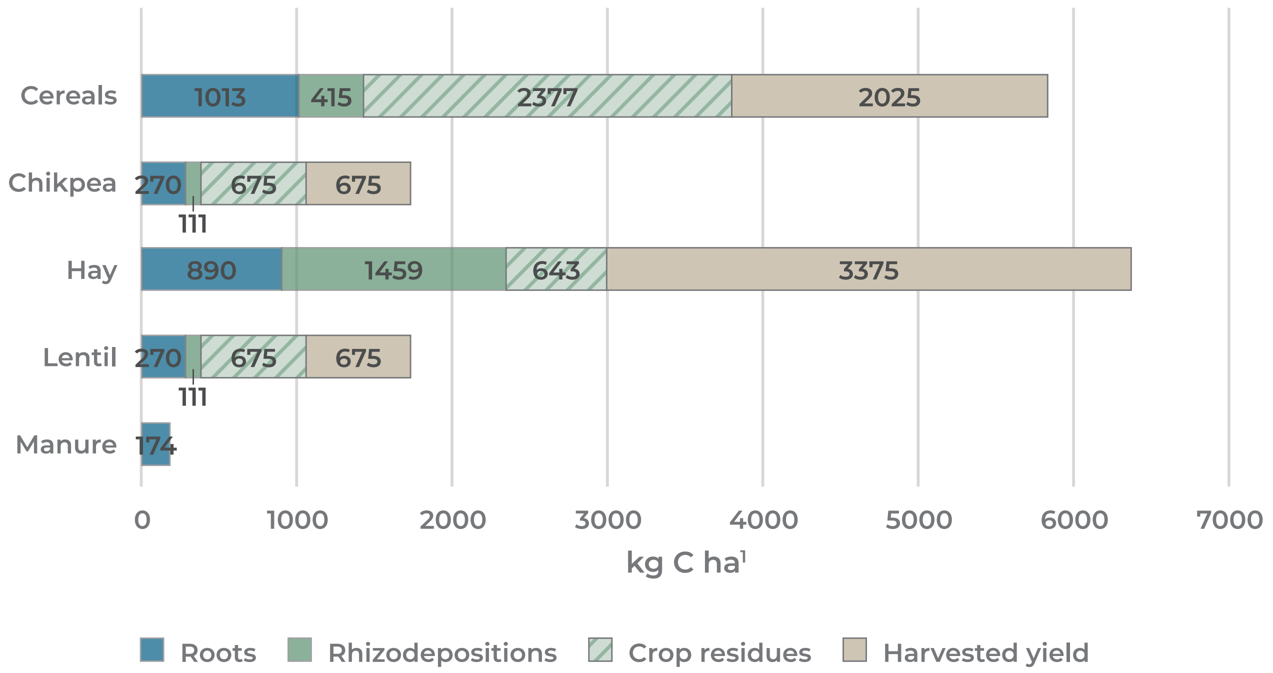

Figure 40. C inputs in current crop cultivation at case farm in Spain.

The annual carbon increment between different carbon farming methods varies (creating carbon additionality) across10 years between 387 – 86 kg C ha⁻¹, and across 25 years the annual range is 262 – 55 kg C ha⁻¹ (Figure 41).

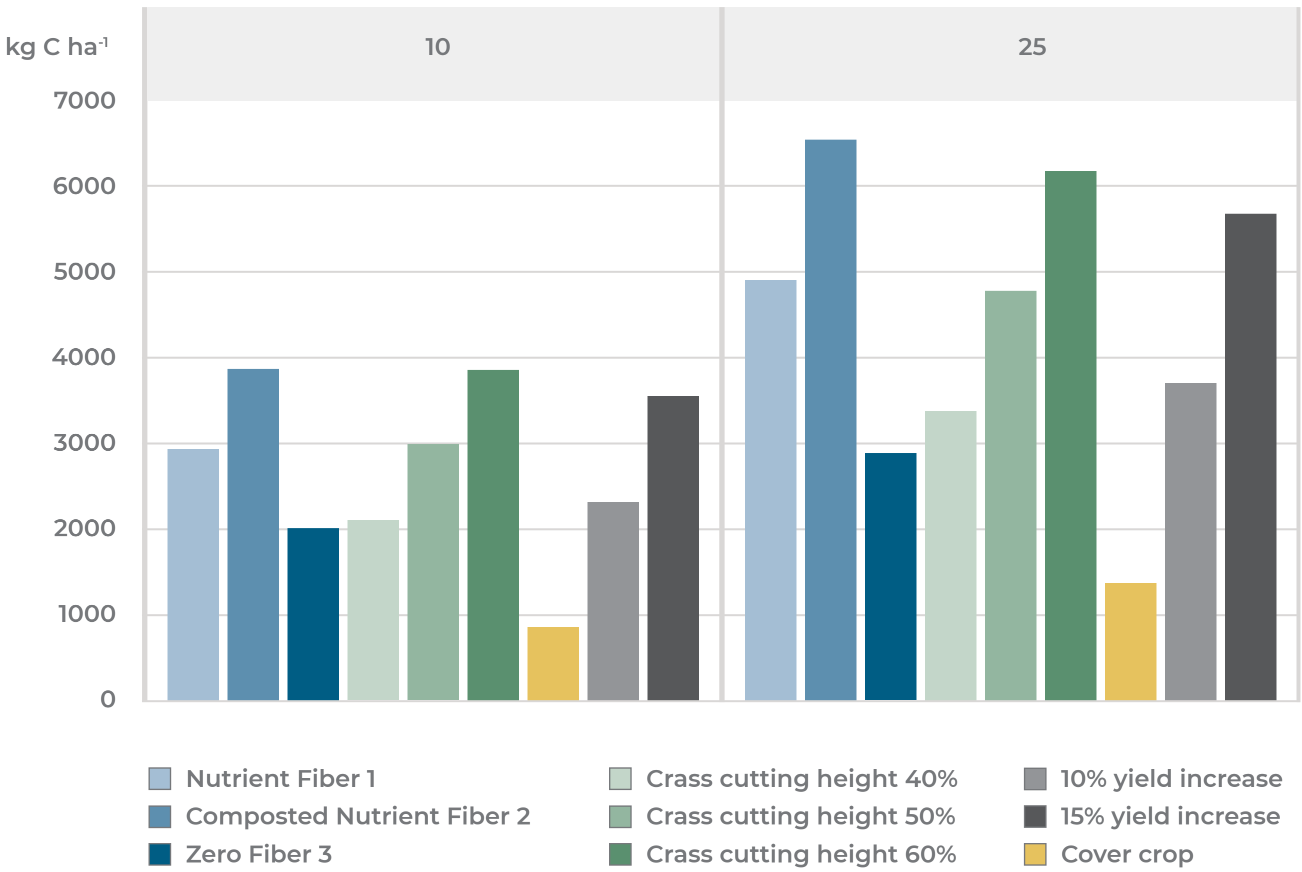

Figure 41. Carbon additionality of different carbon farming practices

4.2. Carbon sequestration potential of carbon farming practices in the forestry case farms

A total of eight forestry farms were interviewed in in the context of their land use and economy. The data was obtained in versatile forms and the forecasting ability varied between farms. The most detailed information was available from two large Finnish farms, one in the north and another one in the south of the country. The stand level carbon accumulation could also be calculated on one Estonian farm and one experimental farm created artificially based on the National Forest Inventory (NFI) measurements (Forest resources LUKE). The total land area of the two Finnish farms was 6512 ha and it consisted of 4993 forest compartments.

During the interviews, we have learned that a thorough discussion and planning activities are still necessary, if the aim is to enhance reforestation and growth of present stands. There is a lot of room for advice from forestry professionals experienced with preparation of the forestry plans and thereby management of forest C stocks. Furthermore, when it comes to the quantification of C stocks and stand growth there is a need for more accurate measurements.

4.2.1 Description of the baseline and estimates of additional forest growth

Farm in southern Finland

The farm in southern Finland consisted of 2830 forest compartments with total area of 2743 ha. The landowner selected 134 compartments to be fertilized based on their suitability. The former annual growth ratio of these selected stands was 684 m^{-3} a^{-1}, and the additional growth gained through the fertilization was 307 m-3 a-1. During a 10-year period, the additional carbon accumulated thanks to the fertilization would have been 690 t C.

On the whole farm level, the annual average growth was 5,6 m^{-3} ha^{-1} a^{-1} and average additional growth thanks to the fertilization stood at 2,67 m^{-3} ha^{-1} a^{-1}. Based on these values it was calculated that the annual growth of all 2830 stands was 15303 m3 (3440 t C), and the additional growth thanks to the fertilization amounted to 7540 m3, corresponding to 1700 t C.

The calculated average additional growth gained through the fertilization during a 10-year period was 17.5 m^{-3} ha^{-1}. When we simulated the growth response with a forest simulator Mela we got an estimate of 14.9 m^{-3} ha^{-1}. The analysis of the accuracy and representativeness of modelled forest growth is important in a sense that this type of models would provide a cost-efficient mean to calculate the effect of different forest practices on carbon accumulation.

Farm in northern Finland

The farm in northern Finland consisted of 2163 forest compartments with total land area of 3769 ha. The annual total stem growth was 8623 m^{-3} ha^{-1} a^{-1} and the annual growth rate 2,29 m^{-3} ha^{-1} a^{-1}. The additional average growth rate obtained by fertilization would be 1,06 m^{-3} ha^{-1} a^{-1}. If all forest compartments were fertilized the additional annual amount of accumulated carbon would be 865 t C. We also forecasted an annual forest growth with use of a Mela forest simulator. In this case, the model overestimated the fertilization effect (Figure 42 ab) giving an annual effect of 1.54 m^{-3} ha^{-1} a^{-1} (total of these two methods being during a 10-year period 6.1 and 9.2 m^{-3} ha^{-1}).

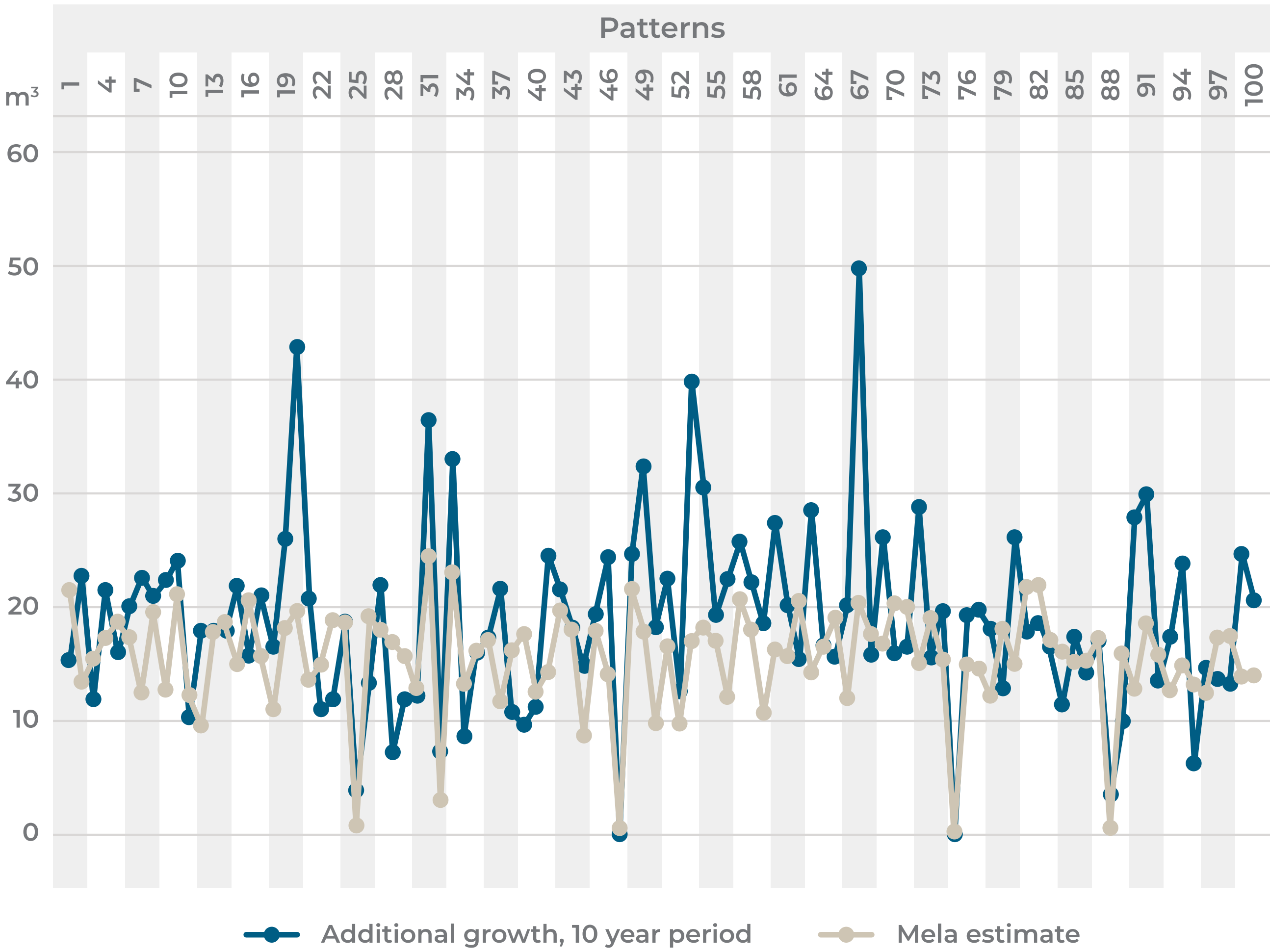

Figure 42 a. The additional growth gained through fertilization calculated and estimated with use of MELA model, based on the example of 100 compartments from southern Finland.

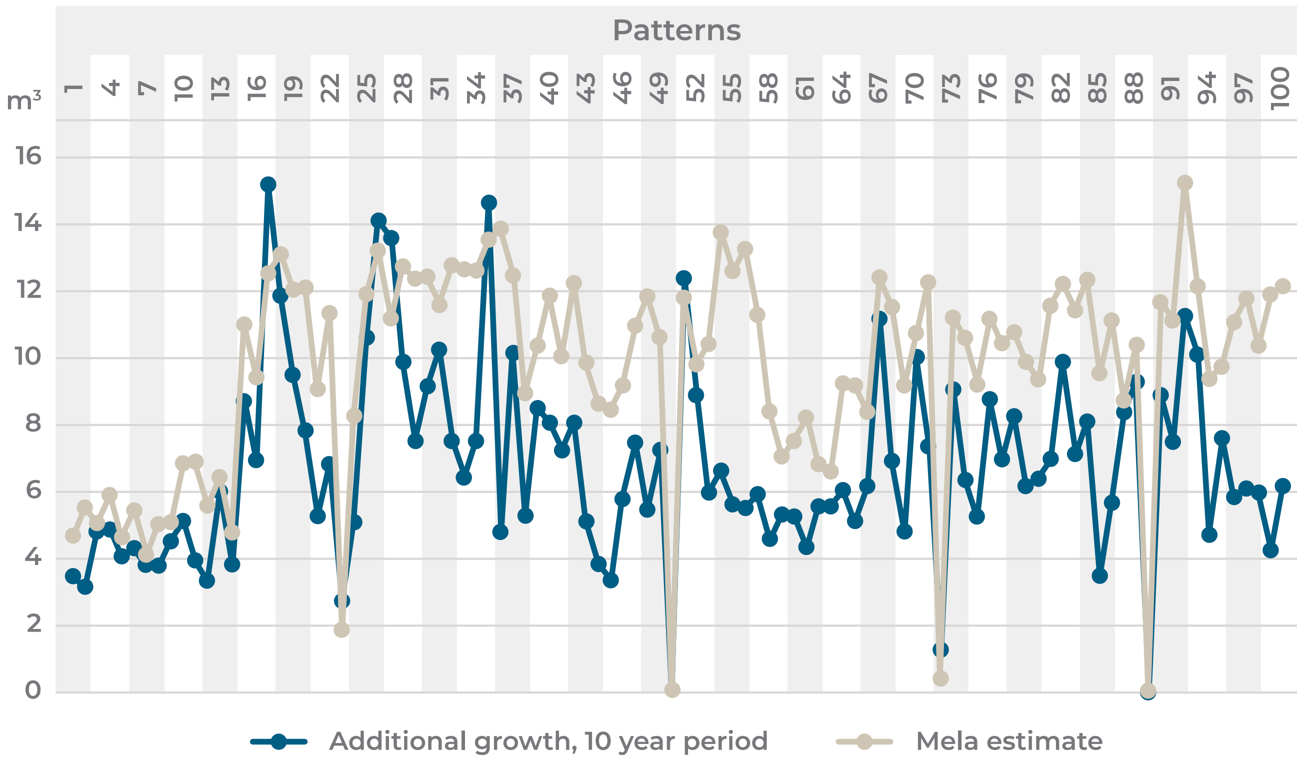

Figure 42 b. The additional growth obtained through fertilization calculated and estimated with use of Mela model, based on the example of 100 compartments from northern Finland.

Farm in Estonia

The total forest area of the Estonian farm was 32.53 ha, consisting 48 compartments. An estimate of the present stand growth of each compartment was available to be obtained from the farm.

The total volume of the stands was 7172 m^3 and the estimated annual growth stood at 146 m^3. If this value was used to estimate the growth of coming 10 years, we would get 1460 m^3 in total.

Based on the site characteristics and stand age we selected for the fertilization 21 compartments of the total size of 22 ha. In the upcoming 10 years, the estimated additional growth there would be 334 m^3, corresponding to 75 t C.

Case study: South-Savo – artificial experimental forest farm

From the silvicultural methods especially fertilization and the use of improved seedling material are effective means to increase tree growth and carbon accumulation in forests. The response of the stand growth to the fertilization is rapid but lasts for a limited number of years. The effect of improved seed material is long lasting but materializes only in the long run (decades).

In this case study, we examine through scenario analysis the effects of silviculture, especially fertilization, on the carbon accumulation. As an example, we present the carbon sequestration potential of an artificial forest farm expected to be located in South Savo, Finland.

The trial farm was established as an average representative farm based on data obtained from National Forest Inventory (NFI 11). The area of such farm is 32 ha, which corresponds to the average size of privately own forest estates in that region. Site type, tree species and age distribution are also typical for the area. The calculation was firstly done at a regional level and then transformed to represent a fictional farm. In the calculation we presented the carbon sequestration potential differentiated by types of forests and varying extent of silvicultural practices implementation.

The main lines of the calculation

The future development of the forest stands is extrapolated with the Motti forest simulation program (Hynynen et al.) and the calculations are based on the present forest characteristics.

The simulations were carried out assuming alternative stand treatment chains agreed upon in advance. The chains are specific for the site type and tree stand properties and vary substantially in terms of intensity and timing of harvests and other silvicultural operations.

Within each scenario an optimal solution for each stand (one chain of silvicultural means) is selected based on the linear optimization. At a district level, we analyzed two different forest use scenarios:

Business as Usual (BAU), where the extent of silviculture and harvests remain as they are and CARBO, which introduces a set of silvicultural means to increase carbon accumulation.

A forecast of harvesting potential as well as carbon sink and C storage changes over a 50-year perspective was performed. The forest district level survey covers the forests which are used for timber production (c.a. 90 % of all forests) and the use of which is not restricted by other obligations.

The C storage includes the above- and below ground-carbon storage in living and dead trees.

Calculations for both scenarios

The future growth of measured stands was simulated with Motti simulation program following several alternative silvicultural treatment chains.

In CARBO scenario one treatment chain was selected for each stand. Stand development, harvest yields, biomass, and carbon content of those were calculated, and scenarios were compared. Additionally, the amount of soil carbon was estimated.

The change in the amount of carbon stored in soil was estimated following the rules of the national greenhouse gas inventory report. The calculation applies the area of forests, stand volume, natural drain, and logging residues. The baseline value of the soil C storage is assumed to be on the average level for southern Finland. The estimations of changes in soil carbon were performed with use of Yasso07-soil model.

Simulations by scenario

In BAU scenario, current level of harvesting and other treatments, based on the available statistics, is to be maintained in the future and so are treatment areas and methods used.

In CARBO scenario the level of harvests remains the same (like in BAU). The carbon accumulation is increased by fertilization and prolongation of the rotation period (Figure 43 and 44).

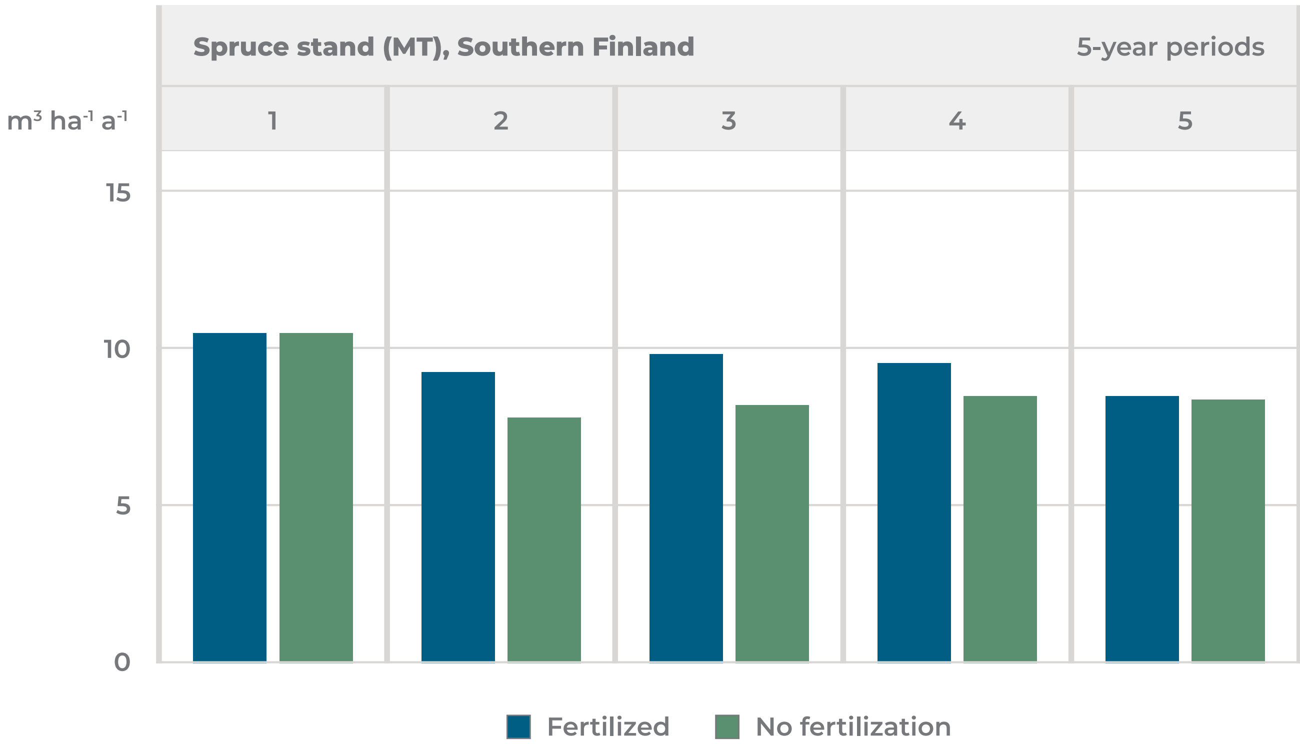

Figure 43. The annual average growth of the stands at the experimental farm in South Savo. These are the results of the case 1, where the starting point was the properties of the forests before thinning. Thinning was then done in the beginning of the first 5-year period in both fertilized and non-fertilized treatments. The fertilization was done in the 2. period, 5 years after thinning.

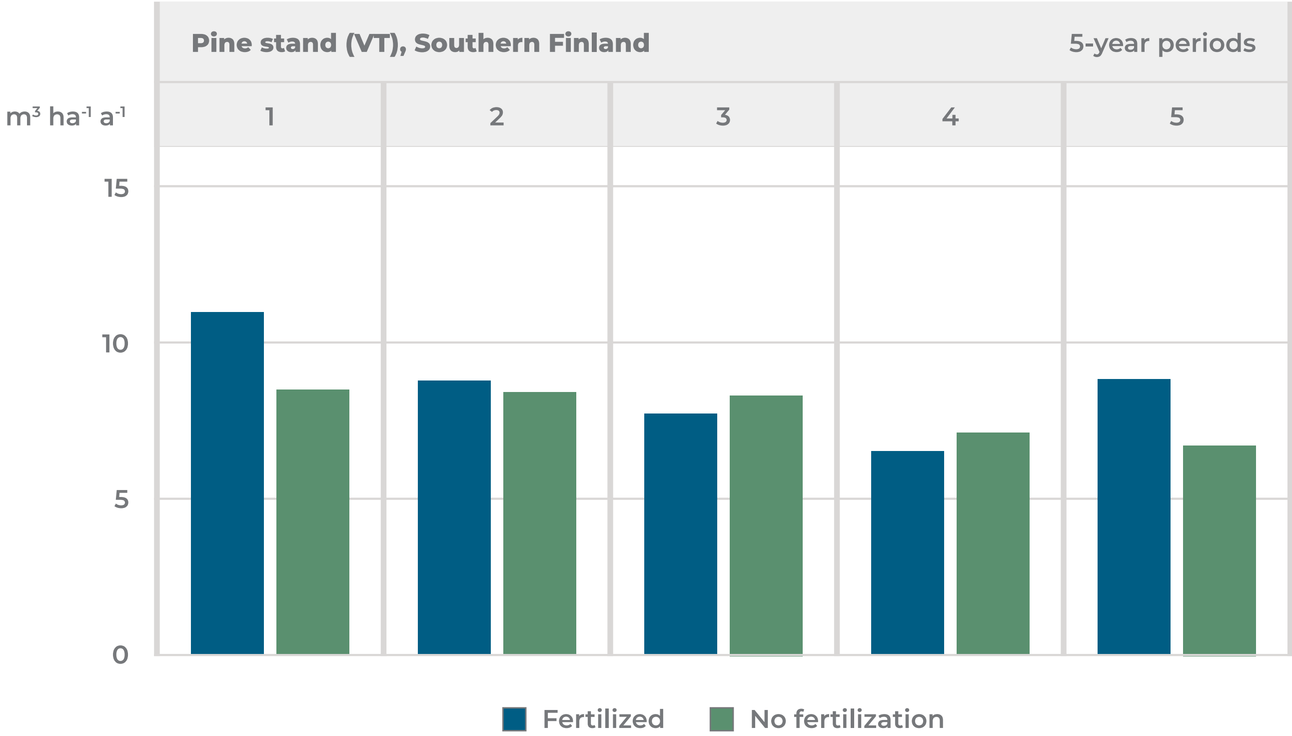

Figure 44. The annual average growth of the stands at the experimental farm in South Savo. In this scenario the forest has been thinned recently. The fertilization was done during the first period (5 years after the thinning). The second thinning was done in period 3 and another fertilization in period 4. The non-fertilized stand was thinned in period 4.

For the following five forest farms methods to sequester additional carbon were not found due to the lack of information such as forestry plan or suitable growth models.

Atlantic

Ireland

Forest farm is located in Ireland. The average annual temperature between 1979 and 2018 is 9.9°C with an amplitude of 9.5. The precipitation average is 1118mm a year.

The total area of the forest is over 10 hectares. The main tree species are beech, ash, and sycamore. Most of the trees are 25 years old. In 2009 beech and hazel trees were planted in a smaller area. A small mixed forest containing Norway maple tree, wild cherry tree, Spanish chestnut tree, and birch was planted in 2009. The farm has faced problems with ash tree diseases in the last years.

Boreal

Finland

Total forest area of the farm is around 50 hectares. Forest compartments represent different types of growing forest, mainly on blueberry-site type lands (Cajander 1926). Forests are treated with use of conventional methods. The aim is to optimize the economic wins, C stock, biodiversity, and improve recreational values.

Latvia I

Different kinds of deciduous forests are spread over 350 hectares. The forest information was collected from the area of 20 hectares. From this area, the main tree species are white and black alder, birch, and spruce. The age of the trees in these stands varies between 1 to 28 years. Overall, 50% of the forest is young (1-15 years old), 35% is between 15 and 30 years, and the remaining 15% is older than 30 years. The good care, including weeding the area around the seedlings of the recently planted stands is important in respect of the future carbon sinks. In this oldest set of stands, the prolongation of the harvest interval is an option to retain C storage in the stand. The fertilization of alder stands with nitrogen is not useful, because alders are nitrogen fixing tree species.

Latvia II

The main tree species in the forest are birch, spruce and two alder's species. The age of the forest is in between 25 and 85 years, with the mean value of 70 years. The common practice is not to fertilize birch stands. In principle, the mixed spruce-birch stands could be fertilized to increase growth and following carbon sequestration, but the response of the trees growing on fertile sites to additional nitrogen is not high. The possible result of potassium, magnesium and phosphorous fertilization is not known. Alder is a nitrogen fixing plant therefore addition of nitrogen in the form of fertilizer is not a suitable mean to increase tree growth of these stands.

Mediterranean

Italy

The total area of the forest stands is slightly above 390 hectares. They are divided into hardwood coppice and softwood forest, both seeded only naturally. The larger hardwood forest includes various tree species from age 0 up to 45 years. The forest growth capacity between different forest stands is 2.4 – 6.1 m^3 per hectare annually. The softwood forest accounts for only 30 hectares but contains various tree species between 35 – 80 years old, with a growth capacity of 3.8 m3 per hectare annually. The altitude of the forest is between 90 – 858 m above sea level. None of the forests are fertilized while the soil types are calcium cambisol and calcium regosol.

5. Discussion

In general, the project was welcomed by farmers. Most of the organizations that we contacted have been interested in collaboration. Discussion has related to calculation methodology, carbon farming practices which are feasible at the farm level and carbon trading solutions. Most of the farmers are familiar with carbon farming what may be a result of their connections with climate-smart organizations and other related projects. Soil carbon sequestration is considered a win-win strategy, improving soil growing conditions and biodiversity, alongside climate change mitigation. From a farmer's point of view, these benefits are often more important than income from carbon trading. Improved soil growing conditions directly increase crop yields and stability of cultivation. As climate change is expected to cause more disturbances in the future, such as extreme weather events and market disruptions, carbon farming practices support adaptation and promote the transformation of agricultural systems towards more sustainable state.

The case farms represented different production sectors, methods used, and sizes from various parts of Europe. In the calculations, we have aimed to consider individual characteristics of each farm and suggest carbon farming practices that are practical and feasible.

Out of the different carbon farming practices, the influence of adding soil amendment fibers on SOC stock is the most reliable in terms of measurement, since only the information on the amount of product used is sufficient to make the assessment.

Most of the suggested carbon farming practices can be combined at farm level. Improved crop rotation, increased vegetation cover, and soil amendment can provide notable co-benefits for farmers, such as improving yields, stabilized over the years.

Empirical estimations for baseline and additionality are time-consuming and expensive to carry out. Modeling offers possibilities to assess roughly the carbon sequestration potential of different carbon farming practices. It is however good to be aware of certain limitations concerning modelling. The estimations of C inputs are based on information regarding crop yields. The actual above- and below-ground biomass allocated to soil is difficult to estimate. In this study, C inputs are estimated with the information provided by the farmer and from literature. The calculation is based on a mathematical formula embedding harvested crop yields. Precise measurement of (especially below-ground) biomass is still limited which increases uncertainty. Literature values are used in the calculation for those indicators, which are difficult to estimate at farm level, such as dry matter values, harvest index, shoot to root ratios, carbon concentrations of different crop parts, and AWENs fractions of different crops. Additionally, the model does not incorporate cultivation practices, which strongly affect the decomposition of organic matter and thus the development of soil C stock.

In real life, the soil C stock varies spatially a lot. In case of lower soil C stocks, the achieved additionality resulting from certain carbon farming practices is higher compared to higher soil C stocks (Figure 45). Consequently, for those farms having already carbon farming practices implemented on their farm, it would be more difficult to achieve carbon additionality compared to those having lower initial soil C stock. If the compensation would be based on management practices, the farmers that have already performed those would be rewarded for doing climate-smart actions, even though the achieved carbon additionality might be somewhat lower compared to the other farms. On top of that, soil C stock rates are also influenced by soil type, temperature, and precipitation.

Our calculation is confined to assessing the potential to increase soil C stocks through implementing carbon farming practices. We did not examine carbon balance at the farm level or consider the impacts on other emissions from the farm which could result from changing farming practices.

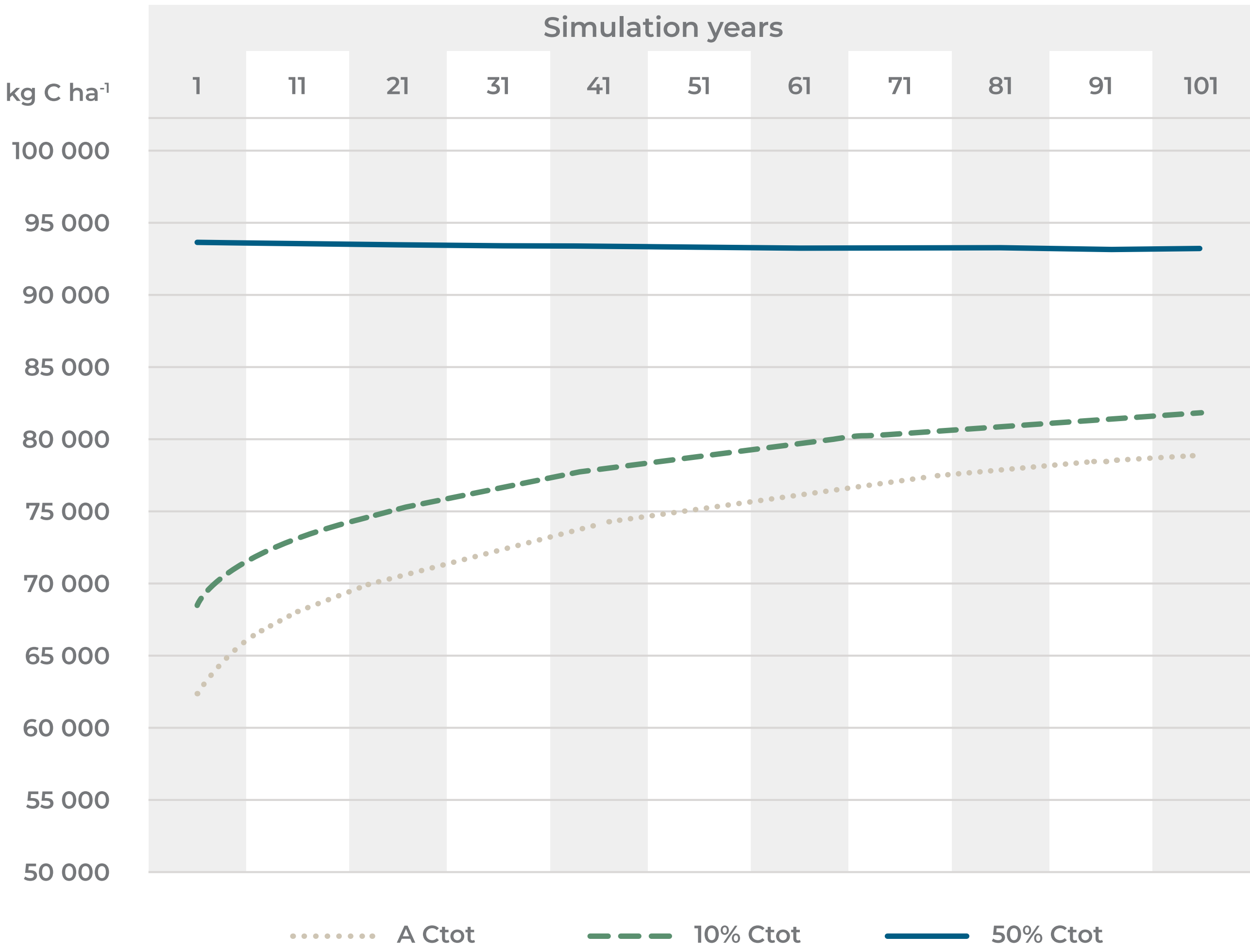

Figure 45. The impact of different soil C stock rates in the baseline on the additionality of carbon with the same carbon farming practice. The dotted line represents the lowest baseline situation with the highest carbon sequestration potential. The dash line represents a situation where the soil C stock is 10% higher in the baseline than in the case of the blue line, and the solid line a situation where the soil C stock is 50% higher in the baseline.

In the forest farms the means to gain additionality are scarce in the areas, where the fertilization is not an option. This holds true for the most part of Europe, where the forest stands are not nitrogen limited. In the Northern Europe the fertilization is a method that gives a fast and repeatable growth response. In some areas re- and afforestation can increase in a long run the C storage in forest stands. Increasing the rotation period of stands can increase the standing tree biomass, but not necessarily the carbon sinks.

6. Conclusions

Carbon farming practices were found to promote climate resilience feasibility on farms. A combination of carbon farming practices would maximize the achieved addition of carbon in soil and provide notable co-benefits for farmers to improve their adaptation to climate change. For farmers, the benefits for climate and soil health were more important than income from potential carbon trading.

The assessment of the additionality in the SOC stock through implementing carbon farming practices is the most reliable for these practices for which the C inputs allocated to soil can be credibly estimated.

We consider the potential for carbon sequestration as higher for farms, which are yet to implement carbon farming practices, compared to farms that have already done it. This should be taken into account when defining the baseline for the calculations. Taking care of the high C storage would also prevent carbon emissions from these stocks spurring to maintain carbon in the soil.

For all carbon farming practices, carbon sequestration advances most quickly during the first 10 years after the introduction of the new carbon farming method. The rapid decomposition of carbon in the soil requires maintenance of carbon farming practices on the farm to keep carbon in the soil and prevent carbon leakage.

In boreal forests, the fertilization of selected stands is the most rapid mean to increase carbon accumulation. The use of fertilization is mainly subjected to the forests of Northern Europe. Re- and afforested forests will start to sequester carbon significantly only after longer periods of the establishment.

The correct use of the different carbon farming practices has the potential to increase the C stock in the soil. The misuse can affect the yields, damage the soil, and water sources, or cause carbon leakage. Wrong reforestation methods and misuse of fertilization can result in the same way. The carbon sinks of agriculture and forestry can be used especially in finding time for energy solutions that are aimed at reducing the use of fossil fuels.

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