CRAFT LIFE

Latvian Fund for Nature

AGRICULTURAL PRACTICES TO MITIGATE CLIMATE CHANGE

GUIDE FOR FARMERS

Contents

Valsts reģionālās attīstības aģentūra

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The interaction between agriculture and climate change is not always straightforward. Although agriculture as a whole is one of the main sources of greenhouse gas emissions, there are farmers all over the world who have managed to change their farming practices so that their farms accumulate greenhouse gases rather than emit them. And farmers' ability to adapt to climate change is also crucial. Smart and creative farmers try to use different natural processes to their advantage wherever possible, both economically and to contribute to climate change mitigation.

Although there are certain conditions written into laws and regulations, Latvian farmers generally have some freedom to decide what and how to produce and how to change their farming to become more climate-friendly and adaptable to climate change. Freedom also means being aware of the consequences of our actions or inactions.

I hope that this book will inspire and help Latvian farmers who are aware of the consequences of climate change and the impact it may have on the farming management conditions that their children and grandchildren might face. Although the book focuses mainly on the reduction and storage of greenhouse gases in soils and introduces methods to help adapt to climate change, the methods described can increase the profitability of farming, make an important

contribution to reducing farmers' dependence on purchased inputs (e.g. fertilisers, plant protection products, fuel, fodder, substrate for seedlings), increase soil fertility, moisture and nutrient retention in soils.

Of course, not all methods are suitable for all farms and the suitability of the methods described in the book for each farm's circumstances and possibilities must be carefully assessed. But it is clear that we cannot expect to reduce the climate impact of agriculture without making changes. So, every farmer who is willing to take action and is already doing something to reduce greenhouse gas emissions and adapt to a changing climate should be celebrated. However, we should avoid lecturing and accusing anyone of doing something wrong or too little, because we simply cannot afford that – every farmer who contributes to the fight against climate change is important. While it is clear that changes in agriculture are inevitable, it is also important to recognise that transforming agriculture in a more climate- and biodiversity-friendly way takes time, and that every day and year we farm "the old way" only deepens the climate crisis.

GOOD LUCK TO ALL OF US!

Andrejs Briedis
Chairman of the Council of the Latvian Fund for Nature

USE OF ROLLER CRIMPER FOR DIVERSIFICATION OF CLIMATE CHANGE MITIGATION TECHNOLOGIES IN LATVIA

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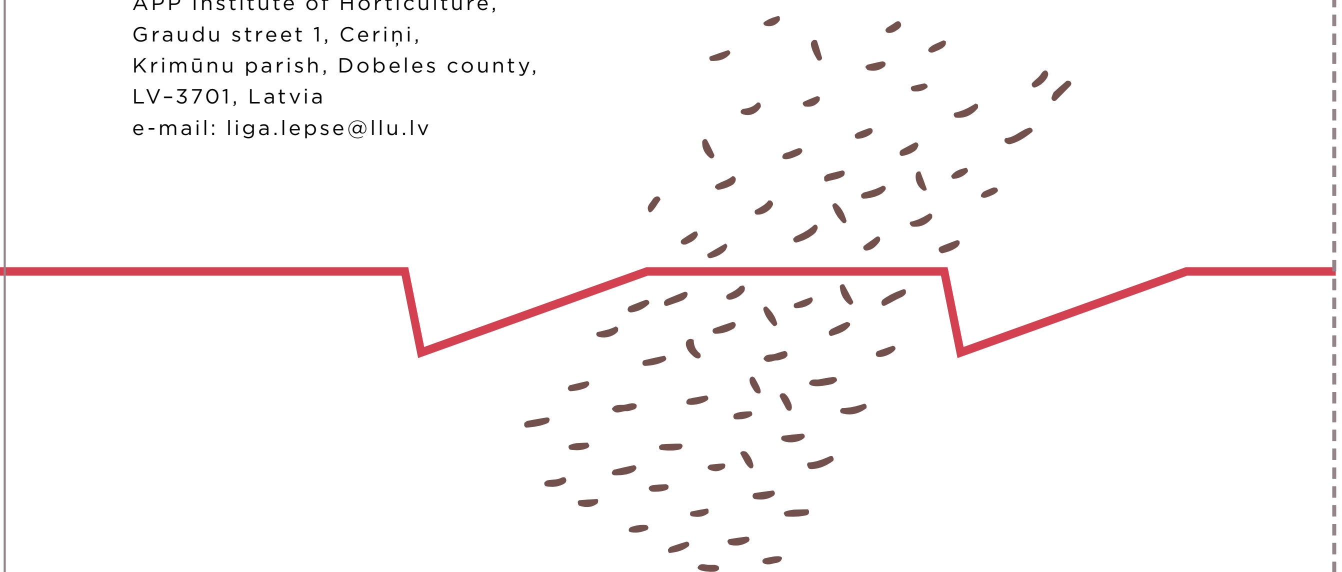


Introduction

Climate change has become a social and political issue in recent decades, but especially in the last couple of years, when several important international agreements to mitigate climate change have been signed – the Paris Agreement, the Kyoto Protocol, the 2019 UN Climate Summit in New York. All these international documents and meetings are aimed primarily at reducing greenhouse gas (GHG) emissions.

As the LULUCF sector (land use, land-use change and forestry) is estimated to be responsible for 24% of direct GHG emissions globally, GHG mitigation actions in this sector could have a significant impact on the climate change process. It is estimated that the LULUCF sector in Latvia is responsible for 22.3 % of GHG emissions, which is also a significant percentage of the total GHG emissions[1]. By changing the technologies of soil treatment and crop production used in agriculture, there is an opportunity to reduce emissions of these gases and to attract GHGs in soil.

The contribution of agriculture to GHG emissions also results from the use of fossil fuels to power agricultural machinery. As the intensity of agricultural production increases, so does the use of fossil energy in the production of products – both as fuel and as energy-intensive products (pesticides and mineral fertilizers). It is estimated that the amount of fossil energy that is used to produce crops [1], is equivalent to approximately 20–30 % of the stored solar energy in these crops. According to Eurostat data and the proposed solutions, changing agricultural technologies and reducing the use of nitrogen fertilizers allow agriculture to contribute to the reduction of GHG emissions by directly reducing NO_2 gas emissions from nitrification and denitrification [2].

One of the possible methods of agricultural production to reduce GHGs is the cultivation of catch crops and the creation of mulch from them. The use of roller crimper is recommended as an effective technological solution for creating mulch. In this context, the roller crimper technology contributes to CO_2 capture in the soil, reduces the use of nitrogen (N) fertilizer and diesel fuel consumption for soil treatment processes.

1 Summary of the greenhouse gas inventory submitted in 2020, Riga, 2020 https://www.meteo.lv/fs/CKFinderJava/userfiles/files/Vide/Klimats/Majas_lapai_LVGMC_2020_seginvkopsavilkums.pdf

Roller crimper technology impact on climate

In the scientific literature, there are quite conflicting data from other countries studies about the economic profitability of the roller crimper technology. Undoubtedly, this technology is considered an important contribution to C capture in the soil. From an agronomic point of view, it is beneficial, as it limits the spread of weeds, pests and diseases in the field and promotes the diversity and distribution of beneficial microorganisms in the soil. This improves soil fertility, buffering capacity and ensures nutrient retention in root zone, which delays the leaching of mobile nutrients (for example, the leaching of nitrates formed in the nitrification process in the soil is reduced by as much as 70 %), as well as reduces fossil energy consumption [3]. The retention of nutrients in the soil at the depth of the topsoil layer is particularly relevant in Latvia, where during the winter months there is an intensive leaching of mobile compounds from the soil topsoil layer and their outflow to the sea with surface runoff waters. From a climate change mitigation point of view, the roller crimper method is an important carbon removal tool – by accumulating it in the biomass of mulch plants, which gradually decomposes and enters the soil in the form of carbon compounds. The last two aspects in the article are analyzed in more detail, focusing on mobile nitrogen compounds and carbon removal in the soil. However, first about the very principle of the roller crimper technology.

The roller crimper technology uses agroecological service crops (ASC), which are grown in the field before cash crops and at a certain stage of plant development, they are rolled by breaking them with a special roller to create a mulch layer (Figure 1). After crimping ASC, they slowly dry out and form a layer of mulch. Within about two weeks after crimping, crops are planted or sown in this field for harvesting (vegetables, legumes, corn, etc. plants that have large seeds or that can be planted with seedlings).

Figure 1. Roller crimper in action; a newly broken maslin of rye and winter vetch; pumpkin growing in mulch

THEORETICAL IMPLICATIONS OF TECHNOLOGY FOR CLIMATE CHANGE MITIGATION AND AGRONOMIC CHALLENGES. Agricultural service crops (ASC) are plants that functionally serve to improve the agro-environment. No harvest is obtained from these plants, but they improve soil properties, ensure a sustainable maintenance of the agricultural production environment and, subsequently, yield of crops [4]. When using the roller crimper technology in planets temperate climate zone, mainly dormant plants (more often cereals) can be used as ASC, which keep plant nutrients in the topsoil during the winter and removes atmospheric nitrogen (in the case of papilionaceous crops) [5, 6, 7, 8]. According to study by the Rodale Institute (USA), crimson clover, winter rye, winter wheat, winter and summer barley, oats, buckwheat, field beans, vetches and peas are recommended as the most suitable annual plants for roller crimper technology. The roller crimper technology will not be suitable for crimping red clover, lucerne, etc. perennial papilionaceous crop due to their stem structure [9]. So, in the context of GHG mitigation, the roller crimper technology can be used for C caption in the soil with plant biomass and, in the case of papilionaceous crops, for additional biological binding of atmospheric N in symbiosis with soil-dwelling nitrogen fixing bacteria (*Rhizobia* spp.). Indirect reduction of GHG emissions can be achieved by reducing the total use of N mineral fertilizers in the production process [10].

Sufficient biomass production is one of the conditions for creating high-quality mulch – it is recommended to obtain at least 7 t ha^{-1} (optimally 8–10 t ha^{-1}) [11, 12] of biomass dry matter to create high-quality ASC mulch [13]. Assuming that 50 % of the ASC plant consists of C compounds, this biomass can fix around 3.5 t ha^{-1} C per one winter-spring season.

Biomass as such has no direct agronomic value – its value comes from the mineralization of plant residues, when bound elements are released, and from the increase of soil organic matter, which makes a significant contribution to the development of soil microorganisms and ensuring their diversity. Therefore, the composition of biomass, the biological active substances it produces, the decomposition rate and quality are the parameters that create agronomic interest. Crimped plant residue decomposition is directly affected by two important external environmental factors – humidity and temperature [14], however, these factors in the changing climate increasingly limit the production of quality yields when growing crops.

In recent years, the lack of moisture at the beginning of the vegetation period and also in general during the vegetation period is becoming more and more relevant. Mulch is one of the solutions for conserving moisture in the soil. Since the roller crimper technology can improve soil properties and create a mulch layer at the same time, it can be considered a promising technology in sustainable horticulture. However, this technology also presents several challenges.

After crimping the ASC, this plant mass forms mulch. One of the functions of mulch is to delay the evaporation of water from the soil, providing a more favorable moisture regime for the plants growing there. However, an important factor must be taken into account here – if it was dry for a long time in the spring period before the ASC crimping, as has been increasingly the case in recent years, then this water resource in the soil is already insufficient at the time of crimping and the soil moisture has been used by the ASC growing there and has also evaporated from the soil. In such conditions, the mass of crimped plants (mulch) will not be able to have a beneficial effect on the soil moisture regime, because there is no moisture to reduce evaporation, so the sown or planted crops may suffer from a lack of moisture. If there has been sufficient rainfall in the spring before the plants were crimped, then the mass of crimped plants forms a good mulch that prevents moisture evaporation, reduces weed germination and creates a favorable environment for various invertebrates, thus increasing their biological diversity in the agrobiocenosis. Under favorable moisture conditions, the crimped mulch provides several benefits: in case of precipitation it helps to distribute the amount of precipitation more evenly, during heavy rain it prevents the formation of soil crusts, plant residues that have already entered the soil reduce soil compaction, which in turn contributes to water infiltration into the soil by as much as 50–800 % [15]; mulch holds the wind, which significantly reduces water evaporation from the upper layers of the soil on windy days. This optimum moisture provision also keeps soil micro-organisms working intensively and plant residues involved in mineralization processes. Since only the lower part of the crimped plant mass is in contact with the soil, the mineralization of these plant remains is relatively slow. Plants with lower C:N ratio (e.g. papilionaceous crops) decompose more rapidly, but plants with a higher C:N ratio (e.g. cereals) decompose more slowly. [14, 16]. A very important aspect to be taken into account is the competition of microorganisms for N compounds during biomass decomposition. If there are insufficient N resources in the soil, microorganisms will consume the soil N resources to ensure the decomposition of ASC biomass (the more mature the ASC biomass is and with a higher proportion of C, the more N will be consumed), causing its deficiency in crops [16]. Theoretically, it is believed that the layer of mulch created with roller crimper decomposes slowly, resulting in a slower and more gradual release of its biomass into the soil, as well as of the compounds and substances present in the crimped plants. However, the general fertility status of the soil must be taken into account - in a fertile soil with a high proportion of organic matter and rich N saturation, the decomposition of the ASC mulch layer will have less impact on the N supply to the growing crop than in a poor soil.

The second important factor affecting the efficiency of roller crimper technology is temperature. The mulch layer lowers the soil temperature under the mulch. In Baltic climatic conditions, this is sometimes not preferable, especially at the beginning of the vegetation period. However, it depends on the crop to be sown in the created mulch, its thermal requirements and the optimal sowing time. In sunny weather, on the other hand, the shading caused by the mulch is good, providing favorable conditions for the roots of crops growing in the rolled mulch and smoothing out temperature variations.

When looking at the range of challenges with this technology, allelopathy should also be mentioned. It is a type of mutual interference between plants, when the substances released by a specific species (allelopathic compounds) have a stimulating (in low concentration) or inhibitory (limitation of weeds, pests) effect on adjacent or subsequent plants [17]. This phenomenon is cited as positive in the context of ASC for the purpose of weed reduction, however, it can harm the growth and development of the subsequent plants. From the range of ASC`s recommended in Latvia, rye, crucifers and yellow melilot [18] are plants with a relatively strong inhibitory allelopathic effect [8, 19].

The above shows that the roller crimper technology is not straightforward and does not always guarantee an immediate effect. The practical implementation aspects of the method are discussed below in order to minimize its drawbacks and contribute to the reduction of GHG emissions, the environment and the soil on a given farm.

Practical implementation aspects of the roller crimper technology

Several factors are significant for the successful implementation of this technology:

- appropriate stage of ASC development, when the plant can be crimped in the most qualitative way – usually budding – the very beginning of flowering [8];
- for a high quality mulch, it is important to crimp the plants directly and not incline them. When the plants are inclined, they rise back and continue to grow, but when they are crimped – they slowly finish the vegetation and dry up (Figure 2);

Figure 2. Properly crimped rye stalk

- correct construction and weight of the roller crimper, which ensures high-quality crimping [20];
- optimal plant biomass, which ensures the formation of a high-quality mulch layer [12].

In the temperate climate zone, the roller crimper technologies most often use the multifunctional rye-winter vetch maslin [8, 15, 3, 14]. As each of these plants has its own function, the seed mixture must contain an adequate proportion of each plant, to provide enough biomass to form a functional mulch layer. Several studies have been conducted in Northeastern Canada for the adaptation of the roller crimper technologies [8]. According to the collected data for this technology, rye in pure sowing can be sown from 110 to 300 kg ha^{-1}, winter vetch in pure sowing – 30 kg ha^{-1}, and 110 + 20 kg ha^{-1} or 90 + 30 kg ha^{-1} winter rye/winter vetches in meslin. On the other hand, in Minnesota (USA) very small winter rye and winter vetch sowing rates have been used – respectively 51+11 kg ha^{-1} [3]. Studies conducted in Latvia have shown that the optimal sowing rate for winter rye/winter vetch maslin is 250+50 kg ha^{-1}, which can yield up to 10 t ha^{-1} biomass under favorable wintering and soil conditions. The optimum sowing time for rye/vetch is mid-September. Crimping in the spring is done according to the development of the rye – depending on when they have reached the beginning of the flowering phase, when pollen is visible on at least 50 % of the plants (Figure 3). Usually, vetches start to bloom a little earlier.

Figure 3. The moment of crimping the rye/vetch sward - the rye is just starting to bloom, the vetches have opened their first flowers

However, the crimping time should be critically evaluated in the context of moisture provision - if there are forecasts of a long drought, then the ASC breaking should not be delayed, it should be done while there is still sufficient moisture in the soil [15]. The maturity of the stems should be checked and if they break well, then it is better to crimp them in time, without waiting for 50% of the plants to start flowering, so that the sward does not waste moisture resources in the soil, but when crimped, it starts to save it already. On the other hand, with increased humidity, it is worth waiting a little longer - so that the sward uses the excess moisture and then crimp it immediately. However, in any case, the time of the crimping must be assessed according to specific circumstances and forecasts. Tthere are several aspects to the choice of crimping time (Table 1):

Table 1

COMPARISON OF THE ADVANTAGES OF CRIMPING TIME FOR AGRICULTURAL SERVICE PLANTS

EARLY	LATE
Soil moisture has time to replenish (if rainfall is expected)	The soil warms up more
Phytotoxic effect decreases (allelopathy)	More biomass grows
Reducing the chances of disease infections	Suppresses weeds better as a result of allelopathy
The mulch layer begins to dry, which facilitates the process of sowing/planting the subsequent crops	Legumes crops are able to attract more atmospheric
Lower C:N ratio in ASC biomass	

It must also be observed that ASC, especially cereals, must be crimped at least two or three weeks before sowing/planting the next plant, so that the layer of mulch dries, thus it would be easier to carry out the next technological steps – sowing or planting – and to reduce the allelopathic effect. A dry layer of mulch is more easily amenable (breakable) to the action of sower or planters, which facilitates the sowing/planting of the next crop. In Latvia, the most frequent time for the crimping of rye or rye/winter vetch maslins is at the end of May/beginning of June.

Soil temperature is an important factor affecting the crimping time – in Latvian conditions, it is better to let the soil warm up before the ASC`s has been crimped, because then the mulch will shade the soil and warm-up will be delayed. To promote soil warming, while the ASC`s are still growing, immature and amenable, molded or staggered strips for crop planting can be created leaving the ASC`s between the rows until they are ready to be crimped and then crimp them (Figure 4) [15]. It will also reduce the allelopathic effect in the sowing/planting columns of vegetable crops, as the allelopathic substances will have already been released and their concentration in the soil will not be phytotoxic. In addition, ASC breakdown in the column will consume less of soil N resources because plants at this stage have a lower C:N ratio.

Figure 4. Soil cutter-mulcher cultivated strips prepared for planting pumpkins in ASC field

In Latvia's climate, the most common crops grown in mulch are cucurbits, legumes, brassicas and corn. This is due to the morphological characteristics of the plants, which are either seedling-plantable or have large seeds that can easily be sown in the ASC mulch, as well as being either heat-loving and late planting/sowing or having a growing season suitable for late planting in early June (determined by the ASC's crimping readiness).

Since the mineralization of ASC residues at the bottom of the mulch layer at the beginning of vegetable growth has not yet occurred fast enough to supply these plants with sufficient N resources, it is recommended to carry out local fertilization in the rows with N-containing manure (preferably of organic origin to promote the activity of soil microorganisms). In addition to N, fertilizer at the beginning of growth will promote the development of plants growing in the mulch, thus also the formation of foliage, which will limit the spread of weeds.

A sufficiently thick layer of mulch will limit weed germination and development and reduce the need for weed control measures. However, the general condition of the field should be taken into account – the diversity and number of weeds. If there is a strong perennial weed population, roller crimper technology will not pay off. During the growing season, the mulch layer mineralizes and becomes thinner, which allows weed shoots and sprouts to emerge and take over the seed/planting. In order to keep the mulch layer as long as possible and to decompose it as slowly as possible, the C:N ratio in the biomass should be around 20:1. At a lower ratio, the mulch layer will quickly break down and no longer function as mulch.

Most practitioners, who use roller crimper technology admit that the positive result of this technology is not immediately visible – it takes about 10-15 years for the soil to improve and become responsive to such technologies. Therefore, roller crimper technology is more effective in soil treatment systems (minimum tillage or no-tillage) [21] than in conventional, intensive soil tillage systems. The economic viability of the roller crimper technology depends on several factors: specific ASC plants and subsequent yield; from meteorological conditions; from timing and method of sowing and weeding of plants; from the contribution of efficacy to improving soil fertility, and, therefore,the sustainability of the environmental service; from the price of N fertilizer and fuel; from the price of ASC seeds (leguminous plant seeds are usually more expensive than seeds of other ASC`s); etc. However, the high price of leguminous plant may be offset by the amount of removed atmospheric N, which in turn will reduce costs on N fertilization. In the case of rye ASC pure sowing, additional N fertilization is needed to obtain an optimal C:N ratio, which would facilitate the decomposition of rye without causing N deficiency in the successive crops.

An overview of research in Latvia

So far, three projects have been implemented in Latvia on the use of the roller crimper in horticulture. The first small trial was carried out as part of a larger project by the Latvian Rural Advisory and Training Centre, where the method was used to prepare the area before planting an orchard. In 2018, a study on the use of the roller crimper in cereal production was launched.

More extensive research results will be presented about two projects: "Improving soil conservation and resource use in organic cropping systems for vegetable production through introduction and management of Agro-ecological Service Crops (SoilVeg)", which was implemented at The Institute of Agro-Resources and Economics (AREI) Stende research center within the framework of *the CORE Organic Plus* projects from 2015 to 2017 and a demonstration project financed by the Ministry of Agriculture – "Introduction of sustainable technologies in vegetable cultivation for increasing soil fertility and efficient use of resources" (2018–2022), with results from four growing seasons.

Within the framework of the SoilVeg project, the first roller crimper was manufactured in Latvia and the technology for the first time was tested not only in Latvia, but also in Estonia and Denmark, which have similar climates to Latvia. The project tested the hypothesis that by not incorporating ASC plants into the soil as green manure, but by crimping them with a roller crimper and creating a mulch layer, nutrient losses and GHG emissions are reduced. This hypothesis was proven, but other challenges arose. Analyzing the obtained results, it should be concluded that they were not encouraging in favor of the roller crimper technology in the context of vegetable yield [16]. The growth and development of vegetables was so poor, that the harvest in the ASC mulch was not obtained in Latvia. However, very important lessons were learned, which are used in future projects to adapt this technology to Latvian conditions: the roller crimper technology is not suitable for fields heavily polluted by perennial weeds (for example, perennial sow-thistle (*Sonchus arvensis* L.), creeping thistle (*Cirsium arvense* (L.) Scop.) and field horsetail (*Equisetum arvense*)); ASC biomass needs to be above 7 t ha^{-1} to suppress the annual weed growth; vegetables in the roller crimper mulch need additional N fertilizer at the beginning of the growing season.

The data obtained from the project, which calculates the preliminary impact of the system over a 30- year period, predicts a reduction of CO_2 emissions by 0.7 t ha-1 per year under the existing climatic conditions and by 0.86 t ha^{-1} per year in CO_2 reduction of emissions, and a 10 % reduction of soil N_2O emissions under adverse climate change scenarios, comparing green manure and the roller crimper technologies.

The analysis of fossil energy (fuel) consumption revealed some important aspects: the roller crimper technology requires less fuel compared to the traditional green manure incorporation technology, which requires additional green mass shredding and incorporation. Properly installed roller crimper mulch technology also reduces energy consumption for weed control and irrigation.

The SoilVeg project carried out a comprehensive assessment of the results from all member states, producing a technology comparison diagram (Figure 5). It clearly shows the differences between the two tested systems – traditional technology (orange) and the roller crimper technology (green).

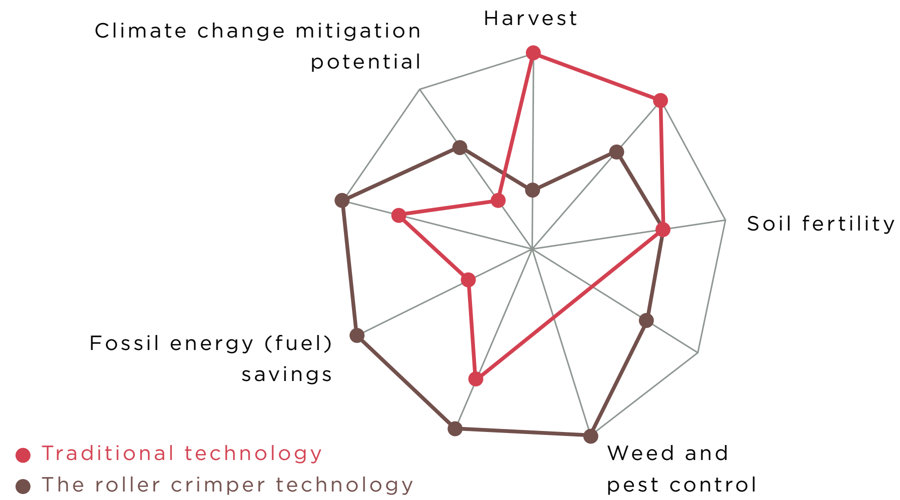


Figure 5. Comparison of the roller crimper technology and the traditional green manure application technology in terms of impact on agricultural system parameters

Looking at the diagram, it can be seen that the use of the roller crimper has a bigger positive impact on environmental elements, such as mitigating climate change, reducing the use of non-renewable resources (fuel), reducing nutrient leaching and increasing biodiversity. However, this technology reduces the yield and quality of the vegetable crop.

In addition to this challenge, research continues in the project "Introduction of sustainable technologies in vegetable cultivation for increasing soil fertility and efficient use of resources", which after four years of results, has also led to a number of valuable conclusions and observations. The main challenge remains the same - obtain satisfactory vegetable yields. In the first year, pumpkins were grown in a winter rye/winter vetch maslin mulch. It was the dry summer of 2018, when the mulch didn't help maintain moisture in the root zone, because there was simply no precipitation – there was nothing to maintain. In addition, ASC`s had consumed moisture resources in the soil for biomass formation, the soil was compacted and the pumpkins practically did not grow. Although additional N fertilizer was given and the plants were irrigated, there was no yield. In the control variant, where the soil was tilled with discs in spring before planting, the pumpkins grew better, but the yield was also very low. In addition to the poor plant development, there was very strong vetch regrowth. The fact that the vetches did not crimp qualitatively, but grew back, adversely affected the C:N ratio in the mulch biomass, where micro-organism didn't have enough N and was taken from soil resources. The pumpkins did not have enough N in the soil to produce a high-quality plant mass, and in drought conditions could not take up the N fertilizer that was given as additional fertilizer. Irrigation was limited. It was done, but it was impossible to compensate for such a large moisture deficit. Soil C analyses for both 2018 variants shows that in the roller crimper variant C in the soil was twice as much as in the control variant without ASC – 2.01 and 1.13%. So, despite other drawbacks, C reference in the soil had occurred.

The 2019 season was better - both in terms of meteorological conditions and technological solutions for cultivation. The conventional soil treatment (control) without ASC cultivation was compared with two ASC variants: growing rye in pure sowing and rye/vetch maslin. The ASC variants were further divided into two sub-variants – 1) in the spring, rye/vetch maslin was incorporated as green manure and 2) the ASC were crimped with the roller crimper and it created mulch. Crimping was done on June 3, but in the green manure variant ASC was incorporated with a disk cultivator at the end of May. Week after the crimping, two pumpkin varieties (*Musque de Provenc* and *Uchi Kuri*) were planted. The pumpkin yield in 2019 was obtained in all variants, although the mulch variant still lags behind the non-mulched variant (Figure 6).

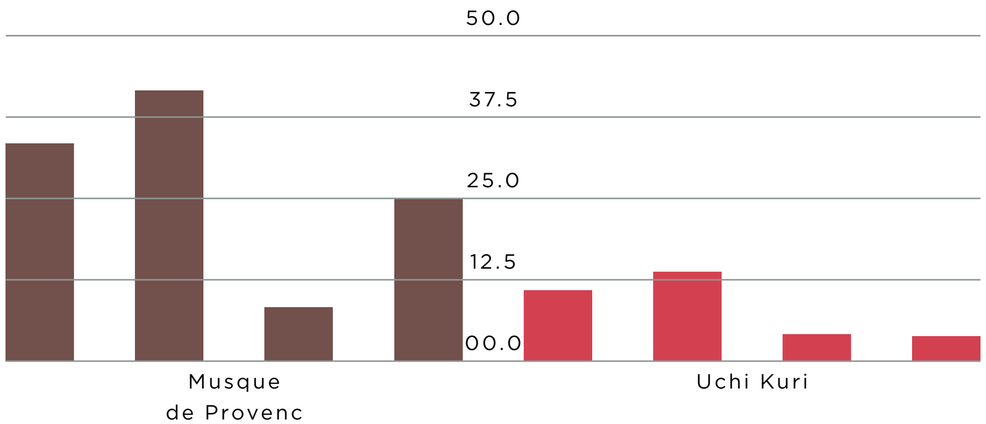


Figure 6. Yield of two pumpkin varieties under conventional soil treatment without green manure (control), with incorporated rye/winter vetch green manure (incorporated green manure), roller crimper rye and roller crimper rye/vetch mulch, t ha^{-1}

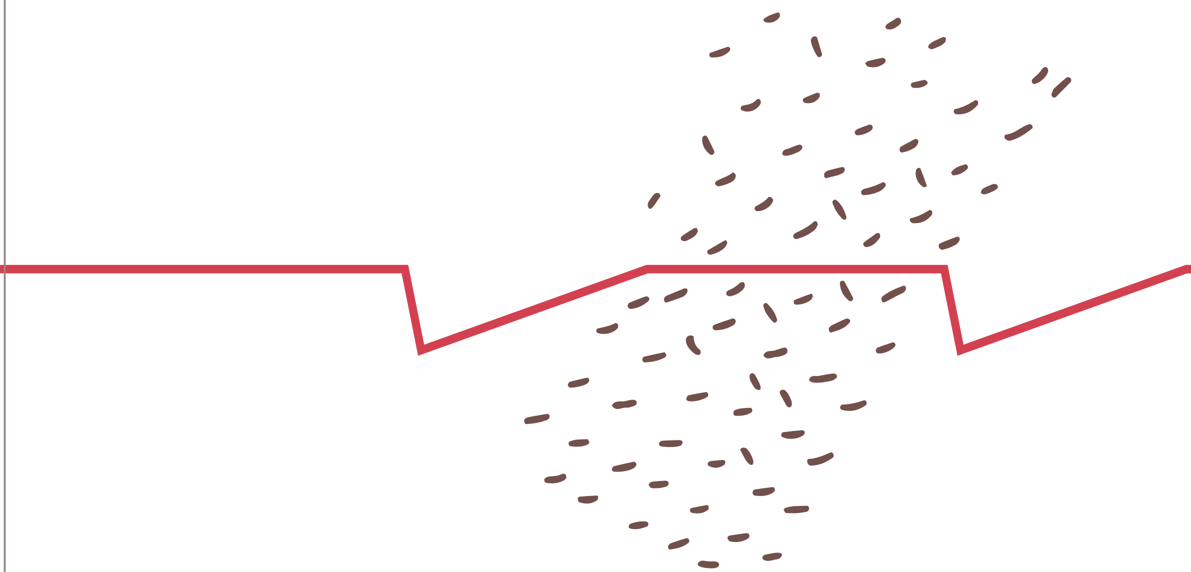
After incorporation of rye/winter vetch green manure, both pumpkin varieties had slightly higher yields than the control variant, but the increase was not substantial. So, the green manure plants have contributed to the soil fertility, which was reflected in the yield. Although many supporters of integrated or minimal soil treatment, who have been working in this system for a long time, have pointed out that the effect of ASC is not immediate – it appears after more than ten years (Genys V. pers. comm. and [15]) -however, labor and energy saving in the roller crimper technology is immediate, because when using mulch, there is no need to weed the plants and to treat the inter-row weed control. It should be noted, that the field must be cleared of perennial weeds.

The results of the roller crimper technology studies elsewhere in the world also show that in climatic conditions similar to Latvia (Canada and the northern part of the USA), the roller crimper technology shows a reduced yield compared to the no-mulch technology. Several authors point to the allelopathic effect of rye, which reduces successive crop yields [22; 8; 3]. According to the recommendation of US researchers, in the ASC field, seedbed rows should be prepared by disc harrow or cutter-mulcher, while in the rest of the field, the ASC should be allowed to grow until they are ready to be crimped [15]. However, even when this technology is tested in the above-mentioned project "Introduction of sustainable technologies in vegetable cultivation for increasing soil fertility and efficient use of resources" in the 2020 and 2021 seasons, a satisfactory yield of pumpkins is still not obtained.

The results of the research so far suggest that the use of the roller crimper technology in growing vegetables still needs to be adapted, but could be promising in perennial crops. The most effective use of the roller crimper technology would be in the care of perennial planting space between rows. In Italy, organic cherry plantations with long-standing roller crimper technology have been seen with ASC maslins and leguminous crops in space between rows. Both the plants and the soil in this garden were healthy and fertile. In Latvia, this technology has been successfully used for several seasons in Lielvārde county in a new apple orchard, growing various ASC mixtures. So far, the fruit trees are developing well, they are healthy and with good growth.

Conclusions

The roller crimper technology is promising in the context of climate change mitigation, improving soil fertility, increasing biodiversity and developing sustainable farming. However, it has its own challenges, which still need to be solved in Latvia`s climatic conditions -harvesting enough biomass to ensure an effective mulch function, the accumulation of moisture resources in the soil before crimping the ASC, providing the producing vegetables with nutrients at the beginning of the vegetation, while the remains of the crimped ASC have not yet mineralized.



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CATCH CROP USE IN CARBON AND NITROGEN COMPOUND ACCUMULATION IN SOIL

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Introduction

Climate change is considered to be one of the "achievements" of modern society and human development with undesirable side effects. The most tangible and economically significant is the greenhouse effect, which is largely the result of increasing concentrations of carbon dioxide and other gases in the atmosphere. There are two solutions to reduce the concentration of greenhouse gases (GHGs) in the atmosphere: one is to limit these atmospheric emissions; the other is to accumulate GHGs in the soil. In the case of the second solution, in agriculture and forestry, GHGs can be accumulated in the soil or perennial plantings (forests, gardens). International Panel on Climate Change (IPCC) guidelines mention that GHG containment and ecosystem adaptation and management mechanisms to current climate change is one of the objectives of future economic activity [1]. As the LULUCF sector (land use, land-use change and forestry) is responsible for 24 % of direct GHG emissions globally, GHG mitigation actions in this sector could have a significant impact on the climate change process. It is estimated that the LULUCF sector in Latvia is responsible for 22.3 % of GHG emissions, which is also a significant percentage of the total GHG emissions[1].

Between 2014 and 2021, a number of significant projects have been implemented in Latvia in the LULUCF sector on GHG emissions and accumulation in the sector. Examples include *LIFE REstore*[2], "Improvement of accounting system and methodologies for estimation of greenhouse gas (GHG) emissions and CO_2 removals from croplands and grasslands"[3] and the LLI-49 project CATCH POLLUTION" Catch crops and their growing potentials".[4] A brief description of the results shows that the accumulation of nitrate compounds and CO_2, as well as emissions, vary between crops depending on the biomass they produce (both surface and underground), organic characteristics and the type of tillage.

Studies have also been carried outside Latvia on the reduction of GHG emissions and CO_2 removal in the LULUCF sector, specifically in agriculture. In recent decades, there have been a relatively large amount of research on the impact of green manure or catch crops not only on soil properties, but also on the usefulness of their application in the context of climate change. The use of green manure in agriculture is nothing new, it is a technology that has been used for centuries to increase soil fertility. Recently, however, this technological solution

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4 ttps://www.arei.lv/sites/arei/files/2019-09/Catch%20crops%20and%20their%20growing%20potentials.pdf

has been given additional importance in mitigating climate change. This article will pay more attention to the possibility of using catch crops as one of the functional groups of green manure plants in the provision of agroecological services. Based on research results and experience in Latvia and elsewhere in the world, the efficiency of these plants in carbon (C) and nitrogen (N) accumulation in the soil will also be discussed.

Catch crop impact on the climate

Historically, agricultural land was developed by deforestation of overgrown areas. Currently they are considered to be one of the largest emitters of CO_2. In particular, intensive tillage technologies used during the 20th century – soil inversion, bare fallow and intensive tillage/cultivation – lead to rapid mineralization of soil carbon compounds and the release of CO_2 and N_2O into the atmosphere, while also reducing soil fertility. The literature provides estimates that suggest, if soil use patterns are ignored and mineralization processes in soil continue at even 10 % of the current level, the amount of CO_2 emitted from the soil will be equivalent to 30 years of anthropogenic carbon emissions [2]. Since the introduction of intensive farming technologies, 78 million tonnes of C have already been emitted from the soil [3]. However, it has been scientifically proven that by improving and perfecting tillage and usage technologies, it is possible to reduce these emissions and accumulate CO_2 in the soil. The idea of targeted CO_2 accumulation in the soil was first published by F. J. Dyson in 1977 [2]. Food and Agriculture Organization of the United Nations (FAO) estimates that by improving and perfecting soil use technologies, it is possible to accumulate 20 million tons of C into the soil in 25 years, which would account for about 10 % of anthropogenic (human-induced) emissions. The IPCC estimates that the C removal potential of the entire planet's soils is 1,2 billion tons per year [1].

The idea of organic C removal in the soil is based on the fact that photosynthesis by green plants on the planet, accumulates 20 times more CO_2 than is annually emitted into the atmosphere. Carbohydrates (C compounds) produced by photosynthesis, make up plant biomass (above soil surface and belowground). Depending on the species, about 40–50 % of plant biomass is thought to consist of C compounds [4;5]. When this biomass is incorporated into the soil, carbon is involved in soil organic processes and turns into soil organic matter [6]. It is considered to be the indirect accumulation of CO_2 in the soil. Direct CO_2 accumulation in the soil occurs in reactions with calcium (Ca) and magnesium (Mg) forming carbonates. Kyoto Protocol also identifies that C accumulation in soil is one of the most important activities to be undertaken to mitigate climate change [7].

When looking at specific agro-technological solutions and mechanisms for C accumulation in soil, one of the most significant is the promotion of the formation of stable and slowly mineralizing soil organic carbon (SOC) compounds. How

can it be done? There are a number of agro-technological solutions to achieve this: no-tillage technologies; high-quality management of plant nutrient supply (with particular attention to nitrogen (N) supply, which contributes to the development of stable SOC compounds); incorporation of plant residues into the soil; maintaining the diversity of soil microorganisms, especially by increasing the proportion of microscopic soil fungi; as well as the intensive use of various types of green manure, which contributes to almost all of the above solutions.

Why is soil microbiological diversity, especially the fungal/bacterial ratio, important for stable C accumulation in the soil? A. A. Malik and his co-authors, using modern biotechnological methods in their research, have found that in a larger fungal/bacterial ratio (above 4), soil is more microbiologically stable and consequently accumulates more C [8]. D. Johnson from New Mexico State University, from long-term research has concluded, that by increasing this ratio in favour of microscopic soil fungi, CO_2 accumulation is more stable and sustainable, since in bacteria, C is involved in simple compounds, and in fungi - in compound complex compounds. In addition, microscopic fungi, including arbuscular mycorrhizal fungi, emit a variety of exudates – including various carbohydrates that form compounds in the soil with a 40year persistence [9]. Consequently, in the process of mineralization, less CO_2 is emitted back into the atmosphere. The authors specifically accent the role of *Aspergillus* sp. fungi in C accumulation in soil. The authors consider these fungi as an indicator of the presence of soil fungi in a particular soil and, consequently, of the correct cycle of C and N in a given ecosystem [10].

The greatest potential of microscopic fungi in C accumulation compared to bacteria, can also be inferred from their different C:N ratio – for bacteria it is 3–6:1, but for fungi 5–15:1. This indicates that fungi need less N-containing nutrients compared to bacteria. This, in turn, means that at the same provision of C, but limited N, fungal growth will be promoted, but at an increased N - bacterial growth [11]. So, in order to contribute to a long-lasting and stable C accumulation, it is necessary to promote the fungal growth in the soil. On the other hand, excessive doses of N (whether of organic or mineral origin) will contribute to the growth of bacteria. Consequently, it is important to keep the N supply in the soil in balance – enough to build plant biomass, but not too much for increased development of bacteria in the soil. This balance can be achieved by introducing an appropriate crop rotation, which includes a variety of green manure plants for fertilizer and catch crop functions. The ideal C/N ratio for green manure plants is 24:1 (Table 1). This green manure composition provides a balanced substrate for the activity of bacteria and fungi and optimal circulation of nutrients [12].

The scientific literature contains a relatively limited range of materials on research into the use of green manure plants, especially in our humid continental climate zone and directly in the context of the catch crop function. However, this is sufficient to gain insight and assess the usefulness of the technology. Definition of green manure: green manure is a mass of purposefully grown plants that are incorporated into the soil to improve its fertility. All green manure plants are considered as C catch crops. Green manure plants do not make a direct profit. Green manure plants can be included in the crop rotation scheme or inserted as intermediate crop [13, 14]. In the past, green manure was primarily perceived as a source of atmospheric nitrogen fixation and a source of increasing organic matter for soil fertility, which is why it was called green manure. Nowadays, green manure has obtained a much wider meaning. Since the plants that are chosen for the green manure or as a catch crop have a specific role and an agro-technical goal and purpose for cultivation, they may also be referred to as agroecological (or agricultural) service crops [15, 16]. Although each plant species has a more pronounced characteristic of why this particular plant is grown, none of them are used solely as an agricultural service crop [17]. The article further analyzes green manure plants as catch crops.

Catch crops are grown between main crops and use nutrients that would otherwise leach, to form their own biomass, thus keeping nutrients in the field and bound in organic mass. Most often, catch crops are recommended to be grown immediately after Fabaceae plants, which have accumulated a significant amount of nitrogen in the soil in symbiosis with the nitrogen fixing rhizobium bacteria. For the formation of biomass, catch crops take N from both the soil and the atmosphere. Often these plants dissolve soil nutrients, that are difficult to soluble and species-specific. Consequently, these elements are contained in the topsoil layer where majority of plants root system is located and in the overground biomass. When incorporated into the soil, a species-specific spectrum of nutrients enters the soil and as a result of the biomass mineralization process, becomes available to successive crops and soil microorganisms. For example, crucifers (radish, mustard, rapeseed, swede rape, etc.) is an excellent source of sulfur (S) and contribute to the formation of plant-usable sulfur compounds in the soil (up to 12 kg S ha^{-1}) [18]. Fabaceae plants accumulate atmospheric nitrogen in symbiosis with rhizobium bacteria that forms on the roots, thus accumulating up to 150 kg of N ha^{-1} [19].

Along with species-specific agro-ecological services, all catch crops perform an important environmental service for climate change mitigation – creating biomass by photosynthetically accumulating atmospheric CO_2. When this biomass is incorporated, a carbon deposit forms is enriched in the soil. According to studies conducted in other countries, catch crops are able to accumulate from 0,3 to 1 t ha^{-1} C to the soil per year [20, 21]. When these plants were grown, bio-fixed carbon in soil increased by 0.20,4 t ha^{-1} C per year [21, 22]. By implementing a complex tillage and management system for a targeted bio-fixed carbon stock increasing, 5–10 t of C ha^{-1} can be accumulated in soil per year [3]. Bio-fixed carbon is important because, with the right tillage system, it is a long-lasting C deposit in the soil while increasing soil organic activity and fertility [9].

While C removal has been discussed previously, in the context of GHG emissions among climate change mitigation, nitrogen (N) is certainly also mentionable, as it is the most ecologically sensitive element in soil, both from the point of view of environmental pollution and correct and effective C removal. Fabaceae plants are usually used to accumulate it from the atmosphere. However, it is necessary to take into account that in the agro-ecosystem there are other sources of N (plant residues, manure of organic origin, mineral fertilizers). Nitrogen is used in soil microbiological processes, but often there is too much of it and it releases into the environment. These N emissions result from the decomposition of plant residues when they are not incorporated in stable soil organic matter complexes. Consequently, soil is also a major emitter of N_2O and as a highly mobile element, nitrogen compounds that are not bound in plants, quickly leaches and enter overground wastewater. Typically, this process occurs in the autumn–winter period, when there is intense rainfall and the soil is without vegetation. Since in recent winters the soil rarely froze, this process is relatively intense, leading to serious nutrient losses on agricultural lands. To prevent N compound leaching during this period and to promote its accumulation in soil organic compounds (especially after Fabaceae plant cultivation), it is recommended to grow catch crops as winter crops, which accumulates N compounds and keep them at topsoil level until spring, when these plants are incorporated into the soil or used to form a mulch layer. Their residues then start to decompose and gradually release N into the soil, allowing it to be taken by the subsequent plants. Winter crops (rye, rapeseed, winter vetch, winter rape) [24] are best suited for this purpose, but plants that create green mass in the second half of summer–autumn period (barley, oats, radishes, mustard) are also suitable. Plants that are left on the field during the winter, begin to decompose and are fully decomposed by spring, thus providing easily accessible nutrients to the subsequent plants early and easily accessible C for soil microorganisms, to incorporate in stable organic compounds. The use of Fabaceae plants, as a catch crop for accumulating nutrients from the soil and atmosphere, will also significantly reduce N_2O emissions [25].

Practical implementation of catch crops

The following summarizes information on the most suitable catch crops for Latvian conditions and their cultivation peculiarities.

Depending on the growing conditions and the seed rate, **rye** (Secale cereale) produces biomass of around 79 t ha^{-1} and can accumulate even up to 100 kg of ha^{-1} N, but more often up to 50 kg ha^{-1}. At medium biomass, in the soil they accumulate 3.5 t ha^{-1} of carbon per year. Depending on the maturity stage, the C:N ratio of rye varies from 40:1 to 80:1 – around 40:1 at the beginning of the flowering and 80:1 for straws, which is a relatively high proportion of C [24]. In addition, the rye root system also brings potassium (K) to the topsoil, improves soil drainage and provides water to the deeper layers of the soil. Rye can also be sown in rows, forming protective plantations , i.e. windrows, on horticultural farms. Windrows are mixed sowings/plantations of different height plants, where higher-growing plants protect the lower-growing plants from the wind, thus creating a milder microclimate and reducing water evaporation. This is the experience on L. Muceniece farm, where rye rows are mixed with pumpkin and courgette plantations (Figure 1).

Figure 1. Rye rows are left as a protective plantation in a pumpkin field. *Author's photo*

Due to the rye strong allelopathy (release of other plant growth restricting substances), it is very good at suppressing weeds. Because of the allelopathy, it is recommended to wait up to two weeks after incorporating rye into the soil and before sowing the next crop. Rye can be sown in September and in warm autumns even as late as October, as it sprouts at +4 °C and continues its growth even in 12 °C. In spring it is recommended to incorporate rye in soil before flowering or at the beginning of the flowering phase. However, in case of agrotechnological needs, it can also be carried out sooner.

To increase the efficiency of the micro-organisms and the formation of stable bio-fixed carbon compounds, it is preferable to increase N input into the soil, since rye has a relatively high C:N ratio. To ensure this, it is recommended to establish catch crop of mixed-species winter crops (mixed plantings/sowings). Winter rye/winter vetch is a good combination (Figure 2), as the C:N ratio of vetches is 8:1 to 15:1 [24].

The recovering of vegetation of **winter vetch** (*Vicia villosa*) in the spring is quite rapid, as the root nodules are already formed and accumulate (Figure 1) up to 123 kg ha^{-1} N [25]. The C:N ratio of vetches is low. In addition, vetches

rapidly form green mass, thereby suppressing weeds. This circumstance, along with the allelopathic properties of rye, ensures a high potential for suppressing spring-germinating weeds of this meslin. The literature mentions different seed rate norms for winter rye/vetch meslin: ranging from minimum norms of 4070 kg ha^{-1} rye + 1525 kg ha^{-1} winter vetch [24] to as high as 150160 kg ha^{-1} rye + 5060 kg ha^{-1} winter vetch [26].

Crimson (incarnate) clover (*Trifolium incarnatum*) is an annual plant, not winter-hardy, stalk is erect and can reach a height of 20–50 cm. Under favourable

Figure 2. Winter rye/vetch meslin in spring as vegetation begins to grow; Winter vetch with well-developed root nodules on the roots in the spring, when the vegetation is just starting to grow. *Author's photo*

conditions, it can accumulate 80–160 kg ha^{-1} of nitrogen to the soil. It best grows in sunny areas and is a very good nectar plant. Regular moisture provision promotes growth and the optimum pH of the soil is 6,6–7,5–. Sow as early as possible in the spring and carry out shallow soil topsoil tillage. In monocrop sow 20–22 kg/ha.

Red clover (*Trifolium pratenese*) makes good progress in cultivated, drained soils with a sufficient content of Ca. Light sand and acidic soils are unsuitable. In peat soils, clover has a weaker winter hardiness. Tolerates drought relatively well. Clover accumulates up to 370 kg ha^{-1} of atmospheric nitrogen and helps to improve soil structure and cleanse it from weeds. Like many plants of Fabaceae family, clover has a strong, deep tap-root that loosens and aerates the soil. Seed rate in seed fields is 8 kg/ha^{-1} and the sowing depth is 0,51–1 cm. Sow seeds in well-embedded, loose soil. After it is recommended to roll down the sowing.

Chicory (*Cichorium intybus*) are perennial plants that, along with the function of the N catch crops, are very good soil structure formers and they have a tap-root, that branches and forms a thick branching of the roots. Seeding rate is 15 kg ha^{-1}. Chicory seed is small and should be sown relatively shallow – about 1 cm. Therefore, the soil should be moist and, after sowing, the sowing should be rolled down to give seeds better access to moisture The plant is relatively heat-demanding and should be sown in May, when the soil warms up, but no later than August, so that the plant manages to germinate before frost. Chicory can be used in mixed plantings with vegetables (especially those that have a shallow and compact root system). Sown in space between rows, they accumulate the N and lay out their root system deeply, without interfering with the growth and development of vegetables. A greater effect of chicory will appear if it is grown for at least two years (this is more the case for continuous sowings).

In order to ensure the most sustainable tillage and land-use, there is often a need for temporary sowing of catch crops during the growing season, to temporarily cover the soil and to keep nutrients in the soil. For example, after harvesting early vegetables in the second half of summer, there are still 2–2.5 months before sowing winter crops or planting winter garlic. To retain nutrients in the soil and bring in biomass, thus accumulating C, during this period, it is also possible to grow catch crops, either single species or mixed-species. Recently, it has become popular to make catch crop sowing as a mix of several species (meslin) and include a wide range of plants, which together provide the necessary package of services. The most common crops for these sowings are buckwheat, westerwold ryegrass, oats, mustard, radishes, phacelia, crimson (incarnate) clover, peas and sunflowers.

Westerwold ryegrass (*Lolium multiflorum*), characterized by fast growth and a richly developed root system, it produces relatively large biomass (up to 15 t ha^{-1}) by accumulating about 60–150 kg ha^{-1} N [27]. The seed rate in pure sowing is 25–30 kg ha^{-1}, but in meslin it is reduced depending on the proportion of the plant in the meslins. In meslins, it is more often sown along with red clover and vetches. Under favourable conditions it sprouts in 57 days and grows rapidly [28].

White mustard (*Sinapsis alba*) is one of the fastest growing catch crops – it begins to bloom after 4–6 weeks, reaching 15–25 t ha^{-1} green mass. Mustard performs a number of services – accumulates nutrients, especially S compounds, that are used for biofumigation and suppresses weeds. According to studies in the USA, mustard significantly reduced the proportion of weeds, in particular where gallant Soldier (*Galinsoga ciliata*) was widespread [29]. Mustard is sown from early spring to early September and can be as a short-lived catch crop. The seed rate is 20–25 kg ha^{-1}. As the seeds are fine, mustard should be sown shallowly 1–2 cm, or not incorporate them into the ground at all, if the soil is moist and there is enough rainfall. As mustard is cruciferous plant, when including them in crop rotation, the growing period needs to be taken into account, since these plants have common diseases, especially club rot, which can be devastating (causal agent *Plasmodiophora brassicae*).

Tillage radish (*Raphanus sativus var. longipinnatus*), is very good at loosening the soil (even on heavy, compacted soils), since the tap-root stretches to a depth of up to 0.7 m. It is recommended to sow in early spring or August, as it germinates better in cool soil than in dry and hot soil. Only in short day conditions (spring and autumn), it grows vegetatively for a long time and without blooming. When sown in long day conditions, the plant blooms quickly and does not form a large root (Figure 3). The growing period lasts 40–50 days until technical maturity. The plant binds a lot of N, as it forms a large biomass, which also suppresses weeds. As the deep root dies and decomposes over the winter, it creates holes in the soil, which then help to absorb moisture, warm up of the soil in the spring and build soilstructure. The seed rate is 6–8 kg ha^{-1}. Sowing depth is 1–2 cm.

Figure 3. Tillage radish sown in June. In August the root is formed, but small. *Author's photo*

Buckwheat (*Fagopyrum esculentum*) is also a fairly fast-growing plant and tolerates poor soils well. It reaches flowering in up to 60 days, when it is also ready for incorporation into the soil. Buckwheat accumulates phosphorus, forms green biomass and with its wide leaves suppresses weeds very well. It is a good nectar plant if allowed to bloom, it quickly decomposes and is easily incorporated into the soil. The seed rate is 70 kg ha-^{1}. Sowing can start after spring frosts and continue throughout the vegetation period. Can also be sown in perennial plantings between rows.

Phacelia (*Phacelia tanacetifolia*) is an annual nectar plant that rapidly forms biomass by accumulating nutrients, especially N from soil compounds and is good at restraining weeds. The seed rate is 10 kg ha^{-1}. The seeds are tiny, consequently the phacelia should be sown no deeper than 1–1.5 cm. Sowing can be done after the frost period ends in the spring and continue throughout the summer, but with the onset of autumn frosts, the phacelia will perish.

Table 1 provides information on the biomass of commonly used and recommended catch crops, the recommended duration of cultivation, the characteristics of N accumulation and the C:N ratio in biomass.

Table 1

CHARACTERISTICS OF CATCH CROPS AND GREEN MANURE PLANTS (SOURCES: 9;30;35)

Plant	Family	Plant biomass	Duration of growth	N release	N accumulates or maintains	C:N
Red clover (*Trifolium pratense*)	Fabaceae	big	14 y.	quickly	Accumulates	17-20:1
Crimson (*incarnate*) clover (*Trifolium incarnatum*)	Fabaceae	medium	69 m.	quickly	Accumulates	15-20:1
Vetches (*Vicia villosa*)	Fabaceae	big	610 m.	quickly	Accumulates	11:1
Alfalfa (*Medicago sativa*)	Fabaceae	big	24 y.	quickly	Accumulates	25:1 (mature); 13:1 immature
Sainfoin (*Onobrychis vicifolia*)	Fabaceae	big	24 y.	quickly	Accumulates	15-20:1
Mustard (*Sinapis alba*)	Cruciferae	big	24 y.	slowly	Maintains	15-25:1
Tillage radish (*Raphanus sativa*)	Cruciferae	big	23 m.	slowly	Maintains	10-20:1
Buckwhead (*Fagopyrum esculentum*)	Polygonaceae	medium	46 m.	medium	Maintains	1
Phacelia (*Phacelia tanacetifolia*)	Hydrophyllaceae	medium	46 m.	slowly	Maintains	10-15:1
Winter rye (*Secale cereale*)	Gramineae	big	6 m.	slowly	Maintains	40:1 (at the beginning of flowering)
Westerwold ryegrass (*Lolium multiflorum*)	Gramineae	medium	1 y.	slowly	Maintains	20-25:1
Chicory (*Cichorium intybus*)	Asteraceae	medium	15 y.	medium	Maintains	12-20:1
Rye (*S. cereale*)/ vetches (*V. villosa*)	Meslin	big	46 m.	quickly	accumulate/ maintains	14-18:1

Depending on the tillage strategy on the farm, the catch crop biomass is incorporated into the soil with a disc cultivator or ploughed in. For large biomass plants, it is recommended to shred the mass before application, but bear in mind that soil microscopic fungi better settle in plant residues of a larger size. To prevent N compound leaching before sowing/planting summer crops, it is recommended to incorporate non-wintering plant residues into the soil in spring [31].

Application analysis of the method, based on a specific example

In Latvia and northern Europe, there have been relatively many studies on the ability of Fabaceae to accumulate atmospheric nitrogen, but relatively few studies on the effectiveness of other families catch crops in the management of nitrogen compounds in soil [32, 19]. Some projects recently have been launched that are still ongoing and results are not yet available. From 2015 to 2017, the Institute of Agricultural Resources and Economics project “Improving soil conservation and resource use in organic cropping systems for vegetable production through introduction and management of Agro-ecological Service Crops (ASC)” (SoilVeg) carried out soil analysis before and after incorporating rye as a catch crop. The results show that in spring, when 7 t ha^{-1} of rye biomass (dry matter) is incorporated into the soil, there is a significant difference in the dynamics of nitrogen compounds from the control fields where the catch crop was not grown during the winter period (Figure 4).

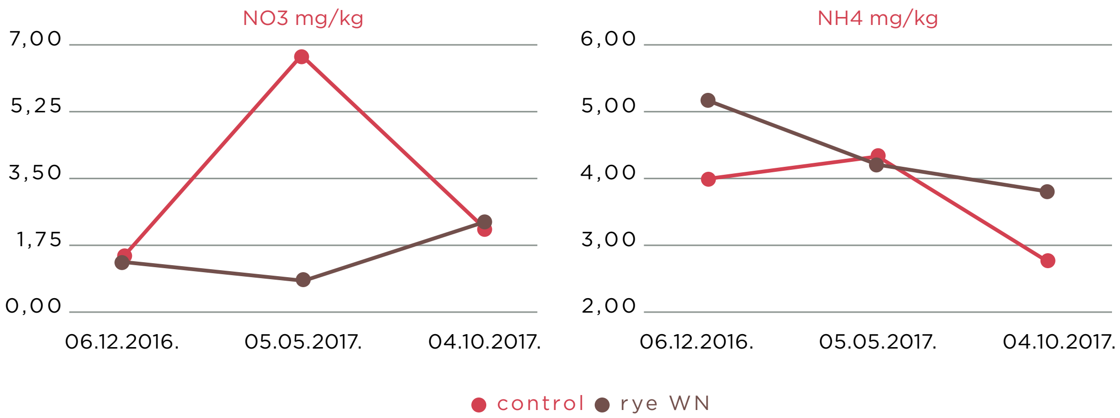

Figure 4. Dynamics of nitrogen compounds in an onion field with rye as a catch crop in the previous winter (“rye WN” in the figure) and without it (“control” in the figure)

Nitrate compounds (NO_3) (figure to the left) in autumn 2016 were present in similar amounts in both variants, but in the spring of 2017 most likely accumulated in rye plant biomass, therefore in the rye green manure field soil analyses showed much less, than in the control variant, where green manure plants were not grown. During the vegetation period, onions were grown on both fields. In autumn, nitrate levels were similar in both fields, but in the control variant lower than at the beginning of the vegetation period, whereas in the rye green manure variant – higher than in spring. This suggests that those nitrate compounds that were not accumulated in the rye biomass in the control variant were leached from the soil or emitted into the atmosphere. Ammonium (NH_4) compounds (figure to the right) also show a similar dynamic – with more ammonium in the control variant in spring 2017 than in December of the previous year, but a sharp decrease of ammonium in the control variant, in autumn 2017. In the catch crop variant, the NH_4 reduction curve is smoother, with a slight decrease in NH_4 ions in the spring, which steadily continued until autumn. Both figures support the claim that the dynamics of nitrogen compounds are slower when catch crops are grown in the field. It is important to note that the dynamics of both these nitrogen ions in the soil are highly dependent on the provision of temperature and humidity [34], consequently these data are considered indicative. However, this illustrative example also coincides with other researchers’ observations, demonstrating the positive effects of catch crops and green manure plants on the circulation of nutrients in soil [35, 36].

Conclusions

Catch crop targeted inclusion in crop rotation ensures sustainable climate change mitigation technology development. Wide range of catch crops and their diverse impact on the soil make it possible to create a range of use plan that suits the specific soil and production characteristics of the farm. Growing green manure plants in Latvia’s climatic conditions is an effective way to increase soil fertility and reduce GHG emissions.

Literature

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INTERCROPPING AND INTERSEEDING USAGE POSSIBILITIES IN HORTICULTURE IN ACCORDANCE WITH CLIMATEFRIENDLY OR SUSTAINABLE FARMING PRINCIPLES

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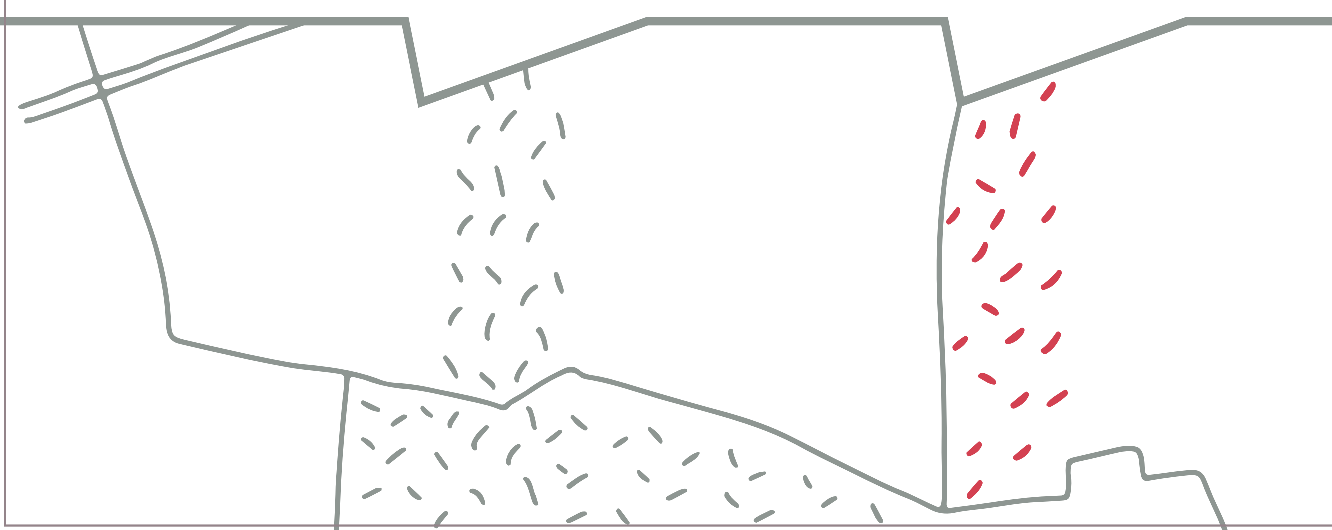
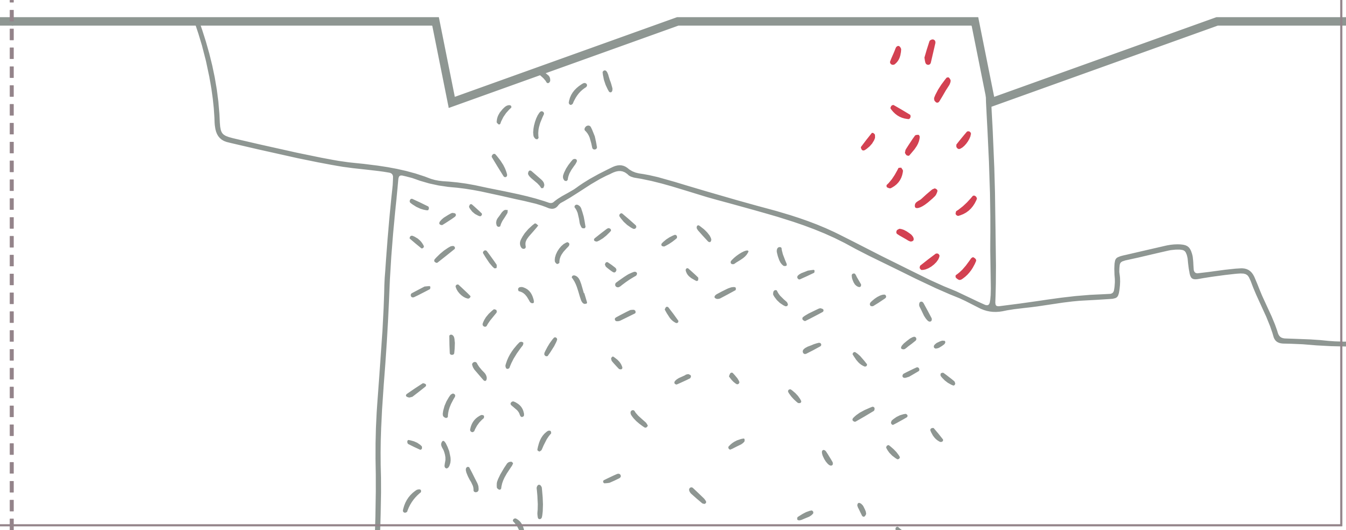


Introduction

10, 20 years ago, news about climate warming seemed like such a false rumor, because it seemed to be getting colder, not warmer. Now the situation has changed a lot. Warming is not only being addressed at a higher level, but a wider part of society is interested in it. The increased popularity is due to regulations and other normative documentation adopted at international and national level, which encourage thinking and acting using climate-friendly technologies, as well as the practical explanations and recommendations for implementing climate strategies – how the climatic conditions will change, what can be felt now and how farming practices should change. Farmers are asked to leave fields without green cover for as short a period as possible - to leave stubble in winter period instead of ploughs, thus reducing nutrient leaching [1], to use direct sowing as much as possible, because soil turning and loosening increases organic matter mineralization and releases more CO_2 from the soil [2], as well as soil micro and macro-flora is traumatized [3]. The procedure for granting direct payments to farmers determines the need for cultivated plant diversification by including a greater variety of cultivated plant species in crop rotations, as stipulated in Cabinet of Ministers terms of March 10, 2015 No 126 "Procedure for granting direct payments to farmers". Use of mixed planting and sowing technology's, depending on the selected plants, gives the farm an opportunity to minimize tillage to increase biodiversity and reduce nutrient leaching. According to data published by researcher Lindsey [4], from 1960 to 2023, the CO_2 content in the atmosphere has increased from less than 320 ppm to 424 ppm. This shows that society's way of life, farming and attitude towards the surrounding environment needs to change rapidly. In Europe as a whole, acreage of arable land for agriculture has decreased by 20% over the last 100 years, in some areas even by 70% [5]. The cause for this can be traced not just to diminishing soil fertility, but also to the diminishing populace in these areas, alongside the conversion of arable land into forested areas or pastures. Food raw material producers are in a difficult situation, because soil salinization is increasing [6] and fresh water reserves are decreasing [7]. The processing industry needs high-quality raw material in a sufficient quantity and the farmer must



comply with environmental requirements, that often affect the amount of the harvest. Mentioned problems also appear in Latvia and in order to avoid a serious impact on production in the future, it is necessary to think about sustainable farming that protects the environment and the climate as a whole. Deforestation of Amazon rainforest, intensive industrial production in industrialized countries and the huge amount of transport have a relatively more significant impact on the world climate than the Latvian economy, however, this does not exempt the Latvian society from protecting and caring for the environment. By setting an example of proper farming, we can begin to reduce the impact of agriculture on climate change and in addition - gain economic benefit from it. By protecting the local ecosystem in our homestead, county and country, we can significantly reduce the impact of agriculture and the related industrial sector on the environment and thus on the climate. In order to introduce climate and environment-friendly farming, preserving and increasing cultivated plant yield and its quality, it is necessary to think about significant improvements in farming, where one of the options is the application of mixed planting and sowing technologies in the production of food raw materials.

Intercropping and interseeding impact on climate

At first glance, the term "mixed plantings and sowings" may seem very complicated and unseen in everyday countryside, however, this type of farming has been known since ancient Roman times, when cereals were sown in spaces between rows of olive tree plantations. Here mixed plantings have been known for a long time. One of its most well-known forms is meslin. In Latvia, this technology is widely used in grain farming, by sowing meslins or cereals with after-sowing of another crop. Mixed planting and sowing are simultaneous cultivation of two or more crops in the same field, which may have similar or significantly different harvesting times [8]. When two or more cultivated plants are grown in spatial proximity, they interact with each other, for example, use companion plants in meslins, plant or sow the second crop, when the first crop has been growing for some time and live mulch, which is sown in space between rows, use as a mulching material and many other options [9]. If the residues of the previous crop are left on the field and not incorporated into the soil, mixed planting and sowing also includes growing cultivated plants within the same vegetation period one after the other. A prime example is living mulch [10], which is obtained by growing specially selected pre-plants, which are broken with a roller crimper and left on the field, before the next cultivated plant is planted or sown in the created living mulch. Mixed plantings and sowings, where the correct plant combination and ratio has been chosen, gives a chance to better use solar radiation, water resources and nutrients, as well as better suppress weeds, reduce the spread of harmful insects and can limit the spread of diseases

[11, 12], which in turn, reduces the need to use plant protection products. This is a significant reduction in the overall environmental impact of agriculture, as less industrial production of fertilizers and plant protection products will be needed. Mixed planting and sowing cultivation technology allows optimum soil upper layer coverage. Complete soil coverage with plant material is one of the basic things that must be observed in order to reduce the release of CO_2 and other gases into the atmosphere during the composting and mineralization [13], and it also ensures greater carbon accumulation for organic matter, as the maximum amount of plant mass or yield is obtained per field unit, increasing the soil use coefficient.

Greater plant diversity means greater diversity of soil microorganisms. It is known that annual plants release 2030 % of their accumulated carbon into the soil through root secretions, which are a direct source of nutrients for soil microorganisms. During root growth and development, 521% of the substances produced in photosynthesis are released into the soil with the help of root secretions [14]. Most cultivated plants have a symbiotic relationship with various soil microorganisms, with their roots colonized by microscopic fungi and bacteria. Some of these microorganisms have adapted to break down various compounds, resulting in the release of tightly bound phosphorus, which becomes available to plants. In this cooperation particularly important are soil microscopic fungi, as they can multiply the absorption capacity of plant roots, dissolve various substances and obtain nutrients where the plant with its roots and their secretions are not present. Increased plant ability to absorb nutrients reduces nutrient leaching and with the help of mycorrhizal fungi, plants make better use of nutrients, providing a chance to optimize fertilization rates, while also increasing plant resistance to various environmental stresses prolonged drought, humidity and drastic temperature fluctuations [15, 16].

One of the main groups of bacteria that receive a lot of attention in agriculture are nitrogen-fixing bacteria. These bacteria can reduce the extra nitrogen needed to ensure high yields. There are certain bacteria groups that symbiotically form nodules on the roots of the plants – mainly Fabaceae, providing the plant with the necessary nitrogen amount, and as the root nodules break down, other plants are also provided with nitrogen. For this reason, Fabaceae and other plants capable of forming a symbiotic relationship with nitrogen-fixing bacteria are among the main components of mixed plantings and sowings. Until the 1950s, the inclusion of Fabaceae in the crop rotation with the aim of providing the necessary amount of nitrogen for crop formation was very widespread. With the development of chemically synthesized fertilizer production, this practice was practically no longer used in Western Europe, although the use of meslin and sowing was partially preserved in Eastern Europe. Now, with a view to reducing greenhouse gas emissions Fabaceae plants are returning to food and fodder production fields.

Mixed planting and sowing implementation practical aspects

Mixed planting and sowing in Latvian countryside are most common in grain cultivation. According to the Rural Support Service data, legume meslin acreage has fluctuated from 8100 ha in 2001 to 5079 ha in 2015 and stabilized around 5400 ha in 2017 and 2018 [17]. Following greening principles and with stabilization of suitable crop rotation, in cereal farms, where cereal sowing proportion is higher, according to collected data in the annual agriculture report, it can be seen that cereal meslins are grown in larger and larger acreage. Consequently, it is necessary to calculate and plan sowings and plantings, so that they are profitable from area payment point of view. When introducing new, climate-friendly practices, it is also necessary to adjust the conditions for receiving support payments. Normative documentation is being clarified and farmers have the opportunity to propose changes so it is possible to apply for support payments for mixed planting and sowing on the merits, rather than just for the main crop, on the grounds that mixed planting and sowing bring more benefits to the environment and are suitable for implementing sustainable agricultural policies. Mixed planting and sowing also reduces the need for tillage. There are not many farms in Latvia that do not need to plow soil and can occasionally use a deep tiller when using different plant mixtures and crop rotation of several fields. This practice is relatively widely used in Lithuania, Poland and other European and world countries. These technologies involve surface soil treatment with different types of cultivators to a depth of 8 cm.

However, it should be noted that mixed planting and sowing has not only many advantages, but also several weaknesses. The main ones are mixed planting and sowing establishing, complex cultivation, work organization, choosing the right plant combination, determining the time of sowing and mutual competition for nutrients, water and light. Bigger problems can be caused by those mixed plantings and sowings, where the plants have to be sown at different times and the care of the combined plants is different both in terms of time and the necessary equipment. Crops must be chosen thoughtfully, taking into account not only the needs of the plants, but also the farm's ability to maintain the sowings and plantings. It should be taken into account that the need for manual labor may increase significantly, as sowing and planting times may vary and the farm's technical fleet may not have specific equipment to cultivate this type of field. Crop rotation can also be a problem, where the basic idea is not to grow the same plant again in the same field for at least three or more years. If mixed planting and sowing includes several plant species, then it becomes difficult to comply with this principle, however, by properly combining plants and carrying out appropriate care, the spread of harmful organisms can be reduced [18], which in the long term would allow deviations from the current basic principles of crop rotation, which would allow reducing the time between repeated crop cultivation in the specific field. The use of plant protection products can also

cause problems, as they must be applied at a specific stage of development of each plant or at a certain level of pest infestation, which may not coincide with the plant protection products allowed for the adjacent plant, and the adjacent plant may already be in the production stage, when plant protection products should not be used.

Since mixed planting and sowing has many implementation variants, grown plant combinations are wide. Obtained results may vary by region, they may be affected by soil indicators and other environmental conditions. In order to gain insight into some of the combinations, farmers were surveyed and several plant combinations were selected, whose main goal was to provide the main crop with the amount of nitrogen it needs using mixed planting and sowing.

Analysis of the use of mixed plantings and sowings based on the example of the EUROLEGUME project

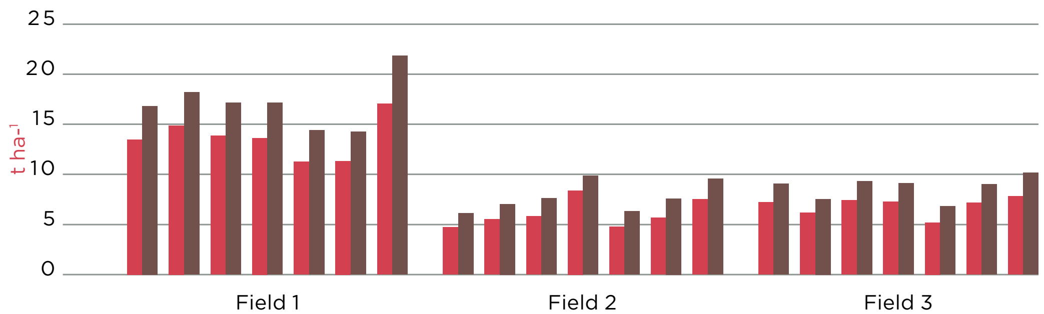
One of the latest studies in Latvia on mixed planting and sowing is the mixed planting and sowing evaluation, which was carried out by research and technological development EUROLEGUME[1] project for European Union's 7th Framework Program "Horizon". The project assessed the impact of Fabaceae plants on adjacent plants, their ability to provide adjacent plants with the nitrogen they need, mutual relations between plants, competition for nutrients, water and sunlight and the impact on yield and its quality. Project partners were researchers from Pure Horticultural Research Station and the main crops studied were strawberries (*Fragaria x ananassa*), headed cabbage (*Brassica oleracea*), onions (*Allium cepa*) and carrots (*Dacus carota*). All of these plants were intercropped with broad beans (*Vicia faba var. major*), while the strawberry planting also included peas (*Pisum sativum*) and alsike clover (*Trifolium hibridum*). Since strawberries are a perennial crop and their yield differs significantly from the age of planting, it was decided to establish three fields, which were planted in consecutive years from 2014 to 2016. This allowed two more replicates for each strawberry growing year, which in turn provided a larger data set from which to draw conclusions.

Obtained data from study on vegetable mixed planting and sowing, it can be concluded that onions and beans are not good adjacent plants. Compared to the traditional cultivation method, the onion yields were significantly lower. This is because onions have a shallow root system, while beans have a deep and strong root system and intensively consume water. Thus, without additional irrigation system in this kind of plating, onions lack moisture for full development

1 ES 7IP projekts: Ilgtspējīgu tehnoloģiju izstrāde pākšaugu audzēšanai un to izmantošanas veicināšana proteīna nodrošināšanai Eiropā pārtikas un lopbarības ražošanai (2014-2017): https://www.lbtu.lv/lv/projekti/apstiprinatie-projekti/2014/ilgtspejigu-tehnologiju-izstrade-paksaugu-audzesanai-un-to

and optimal yield. Broad beans with their long stems shade out the onions, which leads to faster leaf drop, resulting in a shorter crop formation time, which also reduces onion yield. Cabbage and bean combination produced similar yields to the control variant. In the carrot and broad bean combination, carrot yield varied too much in all variants to draw definite conclusions. However, taking into account carrot and bean root system characteristics, as well as the significant moisture influence on carrot yield, it can be concluded that by providing optimal moisture conditions, yields equivalent to those of conventionally grown carrots could be obtained. These results mean that beans are able to provide adjacent plant with the necessary nitrogen to produce a good yield, if the combination is provided with the right growth conditions and the combined plants have a sufficiently strong and competitive root system.

For strawberries, total yield (the mass of all ripe berries) and gross yield (Extra, I and II class berries, which correspond to a high-quality market product) were evaluated. In combination with peas, yield was equivalent to traditionally grown strawberry total yield (6–8 t ha^{-1}). In combination with broad bean (local clones VF_01, VF_02), strawberry yield decreased with each year in line with soil moisture availability (Figure 1).



A1 – broad beans VF–02
A2 – broad beans VF–01
A3 – green peas 'Capella'
A4 – sweat peas 'Ambrozia'
A5 – Alsike clover 'Namejs'
A6 – control without N mēsl.
A7 – control with N mēsl.

Figure 1. 1 Strawberry yield in the first year of field production for three fields planted in consecutive years from 2014 to 2016

Although the lack of moisture did not reduce yield quality (Figure 2), it is one of the factors that affected the total strawberry yield reduction. The fields were additionally irrigated with a drip irrigation system, but in 2016, 2017 and 2018 there were prolonged periods of drought and the natural water reserves from which irrigation water was drawn reached critically low levels, so it was decided to irrigate only in case of extreme need. Consequently, Field 1 shows

a higher yield in the second year of its development, when the first harvest was harvested, compared with significantly lower harvests from Fields 2 and 3, who suffered from long periods of drought. This confirms that moisture provision is one of the most important factors for yield and farms should consider installing irrigation systems and establish a stable water source to reduce the dependence of yield on climatic conditions.

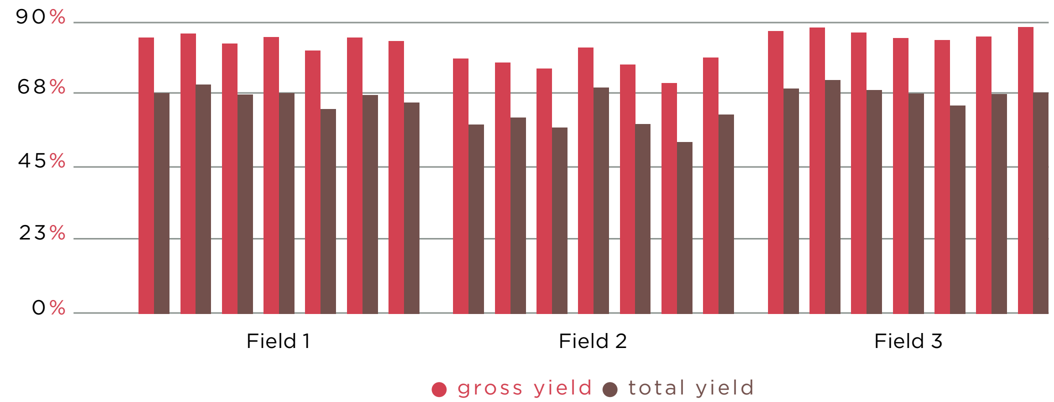


Figure 2. The percentage of Extra and I Class berries from the first year of harvest for the three fields planted in consecutive years from 2014 to 2016 (see Figure 1 for A.1 – A.7 designations)

The data from the vegetable trial also show that broad beans intensively use water and their root system is better adapted to more complete water absorption than the root system of strawberries (Figure 3) and onions.

Strawberries should not be grown together with broad beans if it is not possible to provide favorable moisture conditions for the development of both cultivated plants. In the first year of harvest, when natural rainfall was able to provide the plantation with the necessary amount of moisture, strawberry and bean combination showed an equivalent yield to the traditionally obtained strawberry yield. However, in the following years there were distinct periods of drought, for which broad beans are better suited.

Figure 3. Strawberry and broad bean root system placement

To determine whether the Fabaceae-fixed nitrogen had reached the strawberries, very specific analyzes were carried out in a US laboratory, which confirmed that the Fabaceae-fixed nitrogen was found in the strawberry plants. In addition, strawberries took up most of the nitrogen fixed by peas, but took up slightly less nitrogen fixed by alsike clover and broad beans. Since no additional nitrogen fertilization was used in the variants with Fabaceae plants, but their yields are relatively at the same level as the fertilized control variant, it can be assumed that Fabaceae plants are able to provide strawberries with the necessary nitrogen both in the autumn period, when the next year's harvest arrives, and throughout the vegetation season.

Among the Fabaceae plants included in the trial, it is not recommended to grow strawberries together with alsike clover (Table 1, the lowest indicators are marked in green, the highest in orange).

Table 1

PHYTOSANITARY STATUS OF STRAWBERRY AND FABACEAE PLANT MIXED PLANTATION

	Number of raspberry-strawberry flowers damaged by weevils, pcs. per plot on average		Number of berries damaged by grey mould, pcs. per plot on average	Common spot degree of prevalence, in points per field on average (scale from 1 to 9)
	biennial plantation	triennial plantation		
Beans_VF02	35	44	5.4	3.6
Beans_VF01	31	42	5.2	3.8
Sweat peas	30	45	4.0	4.1
Green peas	42	43	5.3	4.2
Alsike clover	30	47	4.7	5.0
Control without N	33	38	3.5	3.7
Control with N	38	49	6.3	3.6

The trial showed that in combination with alsike clover, common spot spread in strawberries (5 points) and obtained yields were significantly lower than in the traditionally grown variant, although in other phytosanitary indicators, the variant with alsike clover did not differ significantly from other combinations of Fabaceae plants. The number of raspberry-strawberry flowers damaged by weevils in both the biennial plantation and triennial plantation was in the control variant with nitrogen. The proportion of berries damaged by grey mould was also higher in the control variant with nitrogen. The reason for this could be the thickened foliage, which is a result of the easily absorbable mineral nitrogen fertilizer.

Fabaceae plant residues were incorporated into strawberry rows as organic fertilizer and nitrogen source (Figure 4).

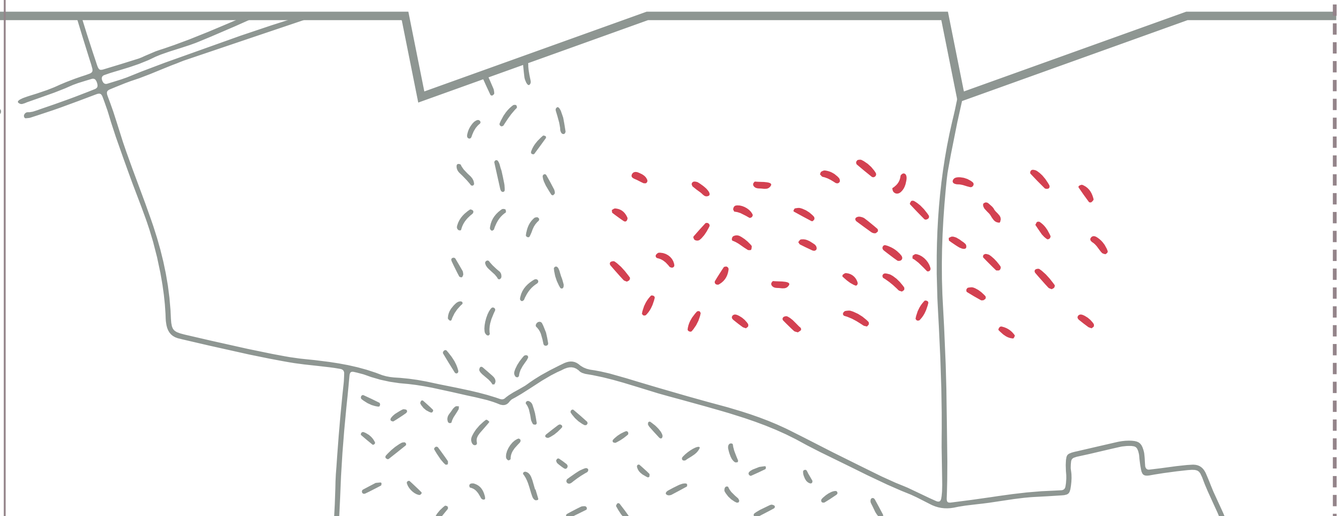
Figure 4. Incorporated fabaceae plant residues in strawberry rows, after harvesting the pods

The main limiting factor for the strawberry floral stalk is nitrogen supply in the autumn period. As their quantity and number of flowers did not significantly differ from the traditional cultivation variant, and when strawberries are combined with peas or broad beans, it can be concluded that the limiting factor in this system is water supply. This also shows that, during the period of flowering, peas and broad beans are able to provide strawberries with the necessary amount of nitrogen. This is due to the decomposition of the nodules in the second half of summer and in early September. The overlapping root systems of strawberries and Fabaceae plants make it more likely, that the nitrogen in the nodules will be absorbed by the strawberry root system (Figure 5). This was found and confirmed by conducting tests of strawberry plants in a foreign laboratory (USA) to determine the presence of nitrified nitrogen in strawberry plant tissues.

To introduce mixed plantings and sowings on your farm, you should definitely carry out an initial agrochemical soil survey. Suitable crops should be selected according to soil pH level and soil properties. When choosing plants for mixed planting and sowing, you must also think about protecting them from pests. If it is integrated farming, it is necessary to ensure the necessary agrotechnical measures for plant protection. The implementation of mixed planting and sowing should be considered in organic farming. Due to the limited range of organic plant protection products, it should be taken into account that growing the wrong combination of plants can significantly increase the cost of hiring labour for maintenance. The next step after choosing the plants is planning when to sow or plant them in order to take full advantage of the possibilities offered by the cultivation system.

At the beginning, when this farming technology is new, it is advisable to observe, how the plants feel and it is especially important to provide the necessary amount of water, but it also should not be given too much. Plant density is also important – when grown too thick, it can promote the spread of diseases, if grown too sparse – it can promote the growth of weeds. Since the soil and meteorological conditions can be drastically different, both within the boundaries of the farm and throughout the country, when starting to apply this type of farming, it is preferable to start with relatively small areas to make sure that the combination, which has been very successful in one place is also successful in another place on the farm.

Figure 5. Overlapping root systems of strawberries and broad beans – bean root are marked with a circle



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MAKING AND USING CLIMATE-FRIENDLY COMPOST TO ENRICH SOIL AND PROVIDE NUTRIENTS FOR PLANTS

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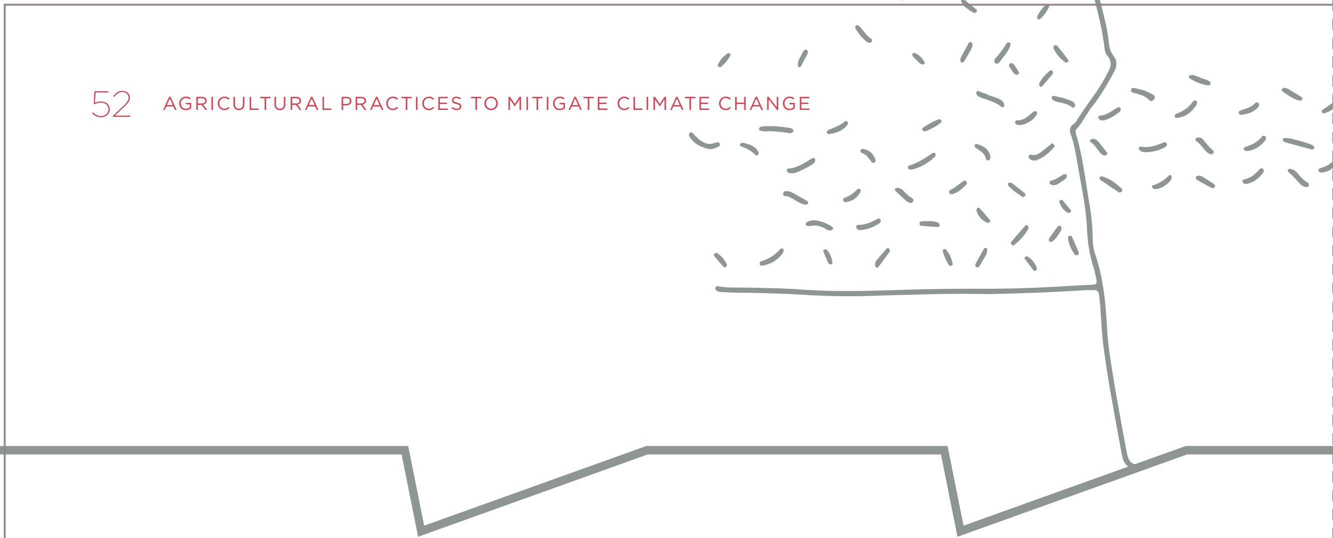
Introduction

Carbon (C) accumulation in the soil plays an important role in environmentally friendly management and in reducing greenhouse gases (GHGs). Through natural processes plants take C and store it in their biomass, thus removing it from the cycle. The challenge for farmers is to promote plant growth and learn not to release this fixed C mass back into the atmosphere. Partly this can be addressed by incorporating plant remains into the soil. For a better plant residue distribution in the soil, it is best, if the incorporated material contains both a dry part (material with a high dry matter content) and a green part (juicy plant parts). One of the best ways to bind C is to make a compost. In addition to being a good nutrient source to plants, compost also improves soil structure [1, 2] and increases its ability to hold water and nutrients [3]. Organic matter is made up of carbon compounds, so increasing the amount of organic matter in the soil also increases the amount of bound C that does not enter the atmosphere and does not increase GHG emissions. Any organic plant material can be composted, you just need to know the ratio of carbon to nitrogen to ensure quality compost. Quality compost is well decomposed, free of plant pathogens, seeds that have not retained their germination capacity and is pest-free [4]. If the compost is not in good quality, there is a risk of increasing the number of weeds in the field [5]. It is therefore preferable to compost all organic plant material that is not used but remains in the waste.



Composting is an organic process that converts organic matter, mainly waste, into humus-like material. These processes are carried out by micro-organisms (microscopic fungi and bacteria), macro-organisms (earthworms) and physico-chemical processes (e.g. mineralization). During composting, the compost mass is regularly dampened, stirred and, if necessary, limed to form a humus-like material – compost [6].

Compost is a mixture of organic residues or soil and organic residues that has undergone an aerobic composting process and is used for soil conditioning or as a fertilizer, including as a substrate for vegetable growing. It's a way for us to give back to the soil some of what we've harvested. So, you need to know how to make good quality compost. There are many opinions and methods, but there are basic principles that should be followed in its preparation. One of the biggest potential advantages of compost is its potential to replace both peat as a substrate and mineral fertilizers as a soil amendment.

As peat extraction is one of the largest agrarian sectors, accounting for a significant share of total GHG emissions [7], options for replacing peat as a substrate and soil amendment with different composts are increasingly being explored [8, 9].

Although compost as such has been known for a long time and has been extensively studied, there are still many uncertainties and unknowns that affect compost quality, such as the extent to which different composts and their raw materials affect the planta ability to absorb nutrients and produce quality crops, as well as the environmental impact of compost preparation processes, in a climate context, where relatively little research has been done and are still many uncertainties. Moreover, the issue of compost as a substitute for substrate has only come to the fore in the last decade. This is also important in Latvia, where bog development from GHG emission point of view is undesirable, so new sources of substrate must be found. Developing a range of composts, that are suitable both as quality fertilizers and as growing environment for plants, would significantly increase the potential for agriculture to accumulate carbon, rather than the increased carbon release that is taking place through bog development.

Compost – an environmentally and climate-friendly fertilizer and soil enrichment agent

During the composting process, various gaseous substances are released from the compost mass, and various compounds are leached out with the excess moisture [10]. Some of these gases, such as nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2), are mainly GHG components [11]. N_2O and CH_4 emissions from different composting materials and compost management options can range from 11464 mg N_2O m^{-2} per day and 0119000 mg CH_4 m^{-2} per day [12]. One of the main contributing factors to methane emissions is increased humidity and low temperatures, when the micro-organisms that could accumulate it are not yet active [13]. GHG release is enhanced also at the beginning and at the end of composting, because the original material still contains sufficient amounts of readily degradable material from which GHGs are released, and at the end of composting the temperature of the compost is no longer high enough to allow active microorganisms to accumulate GHGs [14]. Studies are showing, that after each mixing, compost material that mainly consists of faeces, release increased amount of N_2O [15], but in such compost material, methane release was only observed at the very beginning of the trial. As the author points out, most of the nitrogen loss was due to ammonia evaporation throughout the whole composting process. This was also confirmed in another study about looking at different types of composting of farm manure, with the highest ammonia leaching coming from materials with high nitrogen content [16]. This suggests the need to increase the dry matter content in this type of compost, as it would not need to be stirred as frequently to ensure aerated conditions, composting processes would be slower and the degraded volatiles would be more readily taken up by the composting micro-organisms. This is because in the compostable material, which consists mainly of manure, a denitrification process takes place [17]. To reduce leakage from the compost mass during composting, there are studies [18] that recommend maintaining optimum moisture and temperature by regularly mixing and dampening of the compost mass. Also, comparing different composting methods – ricks, layered compost heaps and forced aerated ricks – ricks were found to be the best option, with the lowest GHG emissions and a higher quality compost [19, 20].

Composting methods

As it takes time to make quality compost from compostable material, your need more than one space for composting. One space is where the new compost mass is stored, the second is where active composting takes place, and the third is for the finished compost. Compost can be made on the soil surface or on a concrete base. You can choose a place where you later want to build a planting bed, as the topsoil under the compost heap will already be enriched with organic matter, which will leach out of the compost and weeds and their seeds have died. In the meantime, is will cultivate and condition the soil. This option is suitable for passive composting. If composting takes place on a concrete surface, water loss and leaching of plant nutrients into the soil can be reduced where it is not needed.

Compost is made up of plant residues, starting from mowed grass to tree branches. Just bear in mind that the bigger the branches, the slower they will decompose. The compost may already be ready, but the large branches have not yet fully decomposed. In this case, it would be preferable to sort the compost by removing the large branches and placing them in a new compost heap. There are different views on the inclusion of animal products other than manure in compost material. Initially, adding meat, bones and other products to compost was discouraged because these types of composts can give off more unpleasant odours and attract rodents and insects. However, recent studies show that adding this type of material to the compostable mass can improve the composting process and the final result. This is mostly studied in household composting practices [21].

When making compost, it is important to include both green material (plant residues, weeds, grass, fruits, vegetables) and brown material (reeds, tree leaves, manure). As compost contains a lot of plant residues, which are high in carbon, it must be supplemented with a source of nitrogen. When building a compost heap, aim for a **30:1 ratio of carbon to nitrogen** [22]. You can try to calculate it accurately by knowing the C:N ratios in the raw material (Table 1), or you can roughly go by feel. Especially if the compost heap is built up gradually – it is very difficult to get a specific ratio in a backyard garden throughout the summer. For this option, it is better to use passive option at first until the end of the season, when the dry tree leaves are added and then mix and water, so that the following year compost is ready by autumn at the latest.

Higher concentrations of nitrogen can speed up the composting process and increase the likelihood of nitrogen compounds being released into the atmosphere and soil [23]. If carbon is present in higher concentrations, the composting process can be prolonged [24]. In the case of intensive composting, this usually takes about six months. Manure is commonly used to normalize the C:N ratio. Weed seeds are better broken down in cow manure, while horse manure contains more viable seeds. If the composting process maintains the optimum temperature and humidity for each stage of composting, weed seeds will die [25]. If manure is not available, Fabaceae plants or other plant residues with higher nitrogen content can be used (Table 1). It should also be borne in mind that if the compost contains a lot of carbon, it needs to be watered more heavily, for example if the compost contains more than 70 % of wood chips.

Table 1.

KNOWN PLANT C:N RATIOS PER UNIT MASS [22]

Material	C : N
Apple marc	21:1
Italian rye-grass in flowering phase	37:1
Italian rye-grass in vegetative phase	26:1
Newspapers	800:1
Vegetable remains	12:1
Grain chaff	80:1
Corn stalks	60:1
Dry leaves	50:1
Fresh leaves	30:1
Cow manure	18:1
Chicken manure	7:1
Horse manure	25:1
Oat reeds	74:1
Wheat reeds	80:1
Deciduous tree chippings	400:1
Coniferous tree chippings	600:1
Freshly cut grass	15:1
Dry grass	19:1
Fish guts	4:1

Compost making can be intensive or passive. The **passive** option requires compost material to be placed in heaps, which are one metre wide and high, but length is unlimited. These heaps compost for about two years. They are not stirred or watered. These compost heaps are usually layered in green (high in organic compounds) and brown (high in C). And so, it goes for several rounds. The green layer includes fresh material – grass, weeds, kitchen waste, fruit, vegetables, manure. The brown layer contains reeds, tree leaves, paper and wood chips. Usually, a liming material is also added to this layer to ensure a near-neutral environmental reaction for the micro-organisms. In such heaps, it is preferable to spread the branches over all layers. This is to allow air exchange, as the compost does not compact too much along the branches. It is preferable to cover such heaps with reeds, to reduce the risk of evaporation and leaching. **Intensive** compost is characterized by active mixing and dampening, and is made from shredded plant parts (Figure 1.).

Figure 1. Compost mass in the intensive option. *Author's photo*

The intensively composted material contains much more high-quality organic compounds, which are broken down and transformed by soil micro-organisms to be taken up by plants. In a backyard garden, this can easily be done if you put the compost material in a barrel with holes on the side. Holes are needed to allow excess moisture to drain out - this can be used for watering plants. The shredded compost material is placed in a barrel and mixed, then placed lying down in a shady place. After about four days, the contents of the barrel should be mixed and checked to make sure that no further wetting is needed. In hot weather, this needs to be done more frequently, as micro-organisms stop working in excessive heat [26], which for most micro-organisms occurs at 60–65°C [27]. Moisture can be determined by taking the compost

in your hands and squeezing it. If the compostable material sticks to your hand, it is at the right moisture. The mixing is carried out by rolling the barrel a few times. For larger volumes, it is preferable to compost on a concrete surface or on well levelled soil with an absorbent layer over the top, unless the site is to be used for growing plants after the compost has been removed. Compost mixers are very convenient, as shown in the figures (Figure 2, 3.).

Figure 2. Compost mixer and compost heap (in ricks) in an intensive composting system. *Author's photo*

Figure 3. Compost mixers. *Author's photo*

These compost mixers ensure good rick mixing and, if necessary, dampening. With this type of mixer, it is possible to have compost in as little as four months (depending on the size and chemical composition of the used parts), as it ensures that the top layer, which is slower to decompose in the standard mixer, is mixed into the total mass. Although mixing the compost mass may increase gas emissions for a while, this is relatively small compared to the rate of compost maturation, and different types of cover material can be used to reduce gas emissions and drying of the compost. It would be a good idea to avoid too much clay particles, because, as those responsible for compost research at the Flanders Research Institute for Agriculture, Fisheries and Food (ILVO) have found, clay particles cause the compost to heat up more (as Koen Willekens said in a personal conversation). This leads to more frequent compost mixing, which in turn prevents the growth of microscopic fungi and actively breaks down the more complex particles in the compost material. Researchers at ILVO recommend keeping compost at 60°C for four days, then 48°C for three weeks to help kill disease agents. For intensive composting, the Institute recommends covering the heaps with pressed, synthetic, breathable material. This improves the temperature regime, reduces water evaporation with various other valuable volatile substances, which micro-organisms then bound to the compost particles. Earthworms usually do not live in such compost heaps because it is too hot [28].

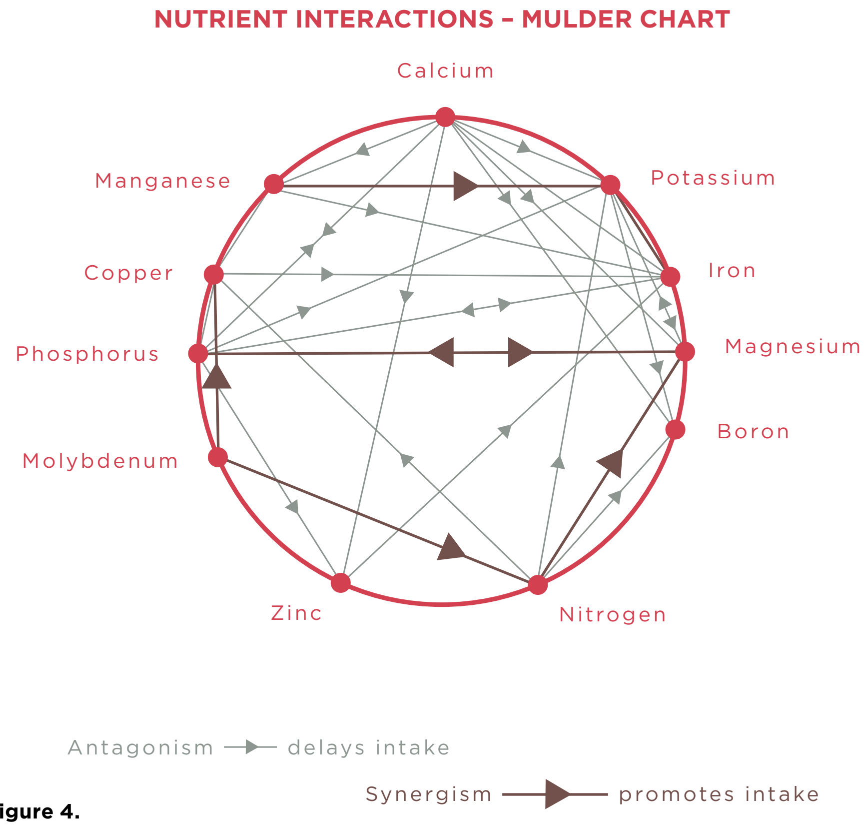


Figure 4.

Practical uses of compost

Compost contains 15–20 % organic matter. It is a concentrate of various organic compounds and nutrients, so it is not advisable to plant plants in pure compost if they are sensitive to increased nutrient concentrations. The organic and nutrient content varies according to the compost material used. Fertilization with compost should not exceed the incorporation rate, as overutilization can lead to nutrient overload, which can be detrimental to plant development. To prevent this from happening, care must be taken to ensure that the activity of micro-organisms is high enough. Micro-organisms ensure the cycling of nutrients in soils [29]. Compost can be applied to soils in the same way as manure, by first spreading it on the field and working it into the soil within three days by ploughing or disking. Compost can also be given to plants locally, especially to an established perennial plant, it can then be spread around the plant and worked into the soil as much as possible or mulched on top to prevent nitrogen volatilization, while improving the soil's moisture regime. If the planned field is nutrient-poor, it should not be given a heavy dose of compost in the first year, so that it seems to have the optimum organic matter content right away. This will shock the micro-organisms in the soil and they may die. Poor soils do not have enough active micro-organisms to take up large masses of organic fertilizers and process them into a form that can be taken up by plants. **Moderation is at the core of everything.** The compost dose depends on the soil analysis, the amount of nutrients the plant needs and the nutrient content in the compost. To know exactly how much fertilizer is needed, agrochemical analyses of both soil and compost must be carried out. The compost needs to be analyzed before each year it is applied to the fields. It is also recommended to analyze the soil annually to see how compost affects soil fertility. The analyses will also allow to monitor whether any of the elements are present in toxic doses and whether the nutrient balance is disturbed, which principles are illustrated in Mulder's chart (Figure 4) [30].

The green arrow is for facilitating the uptake of an element, the blue arrow for delaying. For example, manganese contributes to potassium intake, but high levels of manganese delays iron intake.

Compost offers a wide range of possibilities to enrich our soils for quality crops, but it should be borne in mind that it may not be economically viable at first. This involves setting up a composting site, modifying farming, i.e. transporting plant residues from the field to the composting site, purchasing a mixer, additional labour for composting and monitoring the processes. It should be remembered that compost may not be an instant miracle cure if the soil has not been fertilized with organic fertilizers for years, in which case the soil may not contain the appropriate micro-organisms to help process the nutrients in the compost into a form that can be more easily absorbed by the plants. It can take up to five years for such micro-organism communities to develop.

The type of composting depends on both the amount of plant residues and the possibility of actively building it up. Composting is mainly about optimum humidity and temperature. It is also important to cover the compost to reduce gas emissions and GHG emissions from compost production. An absorbent layer or concrete surface under the compost is also needed to reduce leaching into deeper soil layers. A C:N ratio of 30:1 must be observed.

By actively making compost from the mass of plant waste produced on the farm, as well as from other plant materials, it is possible to significantly reduce the release of C and N into the atmosphere, while at the same time obtaining a high-quality fertilizer, which is rich in active organic substances and nutrients. These substances are bound in organic mass, which ensures their stability and reduces losses through leaching and evaporation.

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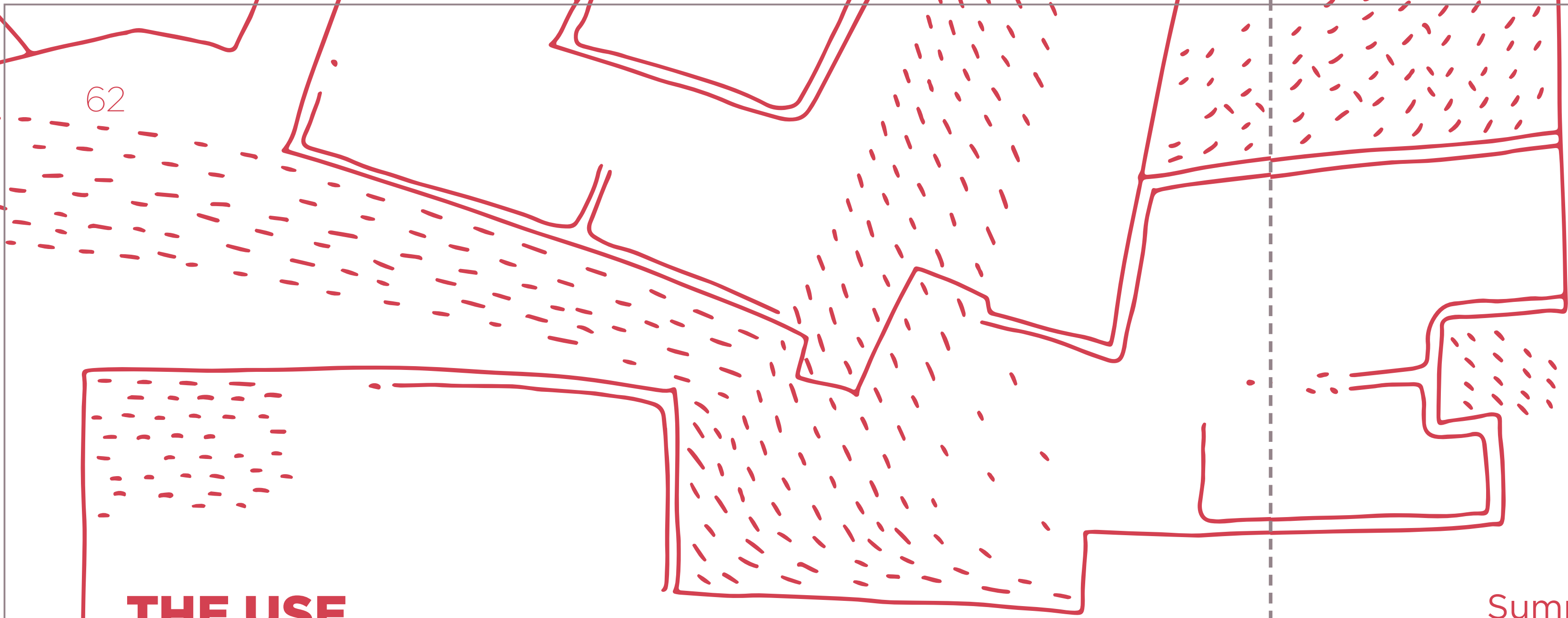

THE USE OF CONTROLLED DRAINAGE TO MITIGATE CLIMATE CHANGE AND ITS IMPACTS ON AGRICULTURE IN LATVIA

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Summary

The agricultural sector will face many challenges, that are related to climate change – changes in weather patterns, air temperatures and water cycle balances. At the same time, demand for agricultural products is rising in line with the world's growing global population. One of the methods recommended worldwide for more efficient use of water and dissolved nutrients in agricultural land is controlled drainage (CD). Within the LIFE CRAFT (LIFE16 CCM/LV/000083) project in Latvia, in Smiltene and Meņģele parishes, two pilot areas tested the suitability of CD in fields as one of the potential climate change mitigation practices in agriculture. The results of the project confirm the world-recognised usefulness of CD in reducing drought risks and nutrient outputs (especially nitrogen and phosphorus compounds). However, the reduction of carbon dioxide emissions and dinitrogen oxide and methane accumulation were only partially observed in the mineral soil areas of the project installed with CD. The ambiguous results from greenhouse gas (GHG) monitoring are due to heterogeneous soil and surface topography conditions. The functioning of the existing land amelioration system varied between the pilot areas and it was not possible to accurately adjust the same level of water retention after the construction of the CD. These conditions prevented a clear distinction of GHG changes between CD and traditional land amelioration system areas in the CD demonstration pilot areas.

Introduction

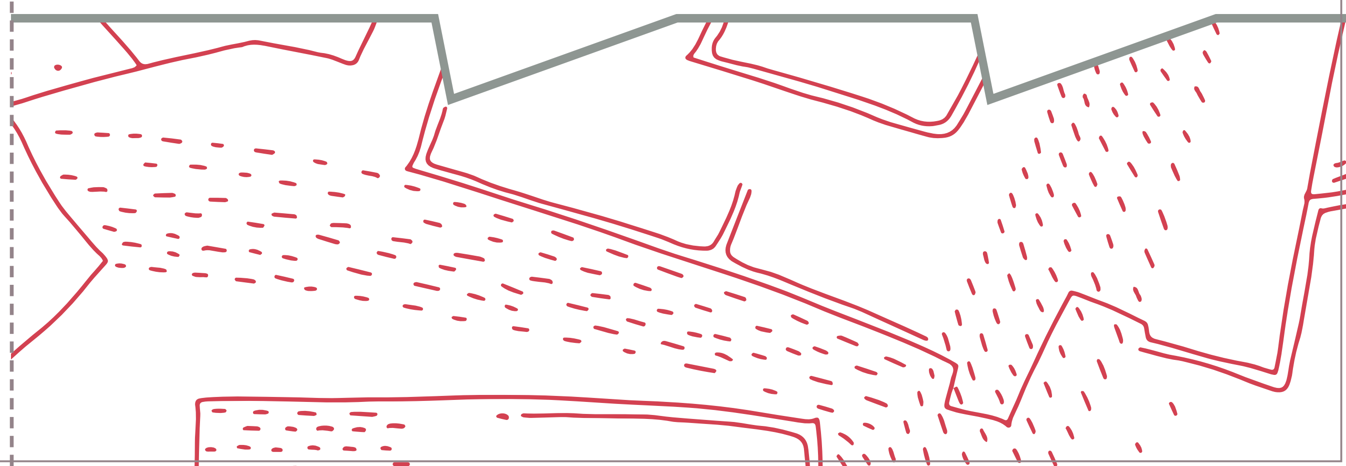
In Latvia, as in the rest of the world, climate change is occurring as average temperatures rise. Globally, it has increased by 1,1°C in the last decade compared to the pre-industrial period [1]. Climate change projections show that Latvia will experience a further 3.5–5.5°C rise in average temperatures over the next century, which will extend the growing season by about a month, significantly reduce the number of frost days and increase precipitation, including heavy rainfall [2]. Precipitation is expected to increase most in winter, less so in spring, while the likelihood of more frequent and prolonged droughts that will increase in summer [3]. Alongside these trends, the likelihood of extreme drought, heat or precipitation is increasing. Such unpredictability caused by climate change, and in particular drought, is considered one of the most economically damaging consequences of climate change for agriculture, both in Latvia and elsewhere in the world [4]. For example, 2018 was the driest year on record in Latvia, causing a total of €163 million in losses for farmers in the country [5].

The use of CD is being applied worldwide both to mitigate the adverse effects of climate change on agriculture and to study its effectiveness in reducing greenhouse gas (GHG) emissions. In the EU, the agriculture sector is the second largest GHG emitter after the energy sector (10,55% of all GHGs), according to 2019 data [6]. In Latvia, agriculture is also second behind the energy sector, with emissions estimated at 2250.88 kilotonnes of CO_2 equivalent in 2020 [7]. Studies show that a properly designed and regulated CD system can reduce GHG emissions from agricultural land [8, 9]. It reduces water run-off and the nutrients washed out of the soil by drainage water, thus contributing to higher yields [10, 11] especially in dry years, and reducing flooding from rainfall in downstream areas [12]. In the context of environmental protection, this practice is particularly important in reducing nitrogen and phosphorus compounds that pollute the water, which are excessively released into the environment from traditionally drained agricultural land [8, 13]. Especially because of the latter two advantages of CD, this type of land drainage is recommended in the EU countries to reduce water pollution caused by nitrates from agricultural sources and to achieve good quality of rivers, lakes and groundwater. The so-called nitrates (91/676/EEC) and water directives (2000/60/EC) have been adopted to achieve these objectives.

CD from a traditional drainage system differs in a way that it is a structure built into the drainage system, located in drainage control wells or on the outlets of drainage collectors. This structure is an adjustable dam that can be used to control the groundwater level in reclaimed areas. The traditional drainage system used in Latvia does not regulate the water table, so water is diverted as quickly as possible from the drained area through a system of drains and ditches. In Latvian regulations, the CD is defined as a two-sided moisture control structure (CM Regulation No 128), but in the context of this article, as in many international scientific articles, the term "controlled drainage" refers to the drainage function, distinguishing it from water supply control mechanisms built in irrigation systems.

The history of land amelioration in the world is as old as civilization itself, having been used by almost all known ancient cultures [14]. It has evolved, with varying flourishes in different parts of the world, to the present day. The term "controlled drainage" in the scientific literature appeared in the 1970s, to study the flood-regulating and drainage function of CD, often in conjunction with irrigation systems, to increase yields in lands where prolonged dry periods are typical during the growing season, such as the US state of South Carolina [15]. Since the 1980s, controlled drainage has been introduced, mainly to reduce nitrogen losses in the US state of North Carolina [16]. According to the number of scientific publications, CD is mostly applied in North America to corn and soy fields, in China to rice fields (together with irrigation) and in Europe mainly in Sweden, the Netherlands and Italy to various crop fields [17]. In Latvia, CD is a novelty, which has only been tested in the last few years in selected research projects - LIFE CRAFT, LIFE OrgBalt and SmartAgriHubs. In Latvia, the establishment of a CD as one of the six environmentally friendly elements of a drainage system is eligible for state financial support through a competitive procedure [18].

This article summarises the results of the European Commission co-funded LIFE project "Climate Responsible Agriculture for Latvia" (LIFE CRAFT NR. LIFE16 CCM/LV/000083) lessons learned in the context of research conducted elsewhere in the world on the installation of CD and its performance in drought mitigation, crop productivity, nutrient output and GHG emission reduction. Within the project, Institute for Environmental Solutions has set up controlled drainage demonstration fields on an area of 42.9 ha in Meņģele municipality, Ogre county in 2020 and 37.7 ha in Smiltene municipality, Smiltene county in 2022. In both pilot areas, the project has implemented a comprehensive monitoring programme, which allows conclusions to be drawn and practical recommendations to be made on the implementation of the CD in other parts of Latvia.



Controlled drainage impact on climate

Globally, CD is primarily used to mitigate the effects of short-term drought and to reduce nutrient leaching (mainly nitrogen and phosphorus) in agriculture [12, 19–21], resulting in higher or more stable crop yields [10, 17]. However, research on the potential use of CD for climate change mitigation and adaptation is increasingly emerging.

In most studies, CD has been shown to reduce the adverse effects of short-term drought by keeping the ground water available to the crop for longer periods, which can be regulated as needed. Different sources claim that it reduces the amount of water drained from the field by 8–35 % [12, 17, 22]. At the same time, it maintains the ability to rapidly drain excess water from the field in the event of an overflow, just as a traditional drainage system does. Therefore, in the light of the climate change projections for Latvia mentioned in the introduction to the article, controlled drainage is considered to be an appropriate and recommended method to adapt to the projected climate change and mitigate its adverse effects on agriculture in Latvia. This is also supported by a study on the differences between controlled drainage and traditional drainage systems in Poland, which concluded that the effectiveness of CD will decrease under increasing climate change (shorter time and less ability to maintain higher groundwater levels), but will still be higher than a traditional drainage system that does not regulate water discharge [10, 13].

However, the entireness of research on CD as a mitigation method is much smaller and the results more controversial. CD is most convincing as an effective reducer of GHG emissions and global warming potential (GWP) when applied appropriately to organic or peat soils, most often managed as grasslands in agriculture [23]. The amount of research to date examining the effectiveness of farmland CD in reducing GHG emissions on different mineral soils, under different management and environmental conditions, is insufficient to allow generalizable conclusions to be drawn.

A wide range of factors have a significant impact on the effectiveness of the CD. Current climate change mitigation studies on controlled drainage are therefore ambiguous, as it is difficult and costly to include all of the following factors in a single study, and most of them are based on measurements over a period of one to three years [8, 24]. They do not constitute as long-term studies. These measures are often incorporated into complex historical or forward-looking models to get a sense of long-term performance [25, 26]. Below is a list and explanation of the factors that need to be taken into account both when planning the construction of a CD and when assessing the impact of its use on GHG emissions from agricultural land.

SURFACE RELIEF. The economic benefits of CD are greatest and most effective in fields with a slope of less than 1 %, and can also be considered in fields up to 2 % [27, 28] i.e. the practice will be more useful for lowland farming. In fields with uneven topography and higher gradients, a denser and topography-appropriate drainage network and the location of drainage control wells are needed, to achieve successfully controlled groundwater level throughout the whole field. This translates into significantly higher costs, as it is recommended to construct a drainage control structure every 30–45 cm of slope for effective groundwater level control [27].

TYPE OF GROUND DRAINAGE. The CD is most often installed on the base of an existing traditional open (open drainage ditch system) or closed (covered drainage system) drainage system, which is converted to controlled drainage by the construction of control structure in the case of covered drainage systems, or adjustable gates in open ditches. The choice of the type of CD needs to be considered in a complex way, as it can give different results depending on the climate zone and the associated evapotranspiration rates and rainfall patterns, as well as soil freezing in winter [29]. However, studies show that, regardless of the climate, a CD constructed on a covered drainage system steadily reduces the volume of water drained from the field [17]. The density and depth of the drainage network influence the effectiveness of water control in a CD constructed on the base of a closed land amelioration system. The denser the drainage network, the faster the water can drain. Therefore, water retention in the CD system needs to be regulated earlier in the spring to keep it in the field longer and to reduce the impact of droughts in the growing season [13]. Similarly, the effect of the type of CD on the crop selected for cultivation may vary, for example, a long-term study in Italy found different suitability of the type of CD for winter crops, spring crops and crops with shallow and deep roots [30]. In Latvia, no such equivalent long-term comprehensive studies have yet been carried out to tell which type of CD would be more appropriate in which cases.

SOIL. Soil type, texture and horizon arrangement affect permeability and water retention by CD [16, 19]. This drainage method can retain water longer in both sandy, [12] and clay soils [30, 31]. However, studies have not compared and characterized soils sufficiently to tell which soils are more effective for CD under otherwise similar conditions [17].

CLIMATE. Globally, the CD shows different performances in different climatic zones. For example, as in Canada [10] or Sweden [29], Latvia needs to take into account the impact of soil freezing in winter. In these countries, soil water saturation increases in late winter as snowmelt melts [17]. Therefore, the regulation of the operation of the CD will differ from countries where there is no frost and snow cover in winter. In addition, it should be taken into account that increasing temperatures due to climate change significantly reduce the period of soil freezing and less snow accumulation in winter, so the regulation of CD needs to be particularly adaptive, as in these countries climate change has a greater impact on the previously normal seasonal water regime in drainage systems [32, 33]. Similarly, air temperature and precipitation and their future projections in the context of climate change vary considerably at both global and local scales. Arable land, air temperature and other environmental conditions all affect how water evaporates from the soil. These factors with rainfall determine the overall soil water balance. The regulation of CD shall be subordinated to the site-specific rainfall regime. Its purpose is to help keep the groundwater level slightly below the root zone of crops during the growing season and to lower it to the desired level at times when snowmelt or rainfall has made the soil waterlogged and therefore unmanageable by farm machinery or is suffocating plants because their root zone is saturated with water [34].

As mentioned above, there is little research on CD as a climate change mitigation method, and some of this GHG research has been carried out by combining CD with an irrigation system that allows a constant groundwater level to be maintained in the field [8, 9]. Without irrigation, the system cannot ensure a constant groundwater level, it can only temporarily keep the groundwater level at the desired level. However, certain coherences on the formation, accumulation and storage of the three main GHGs (carbon dioxide (CO_2), dinitrogen oxide (N_2O), methane (CH_4)) on agricultural land with regulated drainage systems can be attributed to CD. In general, studies now show that CD or CD combined with irrigation in fields with loam or loamy sand soils do not produce more GHGs than in the same fields with conventional drainage, while maintaining CH_4 storage capacity [8, 26].

As with the effectiveness of CD in mitigating drought, its success in reducing GHG emissions is influenced by a wide range of factors: soil properties, climatic factors including temperature and precipitation regime, timing and height of CD adjustments, ploughing, fertilizer timing and application rates, crop choice [35]. This set of factors interacts in complex ways with soil micro-organisms, both anaerobic and aerobic, whose activity in the soil regulates the production or accumulation of GHG emissions [9]. The combinations of all these factors are far from well understood, but some trends have been observed.

CARBON DIOXIDE EMISSIONS. The amount of organic matter in the soil is important in the context of CO_2 emissions. The higher the amount of organic carbon in the aerobic part of the soil, the higher the CO_2 emission potential [9]. Under anaerobic soil conditions, no CO_2 is formed. This is why, on agricultural land on peat soils, which have the highest organic carbon (C) content, it is particularly important to keep the groundwater level as high as possible, maintaining an anaerobic environment in the soil and thus significantly reducing CO_2 emissions. However, peat soils also vary and, in a study, looking at CD regulation in the context of differences in total C content and soil bulk density, the latter two factors showed no significant correlation with changes in CO_2 emissions [36]. Studies on drained mineral soils equipped with a CD with irrigation system have shown that CO_2 emissions are limited by the amount of C available in the surface soil, which is significantly lower than in organic soils, but that after heavy rainfall, as the soil becomes saturated with water, it may release C bound to soil

aggregates, increasing CO_2 emissions [8]. This should be taken into account when analyzing CO_2 emissions in mineral soils under alternating dry and wet periods [37]. Long-term future simulation studies have shown that CO_2 emissions are 6 % lower in CD systems with field irrigation compared to traditionally drained fields [9]. In contrast, short-term observations of such fields can also show the opposite – 20 % higher CO_2 emissions [8]. However, it is generally concluded that CO_2 emissions are most influenced by soil temperature, which promotes the activity of aerobic micro-organisms [8], while fluctuations in soil water levels have less influence on CO_2 emissions [9, 38]. CO_2 emissions may decrease slightly after nitrogen fertilization of fields, due to lower soil pH through nitrification and therefore lower micro-organism activity [39], but these CO_2 changes are generally insignificant [9].

DINITROGEN OXIDE EMISSIONS. N_2O emissions in soil are generated in two ways. Under aerobic conditions they increase by nitrification, under anaerobic conditions by denitrification [9]. If higher water levels are retained in the soil for longer, as in the case of CD, anaerobic conditions are promoted in the soil, with significant implications for N_2O emissions. In Canada, a study of the combined effect of CD with irrigation on N_2O emissions found N_2O emissions from such CD fields to be 2.3 times higher than from traditionally drained fields. As with CO_2, N_2O emissions increase more and are more closely linked to increases in soil temperature and nitrogen fertilization than to higher groundwater levels [8]. Many other environmental conditions affect the release of N_2O emissions to a lesser extent. The results of N_2O emissions differ in fields with covered drainage systems if they have different soil texture, soil pH and exchangeable magnesium content. Of these three factors, soil grading composition has a direct influence, while soil pH and magnesium content, which are indirectly related to soil grading composition, have an indirect influence. For example, soils with higher clay content have lower N_2O emissions, as clay inhibits gas dispersion [40]. Nitrogen fertilization of fields is also important in the context of N_2O emissions [9]. A linearly increasing relationship between nitrogen fertilizer application rate and N_2O emissions is observed, i.e. N_2O emissions increase by 1 % for a 1,6 % increase in nitrogen fertilizer application rate [41]. To reduce this effect, it is recommended to choose a later fertilization time [8] or to split fertilization into two smaller applications [42], and to include nitrogen-fixing crops (e.g. soybeans, beans, peas) in the crop rotation [9], [43]. When assessing the impact of CD on N_2O emissions, attention should be paid to heavy rainfall that saturates the soil with water. It has been found that N_2O emissions increase rapidly 1–4 days after such rainfall events [8]. If prolonged, this creates highly anaerobic conditions in the soil. This can result in the complete gradual reduction of nitrate to the harmless gas nitrogen, but can also initiate the unwanted process of methane formation [26], which is characteristic of irrigated rice fields [44].

METHANE EMISSIONS. In general, mineral soil fields act as an accumulator for CH_4, but as with CO_2, the C content of the topsoil must be taken into account. In soils with a high C content, as the groundwater level rises, the anaerobic space available for CH_4 formation increases. If there is too little aerobic soil remaining in such a field with a high groundwater level in which to potentially absorb the CH_4 produced from the lower anaerobic soil layers, then the CH_4 accumulation capacity of the field may be reduced [8]. However, this explanation is not straightforward and needs to be tested, as another study concluded that CH_4 is formed more in the top horizon of the soil [45]. Fertilization of fields has no significant impact on methane emissions [8]. Previous CD studies have paid little attention to CH_4 emissions and their accumulation in mineral soils in agricultural land. It seems most relevant to focus on CH_4 emissions/accumulation results after high rainfall events, when the mineral soil is more saturated with water and the groundwater level is closer to the surface.

Practical implementation aspects of controlled drainage

When considering the construction of a CD, the first step is to assess whether the slope of the terrain of the chosen field does not exceed the recommended slope of 0.5–1 % [27, 28]. This means that the field should be fairly flat. Secondly, it is suitable for fields that naturally have seasonally high water levels (water saturation within 46 cm of the soil surface) or have been drained for this reason in the past [46]. If a field meets these criteria, the next step is to know its land amelioration history. Whether a field is drained can be assessed by surveying it in the field and checking the cadastral information system for land drainage **www.melioracija.lv**, which is maintained by the Ministry of Agriculture in Latvia.

If the field has a pre-existing land amelioration system, it is necessary to assess its condition and obtain information on ditch depths, profiles, location and spacing of drains in the covered drainage network. If the existing condition of the land amelioration system is not satisfactory (e.g. drainage blockages, excessive tree and shrub overgrowth, beaver dams, ineffective previous land amelioration design, etc.), depending on the situation, improvement of the existing drainage system is required either in advance or in conjunction with the planning of the CD. For example, in LIFE CRAFT project, in the two pilot areas involved the cleaning of collecting ditches adjacent to fields and the removal of woody vegetation.

Before planning the construction of the CD, it is advisable to obtain information on the soil texture, soil type and horizons of the soil. In Latvia, soils can vary considerably even within the same field, so it is worth checking the characteristics and homogeneity of the soil to be used for CD. Latvia, unlike many countries, has a strong diversity of soils on a small scale, formed as the area experienced glacial retreat after the end of the Ice Age [47]. Fields with homogeneous soil composition, texture and arrangement will have a more predictable and controllable CD regime. In fields with heterogeneous soil characteristics, it is preferable to take into account the different water infiltration characteristics depending on soil variability. For a more balanced result, it is recommended that CD designers assess the density of the drainage network in fields with covered drainage systems, adapting it to the site-specific soil water infiltration rates.

Figure 1. Controlled drainage sample in a ditch [16]

As already mentioned, CD can be constructed on ditches (Figure 1) or in fields with a covered drainage system, the latter being the most common. This can be specifically designed when constructing a CD system in a field that has no previous land amelioration system. CD can also be designed and constructed on top of an existing traditional land amelioration system. The design of the CD shall be guided by the site conditions and accordingly the choice of whether the water control structure will be located in an open ditch or at the bottom of a drainage system or its collector before water discharging into the open channel [48]. In the LIFE CRAFT project, the CD was constructed in fields with a pre-existing covered drainage system and converted into a CD by constructing drainage control wells with gate structures at the outlets of the drainage collectors (Figures 2, 3). Key parameters to be followed for the design of a CD on a covered drainage base: 1) one water level control well is required for every 30–60 cm of elevation change in the field; 2) one water level control well is required for every 4–8 ha in the field [46, 48].

Figure 2. Reinforced concrete framework control well with gate construction for regulating water run-off from the field with covered drainage system. An example of a drainage control well built in the LIFE CRAFT project in the Meņģele pilot area. Photo: R. Abaja

Figure 3. Polyethylene control well with gate construction for regulating water run-off from the field with a covered drainage system. An example of a drainage control well built in the LIFE CRAFT project in the Smiltene pilot area. Photo: R. Abaja

For the design of the CD, it is preferable to use a designer that is familiar with the specifics of the CD. It is also worth paying attention to materials that are used in construction. In other countries, drainage pipes are mainly made of polymeric materials, while in Latvia, covered drainage consists mainly of clay drainage pipes [48]. So far, the observation period in the CD sites installed in Latvia is too short to assess clay drain clogging, which has not been observed in the LIFE CRAFT project during the full operation of the CD in both pilot sites, i.e. 2–3 years. The inspection chambers are constructed of different materials – reinforced concrete frameworks (Figure 2) or polymer material solid wells (Figure 3) or stainless-steel wells (Figure 4).

There are different solutions for the water control mechanism in wells, which can be adjusted manually or controlled remotely. The LIFE CRAFT project tested two solutions for the gates in the wells. In the Menģele pilot area, the wells were originally constructed with a wooden boarded adjustable partition (Figure 5). After about one year of observation, it was found that the wooden planks were not adhering tightly enough and unwanted leakage of retained water was occurring. This was later replaced by a continuous polymer wall with a gate at the base through which, if necessary, the water retained in the field can be completely drained. To regulate the level of retained water, the new gate system incorporated two openings, 15 cm apart, which could be fully or partially closed as needed (Figure 2). The partly hinged lids had two types of V-shaped narrower and wider opening angles (shown on the right and left of Figure 3). A wider angle will allow water to flow through the opening faster, a narrower angle will allow it to flow

Figure 4. Stainless steel control well with gate for regulating water run-off from the field with a covered drainage system installed on the drainage collector. Figure on the left – drainage control well. Figure to the right – internal view of the well at the water overflow over a gate set at a certain height [16]

more slowly. Such a control mechanism was also installed in the Smiltene pilot area (Figure 3). In both LIFE CRAFT pilot sites, the wells were installed with lids. In the Smiltene area, with a lockable, hinged polymer lid, and in the Meņģele area with a freely removable wooden lid, that occasionally are blown off the wells by stronger gusts of wind. We therefore recommend lightweight, waterproof but lockable lids in future. In other parts of the world, the water control structure in wells can be a T-joint tubular joining with incorporated sliding structure for level adjustment (Figure 6) [13, 49].

The design and construction of a CD is similar for a land amelioration system that can be adapted to the needs of the CD, as well as for a CD in a field that has not had a previous land amelioration system. In LIFE CRAFT has developed and on website made available a simplified brochure on the design and construction process of CDs, "Land amelioration system adaption to controlled drainage" – a guide for anyone considering the implementation of CDs in Latvia [50].

After the correct construction of the CD, the most important thing is to learn the most effective control regime according to the specific soil conditions, the chosen winter or spring crop, the management regime and the weather conditions. The basic principle of the gate regulations are as follows: 1) The gate is opened before mechanized field management (i.e. ploughing, cultivating, harrowing, sowing, fertilizing, spreading pesticides, harvesting) if the field is too wet for agricultural machinery; 2) The gates are resealed immediately after mechanized management to reduce nutrient leaching from the field and reduce the effects of drought during the crop growth period. The maximum water retention level of the gates is determined by the depth of root penetration of the

Figure 5. Adjustable gate system with wooden boards in the drainage control well. Photo: R. Abaja

Figure 6. Tubular T-joint joining with incorporated sliding structure for level adjustment [49]. Photo: R. Rosendahl

crop selected for the season, with the water level adjusted slightly below the root growth zone. For example, in the USA, for corn, soybeans and wheat, the water level is recommended to be 45–60 cm below the upper layer during the growing and maturing stages, while for wheat it can be slightly higher - up to 30 cm below the upper layer during the establishing and side-dressing stages [16]. Ainis Lagzdiņš [48] recommends that in Latvia, for fields left fallow or after harvest, the soil water level can be maintained between 15–30 cm below the soil surface, 50–80 cm below the soil surface at the crop growth stage, and no more than 70–80 cm below the soil surface before mechanized field management. Wells with a manual adjustment mechanism require a centimetre gauge for accurate adjustment of the appropriate water level in relation to the soil surface.

In Latvia, it is necessary to pay attention to the site–specific rainfall regime and the water infiltration characteristics of the soil, as this helps to assess how far in advance of field management it is necessary to open the gates and whether this should be done completely or only partially by lowering the water level. It is also important to assess after how much intense and heavy rainfall it is necessary to lower the water level during the crop growing season to avoid drowning. In LIFE CRAFT's experience, this is a factor to pay attention when growing winter crops, as depending on the soil's frozen state, excessively wet conditions can develop in the spring after snowmelt, which can cause patches of drowned crop or delay the development of winter crops. You need to be careful in situations where there is a lot of snow, but the ground underneath is not frozen. In this case, it may be necessary to lower the water retention level in the control structure during the snowmelt period.

To learn the most appropriate CD control regime for the field and crop, it is advisable to monitor rainfall and temperature data from the nearest weather station, as well as visual monitoring of field moisture and water levels in the CD control wells. For more accurate results, it is recommended to install a simple local weather station and at least one groundwater level monitoring well, which ideally automatically records and transmits the data in an easy-to-use application. In the LIFE CRAFT project, such an application was developed and provided by a Czech company – Czech Center for Science and Society (for Smiltene pilot are: **https://smiltene.ccss.cz/**; for Meņģele pilot area: **https://mengele.ccss.cz/**). In general, it takes several seasons to determine the optimal CD regime. In the LIFE CRAFT project, CD observations could only be made for two seasons with a proper functioning, which is insufficient to find a fully adapted and well-developed CD control regime.

Analysis of the use of controlled drainage based on the LIFE CRAFT project example

In the LIFE CRAFT project, a monitoring programme was implemented to assess the success of the CD, which included the following measurements:

1. Data acquisition on groundwater level changes and local meteorological observations – to assess the impact of CD on drought risk mitigation;
2. GHG (CO_2, N_2O, CH_4) emissions measurements – to assess the impact of CD on GHG mitigation;
3. Soil agrochemical and drainage water sample chemical composition analyses – to assess the impact of CD on nutrient leaching reduction;
4. Harvested yield – assessing the impact of CD on yield.

Monitoring data from the LIFE CRAFT project shows that CD helps to retain water in the soil. This was more pronounced when comparing the drought periods in the CD fields before water level regulation and during CD regulation at maximum water retention. In the CD fields, the groundwater level dropped about twice as slowly as during drought periods of equivalent duration before the CD system was established and regulated in these fields. The height of the retained water level during the drought period was on average 10–20 cm higher than during a similar drought period without the application of CD controls. It should be noted that it was difficult to make comparisons across sites because most of the comparison fields had initially unequal groundwater levels before the establishment of the CD, which was obviously due to the different micro-relief and soil characteristics of the fields or parts of them. Figure 7 shows an example where the CD field and the reference field before CD adjustment show practically the same groundwater levels, so for this area most evident in the data is the effect of CD impact on soil water retention.

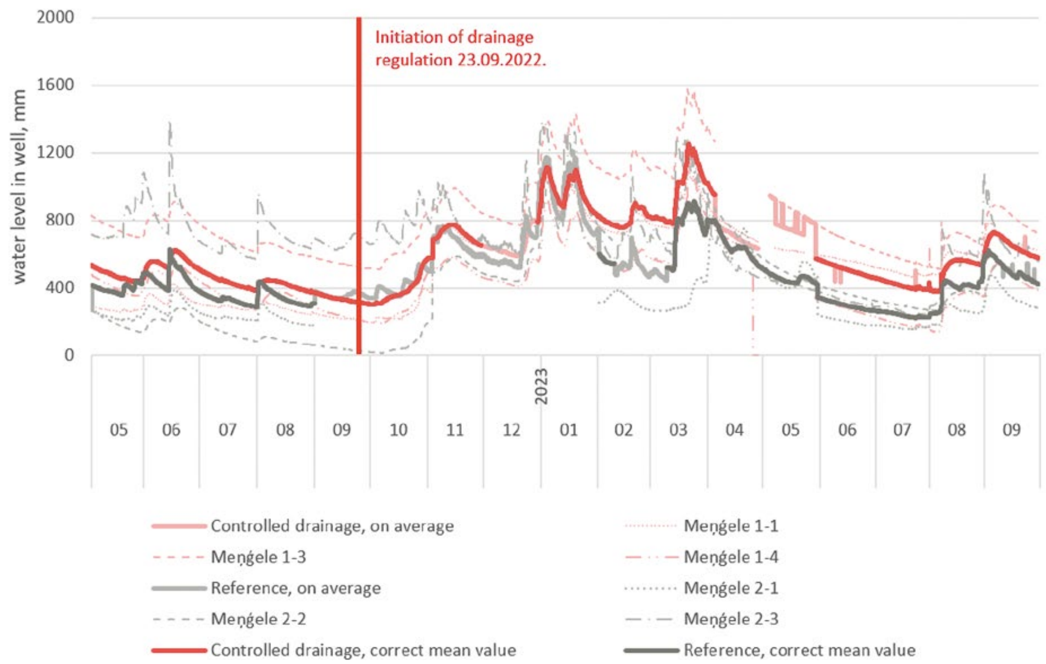


Figure 7. Average groundwater level changes in the controlled drainage and adjacent reference field in the LIFE CRAFT of Meņģele pilot area – one of the three controlled drainage demonstration areas set up in the pilot area. Groundwater level measurement wells of the controlled drainage field – Mengele 1–1; 1–3; 1–4; groundwater level measurement wells of the reference field – Mengele 2–1; 2–2; 2–3. Saturated pink and gray coloured mean curves reflect the mean values for the control or reference field measurements when the data are simultaneously from all groundwater measurement wells, while dimmer mean curves for these colors shift due to missing one of the well measurements. Data source: Czech Center for Science and Society.

The results of the CO_2 measurements obtained in the project are ambiguous. Practically all the reference fields in the pilot areas already have lower CO_2 emissions during the growing season, before any significant CD adjustment. For the 2023 season, a change in the reduction of total CO_2 emissions in the CD fields was expected, or at least a comparable or lower CO_2 emissions compared to those observed in the reference fields, but no such conclusive results were obtained. The best and closest to the expected results were achieved in one of the fields in Meņģele (Figure 8) and Smiltene CD (Figure 9). In these fields, the difference between the reference and CD fields has levelled off at the end of summer, when the season's highest CO_2 emissions appear in the data, or even CO_2 emissions are lower in the CD fields. These observations suggest, at least in part, that in CD fields it is possible to mitigate CO_2 emissions through CD at sufficiently high-water level rise. It should also be noted that these trends were observed in late summer 2023, when there was virtually no significant precipitation for almost three months, so the differences in CO_2 values were observed at a time when the impact of CD is most pronounced.

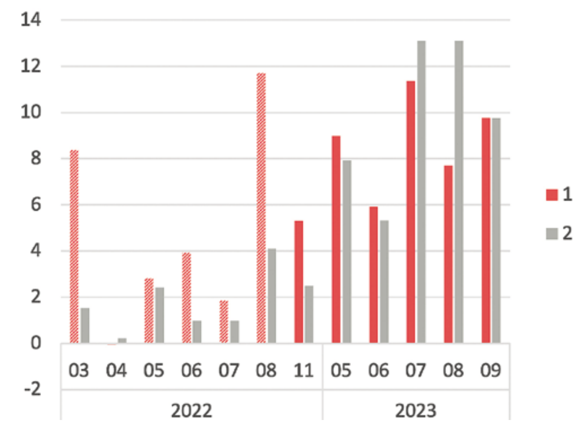


Figure 8. Average CO_2 emissions (t/ha per year) and their changes after water retention in the controlled drainage (CD) field (1) compared to the adjacent reference field (2) in the LIFE CRAFT Meņģele pilot area – one of the three controlled drainage demonstration areas set up in the pilot area. Legend: pink striped columns – no water retention in CD field; filled pink columns – maximum water retention in CD field occurs.

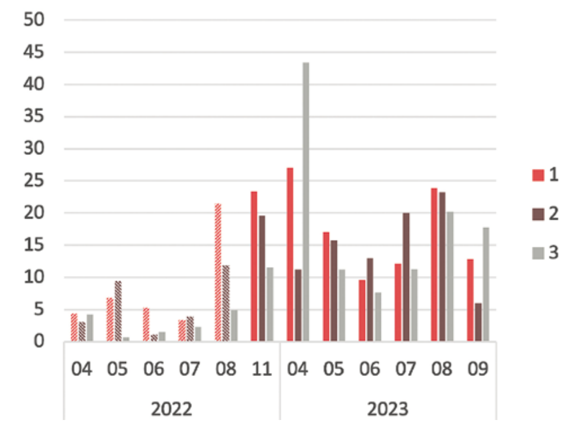


Figure 9. Average CO2 emissions (t/ha per year) and their changes after water retention in the controlled drainage field sections (1, 2) compared to the adjacent reference field section (3) in the LIFE CRAFT Smiltene pilot area. Legend: pink striped columns - no water retention in CD field; filled pink columns - maximum water retention in CD field occurs.

The N_2O data show that all fields (both CD and reference) attracted N_2O. In general, the highest N_2O accumulation in the pilot sites occurs in early spring and late autumn. It should be noted that the fields were covered with snow in winter and then no GHG measurements were made. N_2O accumulation in summer was the lowest. In the Meņģele pilot area, compared to the reference fields, increased N_2O accumulation was observed in almost all CD fields with run-off retention (Figure 10). In contrast, the data from the Smiltene pilot area were less clear (Figure 11). There contrary to expectations, in the part of the field where more soil moisture was retained, N_2O accumulation was lower or even turned into negligible N_2O emissions in some months. This is unlikely to be due to waterlogged soil conditions, as the opposite effect was observed in summer, when generally prolonged drought conditions were pronounced and the retained soil water level was about 50 cm lower than in spring, when at even higher water saturations, N_2O was accumulated in the soil at least as much as in the reference area. N_2O issuance observed in September cannot be associated with wet conditions either, as September 2023 was also drier, but hotter than usual. Perhaps a relatively higher soil saturation with water and a markedly higher soil temperature in the second half of summer in soil are more significant here, when both these conditions have contributed to greater anaerobic microbial activity in the KD field.

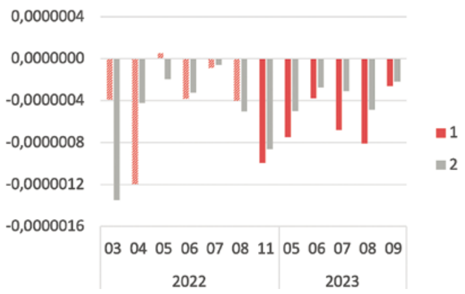


Figure 10. Average N_2O emission (t/ha per year) removals and changes after water retention in the controlled drainage field (1) compared to the adjacent reference field (2) in the LIFE CRAFT Meņģele pilot area – one of the three controlled drainage demonstration areas set up in the pilot area. Legend: pink striped columns – no water retention in CD field; filled pink columns – maximum water retention in CD field occurs.

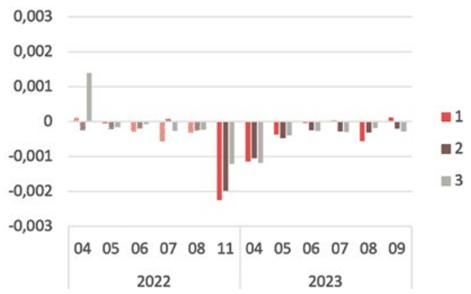


Figure 11. Average N2O emission (t/ha per year) removals and their changes after water retention in the controlled drainage field sections (1, 2) compared to the adjacent reference field section (3) in the LIFE CRAFT Smiltene pilot area. Legend: pink striped columns – no water retention in CD field; filled pink columns – maximum water retention in CD field occurs.

According to the literature, mineral soils on agricultural land are methane sinks, as also confirmed by LIFE CRAFT monitoring data. In general, CH_4 accumulation, as with N_2O, is more pronounced in early spring and autumn and decreases in summer. Total methane accumulation is relatively low in both pilot areas. The effect of CD is minimal, but CH_4 accumulation is reduced compared to the reference areas. This cannot be said for later autumn and early spring, when it is still higher and, in terms of CH_4 emissions, 10 times higher than in summer.

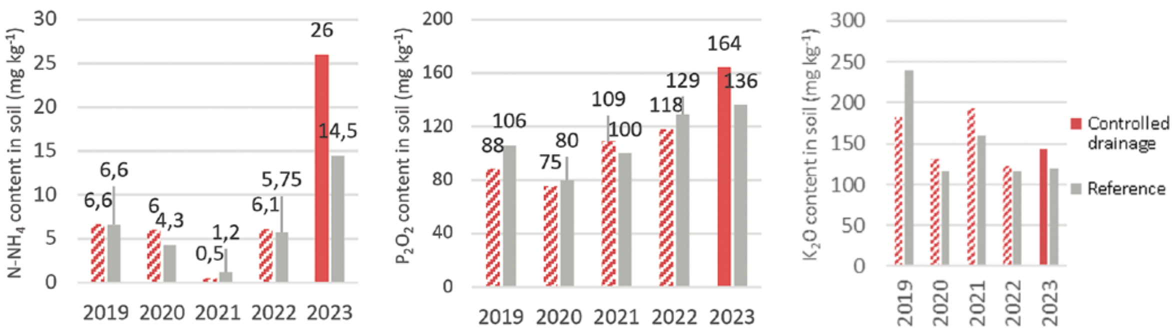


Figure 12. Changes in the average values of soil agrochemical parameters (N-NH_4, P_2O_5, K_2O) after water retention in the controlled drainage field compared th the adjacent reference field in the LIFE CRAFT Meņģele pilot area – one of the three controlled drainage demonstration areas set up in this pilot area. Legend: pink striped columns – no water retention in CD field; filled pink columns – maximum water retention in CD field occurs.

The results of the CD on nutrient retention were quite in line with the expectations of the LIFE CRAFT project. Soil agrochemical analyses showed that after water retention in CD and regulated fields, ammonium nitrogen (N–NH_4) and phosphorus oxide (P_2O_5) content increased, but nitrate nitrogen (N–NO_3) content had unexpectedly decreased. This was particularly true in the Meņģele pilot area, where the CD and reference fields were already the most similar in terms of soil, topography and hydrology before the experiments were carried out. In this CD area, after water retention, the N–NH_4 and P_2O_5 contents of the soil were in average 11,5 mg/kg and 28 mg/kg higher than in the reference area, the content of K_2O in soil (less pronounced than the two parameters mentioned before in both Meņģele and Smiltene CD fields) had also increased after water retention (Figure 12). Previously, in both pilot areas, the soil content of K_2O was higher in reference areas. In the Smiltene pilot area and other parts of the Meņģele pilot area, these observations were not as pronounced due to the larger differences between the CD and reference fields. The other soil agrochemical parameters evaluated (exchange Mg, Ca, sulphate sulphur (S–SO_4) and trace elements B, Zn, Cu, Mn in soil) showed no clear connection with the effect of CD regulation in the pilot areas.

Data on changes in dissolved phosphorus and nitrogen nutrients (P–PO_4, N–NH_4, N–NO_3, N–NO_2, total N, total P) in drainage water between the CD and reference fields were also collected by the LIFE CRAFT project. However, the data obtained are not sufficiently convincing for conclusions to be drawn. After the commencement of water control for CD wells during the summer season and in particular due to the beginning of the dry summer of 2023, water flow over the shutters did not develop, therefore it was not possible to obtain samples for analyses with such a methodological approach. On the other hand, it demonstrated the efficiency of the water retention of the CD wells, as there was no water drainage from the field. This means that nutrients were not flushed out of CD fields during this period, as opposed to reference fields which did not produce any drainage from the field during the driest period of the season only. These results, together with a more detailed analysis of the above monitoring results, will be presented in the final monitoring report, which will be made publicly available on the LIFE CRAFT website at the end of the project.

The effect of CD on yield was negligible and remained similar between CD and reference fields in the LIFE CRAFT pilot areas. In the pilot area of Smiltene this can be explained by precision farming, which is adapted to the changing conditions of the site and accordingly delivers optimum amounts of fertilisers and pesticides for maximum productive yield. In the Meņģele pilot area precision farming was not applied. For this area the explanation could be the heterogeneous soil and terrain conditions of the CD and reference fields, which were reflected differently both in the operation of the CD system and in the overall harvest data respectively. Furthermore, the Meņģele farmer was not able to supply individual harvest data for each reference and CD field area studied, only the total annual harvest data for the entire area of the pilot site were supplied for monitoring analysis.

Conclusions

Overall, the results of the LIFE CRAFT project in Latvia and studies on CD in other parts of the world show that CD is recommended for agriculture to reduce drought risk and ensure a more balanced water regime to adapt to and mitigate the adverse impacts of climate change on the agricultural sector. In order to achieve the desired effect, it is essential to properly assess the suitability of the field for CD establishment, taking into account the characteristics of the soil, the homogeneity of the terrain and the condition and layout of the existing land amelioration system. In fields with homogeneous soil properties, flat terrain with a slope of no more than 1 %, CD will give the most effective results with the selected crops (winter or spring) and a water level regulation appropriate to the rainfall regime. It is essential to familiarize designers and builders with the specifics of not only the installation but also the adjustment of the CD, including the equal height ratio of the drainage control wells of the gate system from the topsoil, and design the CD system to enable the fields to homogeneously retain groundwater at a certain height from the topsoil. This may not always be possible in rural areas where the layout of the previous land amelioration system does not allow it.

The aim of the LIFE CRAFT project was to test the use of CD in situations that are most common in Latvia, i.e. most fields do not have highly homogeneous soil characteristics, most of them have a pre-existing, mostly pre-1985, traditional covered land amelioration system and in most cases, with the exception of the Zemgale plain, Latvia has more or less pronounced surface relief variability within the fields. The two pilot areas of Smiltene and Meņģele met the circumstances and the results show a relatively wide range of difference. The results of studies carried out elsewhere in the world are easier to interpret and compare because the trials are specifically designed to investigate specific factors in detail, so the study sites for the CD and reference sites are specifically designed to be identical. The LIFE CRAFT project is a test of this previous scientific research in real agricultural production conditions in Latvia. Overall, it shows that:

- In Latvia, CD can be recommended primarily to reduce drought risk and nutrient output reduction. This can benefit farmers through lower fertilizer application rates and for the environment, in particular aquatic ecosystems – reduce the adverse effects of eutrophication.
- With regard to GHG mitigation in fields dominated by mineral soils with relatively low carbon content, further multi-seasonal studies of CD under more homogeneous field conditions would be needed to clarify the main influencing factors and to provide a precise assessment of the recommendation of CD as a potential climate change mitigation practice.

- The results of the LIFE CRAFT GHG monitoring generally indicate that the in-season practice of CD does not cumulatively reduce the N_2O and CH_4 sinks of these fields in Latvia, but the impact on C_2O emission factors needs to be further investigated, as the results from the project were ambiguous – in some fields CD regulation coincided with CO_2 emission reductions, while in others it did not.

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INSIGHTS FROM CLASSICAL LONG-TERM EXPERIMENT IN DENMARK: STORING CARBON AND COMBATING CLIMATE CHANGE BY CONVERTING POOR ARABLE LANDS INTO SEMI-NATURAL GRASSLANDS

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Abstract

Converting poor arable land to permanent grassland remains an efficient option for increased carbon (C) storage in agricultural land. Here, I reviewed some related literatures with focus on a recent study by Hu *et al.*, 2019. They quantified changes in C and nitrogen (N) in topsoil from the Sandmarken experiment (initiated in 1894 in Denmark) before and after its conversion to semi-natural grassland in 1998. In the arable phase, sandy topsoil showed mean losses of 0.10 tonnes C and 0,01 tonnes N ha−1year−1,whereas $\delta^{13}C$ increased by 0.002‰ and $\delta^{15}N$ by 0.013‰. Grassland establishment reverted losses of C and N to gains of 0.29 tonnes C and 0.017 tonnes N ha^{-1} $year^{-1}$; $\delta^{13}C$ now decreased by 0.065‰ and δ15N by 0.074‰. Converting this low-yielding sandy soil from arable to grassland use provided an overal annual gain of 0.39 tonnes C and 0.029 tonnes N ha^{-1} in the topsoil. Changes in $\delta^{13}C$ and $\delta^{15}N$ indicated a reduced rateof C turnover and a less leaky N cycle under grassland.

Introduction

Soil is a key compartment for climate regulation as a source of greenhouse gases (GHGs) emissions and as a sink of carbon (C). Soil stores vast amounts of C, and the first meters of mineral soils contain between 1.500 and 2.400 Pg (Petagram, Pg=1015 g) of organic C. That is approximately three times the stock of carbon in vegetation and twice the stock of C in the atmosphere [1]. About 44 % of this C pool is held in the top 0.3 m of the soil, the layer that is most prone to be altered by changes in soil use and management [2]. Therefore, small changes in soil C stocks can have significant impacts on the atmosphere and climate change, and it has been suggested that C sequestration into the soil could be a significant greenhouse gas removal strategy [3].

Land use, land-use change and forestry (LULUCF) is one of the five sources of greenhouse gases included in the United Nations Framework Convention on Climate Change (UNFCCC) and impact global GHGs emissions, biodiversity and land quality [4]. The loss of soil organic carbon (SOC) from agricultural land is identified as one of the eight major threats to soils as it negatively influences soil fertility and the soil's function of providing ecosystem services [5]. There is growing international interest in better managing soils to increase SOC content to contribute to climate change mitigation, to enhance resilience to climate change and to underpin food security.

Cropland and grassland are the major land uses in Europe, and the size of the soil C pool in both cropland and grassland could significantly impact the European C budget [6]. Changes in any of these land use can have substantial effects on the amount of C stored in soil [7]. Large losses of soil organic carbon usually occur when converting permanent vegetation such as grassland to arable rotations dominated by annual crops with rapid losses of C in the early phase after conversion and slower losses as the arable land use continues [8].

Poeplau and Don (2013) carried out the study in 24 paired study sites in Europe comprising the major European land use change types, cropland to grassland, grassland to cropland, cropland to forest and grassland to forest. The researchers found that the SOC sequestration after grassland establishment on croplands equaled the SOC sequestration of cropland afforestation [9]. Therefore, one possible option to store more C in soil can be reverting degraded and arable lands with small C content and limited productivity to permanently vegetated soils such as semi-natural grasslands [10]. This chapter is based on the study of Hu *et al.* (2009). They evaluated the decadal-scale changes in topsoil carbon (C), nitrogen (N), ^{13}C and ^{15}N contents of arable land with different management in Denmark over decades and then converted to semi-natural grassland.

Changes of soil organic carbon contents result in carbon emissions

The EU Commission has identified organic carbon (or organic matter) decline as one of the main threats to soils within Europe [11]. In general, a soil with higher organic C content will have more stable structure than the same soil at lower organic C content, be less prone to runoff, erosion or surface capping and have a greater water infiltration rate, water retention and greater porosity. The C balance of soils is mainly controlled by land use, cultivation history, vegetation dynamics, soil characteristics and climate. The input of C to the soil is affected by biomass production, loss of biomass via land use (harvest) and the rate of biomass allocation from aboveground to the soil. The output of C can be through the mineralization which the rate is controlled by soil texture, soil acidity, organic matter content, labile C pool, litter quality, soil moisture and soil temperature resulting in high or low microbial activity 1. In terms of soil C sequestration, the benefit of converting long-term arable land to semi-natural grassland has two components: the increase in soil C ascribed to grassland vegetation, mostly below ground, and the avoidance of soil C losses resulting from a continuation of the arable management [12, 13]. Additional of macro nutrients such as nitrogen (N) and phosphorous (P) might be a major benefit on poorly managed or degraded sites, such as unimproved grasslands [14].

For example in UK [15], land use, land-use change and forestry (LULUCF) projections on achievable carbon sequestration in mineral and organo-mineral soils suggest that grassland soils will sequester 10.347 k tonnes of CO_2 by 2050 (i.e. ~10 million tonnes of carbon dioxide (CO_2) in the 0 to 1 m soil depth layer). Grassland cover is about 36% of the land area in the UK, and this means a soil C sequestration potential of roughly 2822 k tonnes of C over the next 30 years. Most of this soil C (1865 k tonnes of C) will be sequestered in 'remaining grasslands' (not change in land use). About 1000 k tonnes of C will be gained in soils from the conversion of cropland to grassland. Cropland is not associated to any C gains in mineral soils but is considered a net source of C emissions (3842 k tonnes of C by 2050).

Policymakers are increasingly focusing their attention on measures for SOC conservation while considering other potential environmental impacts on increasing the rate of C sequestration (e.g. Increased soil N from fertilization in the sequestered organic matter could lead to increased nitrate leaching or N_2O emissions from soils [16, 17]).

Agricultural management effects on soil organic carbon contents

Agricultural soils have the potential to act as carbon sinks following implying some measures such as: changes in land-use from arable cropping to long-term grasslands, the introduction of no or conservation tillage systems, changes to fertilizer inputs, increases of C input from organic amendments, maintaining a more shallow water table and rewet grasslands on peat soils, considering permanent revegetation of set-aside areas with perennial grasses, cover crops or woody bioenergy crops instead of rotational fallow [18]. Further, improvements in farm machinery may also have led to increased crop residue removal. Changes in practice over the period, such as increasing production of silage in place of hay, which removes more residue and decreases soil C stocks may also have led to more crop residue being removed from managed cropland and grassland. These changes in technology and practice are predicted to have a large impact on soil organic C stocks in the future [1, 19].

Among all possible potential methods to sequester C, grassland remains a very important carbon 'sink'. It has been shown that conversion of arable land to grassland could increase rates of soil C sequestration between 0.3 and 0.8 tonnes C ha^{-1} yr^{-1} (Dawson and Smith, 2007). Comparing soils across seven sites in the UK, Powlson *et al.* (2012) showed that zero tillage contributed to increased soil C accumulation by 0.31 tonnes C ha^{-1} yr^{-1}. Evidence using the agricultural model (Roth-CNP) shows that arable land in the UK has lost SOC by − 0.18, − 0.25 and − 0.08 tonnes C ha^{-1} y^{-1}, whereas land under improved grassland (e.g. better crop varieties and mechanization) has increased SOC stock by 0.20, 0.47 and 0.24 tonnes C ha^{-1} y^{-1} during 1800–1950, 1950–1970 and 1970–2010, respectively [20]. Furthermore, larger C inputs from above- and below-ground grass residues usually enter in topsoil during the grassland phase rather than arable land phase, and the quality of materials are ranked in lignin and waxes which have low decomposition rate in compare to crop residues from arable lands [21].

Case studies from recent and more than century long experimental plots

Agricultural management has a long-lasting influence on soil organic carbon. The long-lived effects of agricultural management can be found in the cropland sites at Rothamsted UK, which show that the influence of manure that was applied between 1852 and 1871 and then discontinued, could still be seen in the organic matter levels over 100 years later [8]. Another study shows how ryegrass (*Lolium perenne* L.) ley set-aside significantly contributed to enhance soil conservation and how soil organic matter content increased consistently and significantly from 20.4 g kg^{-1} in 1991 to 31.1 g kg^{-1} in 2001 on the set-aside experimental plots [22].

The absence of tillage seems leading to development of the grass root system with associated positive effects in pointing out the necessity to consider bonding as well as binding mechanisms in soil structural stabilization [23, 24].

In the study by Hu *et al.* (2019), it was hypothesized that conversion of cropland to permanent grassland would increase soil C stocks, and SOC stocks would be larger in plots with a history of manure or fertilizer inputs than in plots with no fertilizer. Therefore, they evaluated changes in C and N in topsoil from poor sandy soil in Denmark before and after its conversion to unfertilized semi-natural grassland. The soil of study was considered marginal for arable due to its poor productivity. Therefore, the risk of indirect land-use change to compensate for lost production was minimal. The experiment was part of Askov Long Term Experimental Station started in 1894. The field was kept under well-documented arable management for 75 years. Following the crop harvest in 1997, nutrient additions ceased and the arable crop rotation site was converted to permanent grassland with perennial ryegrass and red fescue (*Festuca rubra* L.) sown in mid-March 1998. The grass was mown once or twice every year with the cut biomass left on the plot. Thus, grass productivity was not determined. The Sandmarken site has been considered since 1998 as a semi-natural grassland with no fertilizer application and no removal of plant biomass. Since the soil is acidic, Magnesium-enriched lime was applied in 1997 (4 tonnes ha^{-1}) before grass was sown and again in 2005 (3.5 tonnes ha^{-1}) when grass was reseeded directly into the grass sward without any other cultivation.

The available information on weather records, harvest yields and soil characteristics made this site a unique research platform. Archived soils sampled during 1942–2012 were analysed for C, N, ^{13}C and ^{15}N. The results are shown below from Hu *et al.*'s paper.

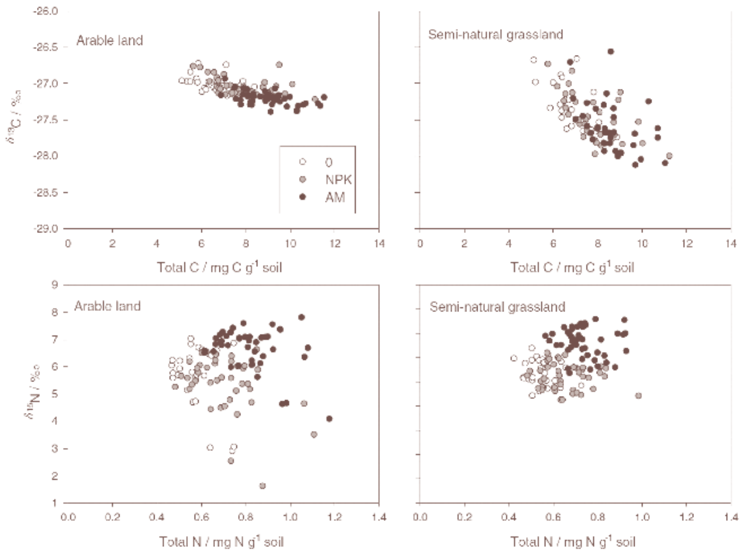

Figure 1. The relation between concentration of C and $\delta^{13}C$, and between concentration of N and $\delta^{15}N$ in Sandmarken topsoil (0–20 cm) during the arable land (1942–1997) and semi-natural grassland (1998–2012) phases. The treatments unmanured (0), mineral fertilizer (NPK) and animal manure (AM) were applied only in the arable phase.

In Denmark, pre-1894 agriculture was based on rotations dominated by grass–legume leys used for hay [25]. The grass–legume sward was ploughed after 5 to 7 years, then one cereal rye crop was grown followed by two to three oat crops. The change from this ley-rich management system to the experiment's rotation in 1894 with a dominance of annual crops, removal of aboveground plant biomass and frequent tillage has probably introduced a general decline in soil C content regardless of subsequent fertilizer regimes. This decrease in pre-1894 soil C probably explains why the topsoil continued to lose C and N during the arable phase. Since 1923, losses occurred at the same rate but the different treatments had different yields at harvest, and thus different returns of crop residues to the soil were reflected in the contents of C and N (0<NPK<AM). The simultaneous loss of C and N meant that the C/N ratio differed little during the arable phase.

The $\delta^{13}C$ is an isotopic signature, which is widely used in the reconstruction of past events. In Hu *et al.* (2019)'s study, the increase in $\delta^{13}C$ was associated with an increase in the proportion of stable soil C ascribed to resistant soil organic matter. The decrease in topsoil $\delta^{13}C$ during the grass phase averaged 1‰ and is attributed to the more negative $\delta^{13}C$ of the grass input and a larger C input with above- and belowground grass residues. A selective accumulation of resistant to decomposition plant residue components that has small ^{13}C content (e.g. lignin and waxes) might have contributed to the decline in $\delta^{13}C$ that occurred when the arable land was converted into unfertilized grassland [26].

Changes in topsoil N differed from changes in C, and the C/N ratio of the soil organic matter increased from 8 in the arable phase to 17 in the grassland phase. During the grassland phase with no N2-fixing legume component and no applied N, the only source of N would be atmospheric deposition. In the Askov area, wet deposition (not considering dry deposition) of ammonia and nitrate accounts for 0,02 tonnes N ha^{-1} $year^{-1}$. This N input corresponds to the average annual increase in soil N measured during the grassland phase (0,02 tonnes N ha^{-1}), suggesting that little N was lost from the topsoil after conversion to grassland. The establishment of a less leaky N cycle in topsoil under unfertilized semi-natural grassland corroborates our data on ^{15}N abundance. Because of isotope fractionations associated with losses of N by ammonia volatilization and by nitrification with nitrate subject to plant uptake, leaching or denitrification, soils with considerable losses of N become enriched in ^{15}N. During the arable phase, the topsoil showed an increase in $\delta^{15}N$ with soil subjected to the AM treatment; the values were larger than for unmanured soil and soil with the NPK treatment. The larger $\delta^{15}N$ value in AM soils was a result of application of ^{15}N-enriched manure 27.

Conclusion

Converting low-yielding arable land to semi-natural grassland can be an efficient management option for increased C storage in agricultural land. This is because of increased C inputs from grassland vegetation and the elimination of a continuous loss in C from soil under arable management. Although different fertilizer history in the case study did not affect changes in C significantly, the soil with the smallest initial C content had the greatest potential for C storage when converted to grassland. Changes in $\delta^{13}C$ and $\delta^{15}N$ suggested a reduction in the rate of C turnover and a less leaky N cycle under grassland. In conclusion from case study of Hu *et al*. 2019; during the 75 years of arable management in the experiment, the average annual loss of soil C was 0.10 tonnes ha^{-1}. Then during the 14 years of unfertilized semi-natural grassland, the soil gained C at an average annual rate of 0.29 tonnes C ha^{-1}. Thus, the overall benefit of this change in land use from unproductive cropland to unfertilized semi-natural grassland represents a net rate of C sequestration of 0.39 tonnes C ha^{-1} $year^{-1}$.

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NO – TILL AS AN OPTION TO REDUCE CO_2 EMISSIONS

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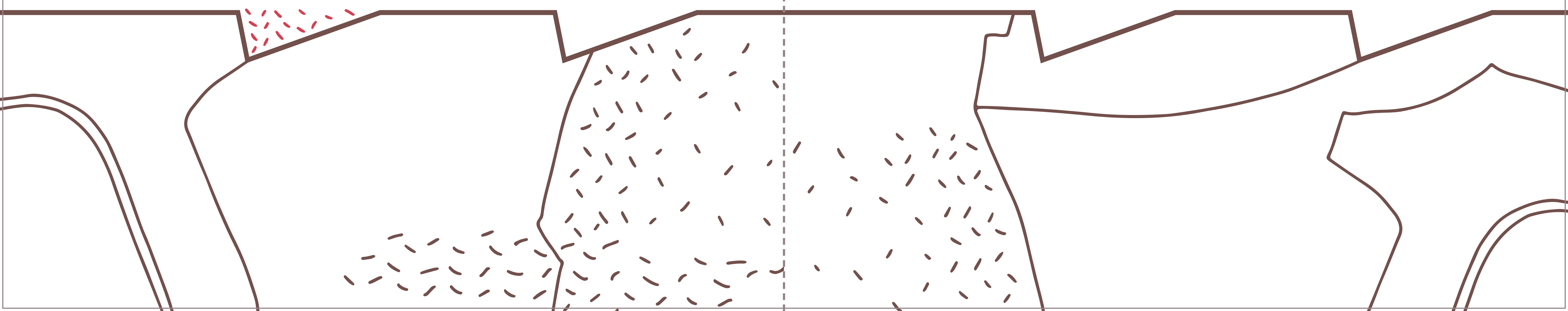
Introduction

Soil is the main resource for agricultural production, has formed over thousands of years and is taught in natural science classes already from 4th grade. Soil formation is unthinkable without plants, different organisms, sunlight, heat and water. Nature has it so that all these components interact with each other and everything seems to happen by itself. However, a deeper look reveals that the processes of soil formation are logical and follow a certain order. The seed germinates only when it is in the soil, when the soil is sufficiently warm and moist, and when there is enough sunlight for the whole process. Once the sprout has sprouted, photosynthesis starts, thanks to sunlight and carbon dioxide in the air, which leads to the formation of different carbon compounds – sugars. Interestingly, about 1/3 of the sugars produced by photosynthesis are literally sucked up by the plant through the root system into the soil [1], where these compounds serve as food for soil micro-organisms, which in turn convert these sugars into nutrients available to plants, thus returning the nutrients produced by the plant itself back into the plant and ensuring its growth. Once the plant has grown and fruited, it slowly dies and ends up on the surface of the soil, where it is crushed by insects and then literally recycled by fungi and bacteria - just like in a compost heap. It is very important to understand that every step in this natural process is important – if any one of them falls out or becomes weak, the whole process is disrupted. Unfortunately, it must be acknowledged that, it is humans who are disrupting the normal processes of soil formation by over-tilling and using plant protection products [2].

Direct sowing is a form of no-till technology. In this method, the only soil treatment is the lifting of the seed into the soil. This leaves the soil virtually untouched and preserves plant residues, which in turn protect the soil from the harmful effects of the weather, limit the growth of annual weeds and provide a food base for the various organisms that live in the soil. The result is improved microbiological activity, soil structure, water and air cycle, fertility, organic



matter content and disease resistance. Direct sowing reduces the amount of CO_2 released from the soil and successfully accumulates the carbon in the air through the plants and micro-organisms growing in the soil, thus increasing the organic matter content of the soil in the long term. Examples from around the world show that direct sowing fields tend to produce even higher yields [3] than conventional soil treatments. Direct sowing significantly increases productivity, but reduces labour and fuel consumption, as well as expenditure on machinery, repairs and maintenance [4].

Within the LIFE CRAFT project, Latvian Rural Advisory and Training Centre in cooperation with eight farms in Latvia is testing the direct sowing method. To compare the obtained results, the project farms also maintain fields where farmers continue with traditional soil treatments. These fields have the same growing conditions and crops as those sown with direct sowing.

Although there are farmers in Latvia who are already working with different no-till methods, the LIFE CRAFT project helps to evaluate the effectiveness of direct sowing and strip-till by analysing the soil structure and composition, the obtained yields and the resources needed to use the method.

Direct sowings impact on CO_2 emission intensity

In agricultural production greenhouse gas emissions are an unavoidable factor, both directly from soil treatment and operating machineries and indirectly from the production of fuel, fertilisers and machinery.

If we know how much a tractor emits during work hours, the cost of producing diesel is about 30 % higher [5]. If we know that, for example, when using direct sowing method a 200 hp tractor uses about 15 litres of diesel per hectare, and that one litre of diesel burns about 2.7 kg of CO_2 [6], then the total CO_2 emissions per hectare are 2.7X15+30%=52.7 kgC from diesel alone.

When it comes to CO_2 emissions from fertilizer use, scientists at the University of Cambridge estimate that they account for around 5 % of total greenhouse gas emissions. Together with organic fertilizers, the use of mineral fertilizers emits 2.6 gigatonnes of CO2 into the atmosphere every year – more than the combined emissions of aviation and shipping. Scientists estimate that almost half (48 %) of the world's population consumes food which is produced with synthetic fertilizers. The good news is that, if managed wisely, these emissions by 2050 can be reduced by 80 % [7].

Studying four different soil treatment technologies on a sandy-clay soils in the northwestern US, scientists recorded CO_2 emissions over 19 days from the time the soil was tilled [8]. Tillage with a plough incorporated all plant residues into the soil, leaving the soil upper layer loose and at the

same time generating the highest CO_2 emissions. Carbon emissions in the form of CO_2 as a percentage of that year's residual plant carbon (C) over 19 days from the four different tillage treatments were 134 % for the plough (actually more is lost than is present, with a constant decrease in soil organic matter year on year), 70 % for the plough in combination with discs, 58 % for discs, 54 % for the furrow cultivator and 27 % for direct sowing.

According to research by scientists at Ohio University, wheat reeds have a C/N ratio of about 80/1, which means that for every kilogram of nitrogen, the straw contains 80 kilograms of carbon [9]. On one hand, this ratio is the reason why reeds decompose relatively slowly (rapid mineralization occurs when the C/N ratio is less than 20/1), but on the other hand, it is the actual kilograms of nitrogen and carbon that remain on the field after harvesting. What we do with them is our choice. To give you some food for thought, let's calculate how much carbon we lose from different types of soil treatments. If we assume that one tonne of winter wheat reed contains about 5 kg N [10], then this equates to 400 kgC/t when converted proportionally. Assuming a yield of a modest Zemgale field are 6 tonnes per hectare, the total C content of the reeds is 2400 kg. So, 3216 kgC per hectare is lost each year by plough, 1680 kg by plough in combination with discs, 1392 kg by discs, 1296 kg by furrow cultivator and only 648 kg by direct sowing. Direct sowing leaves more than one and a half tonnes – 1752 kgC – per hectare in the field as food for different soil organisms. This trend is also very evident in the measurements carried out during the project, as shown in Figure 1.

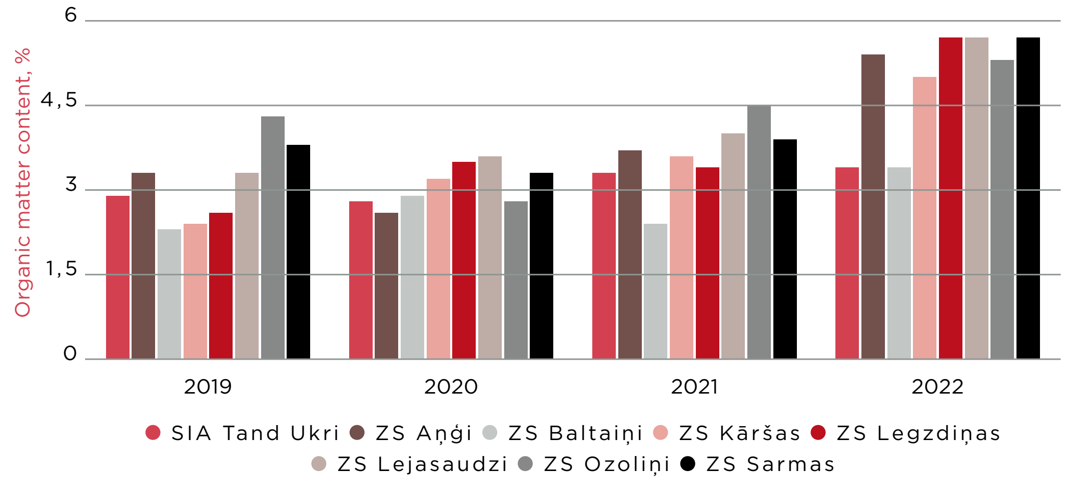


Figure 1. Soil organic matter content (%) in direct sowing fields in 2019–2022. The figure shows that the soil organic matter content is constantly increasing.

Practical implementation aspects of direct sowing

The introduction of direct sowing and strip-till, like any sowing process, starts at harvest. Unlike traditional technology, where the plough can correct harvesting mistakes by ploughing in the reeds, in direct sowing, uneven spreading of reeds can lead to poor field germinability. Reed tends to interfere with seed-soil contact – especially if you are working with a disc drill and the reeds are wet. In this case, the disc simply pushes the reeds into the seed furrow and sows the seed on it – there is no soil contact and no moisture for germination. To avoid this, you need to think very carefully about how the combine harvester moves through the field, trying as much as possible not to stop when the thresher is still working and the reeds are piled up. The problem can be partially solved by using a reed harrow, but this means extra time, fuel (although relatively little – around 2l/ha) and an extra machine – all of which make the process more expensive. Regular checking, sharpening or replacing of the reed shredder's blades will also help – and a chaff spreader will not be an unnecessary luxury.

Although our Finnish colleagues recommend a couple of years of grassland generation before switching to direct sowing in wheat/rapeseed fields, during the project we have come to the conclusion, that direct sowing works without this condition. Initial concerns of dramatic yield reductions have disappeared without a trace. On the contrary – on farms with particularly difficult soil conditions, these heavy fields no longer need ploughing, and from soil sampling twice a year it is very clear to us, that the soil is gradually becoming more alive, plant roots are penetrating deeper and the soil is even changing colour – becoming darker. The paradox seems to be that heavy soils are even better suited to direct sowing, as they are better able to retain their structure than sandy soils.

Of course, the choice of sower machine will always be an issue. You have to realize that there is no perfect sower machine and each has its advantages and, above all, its disadvantages. On some technical matters.

If disc sowing ploughshares are chosen, seed germination problems can occur in wet, unevenly dispersed and poorly chopped reeds. Discs tend to press the reeds into the soil (especially in light and loose soil) without cutting them and creating the so-called hairpin effect, where the seed is planted on the reed and it has no contact with the soil and its moisture.

This problem can be somewhat prevented by fitting a separate row of discs to the sower machine before the ploughshare. A disc in front of each ploughshare reduces drag, cuts reeds and roots, creates a seedbed and helps the ploughshare to sow the seed better. Depending on the composition and quantity of plant residues, you can choose smooth (least plant residues), corrugated or wavy discs. The latter clean the plant debris and slightly loosens the furrow where the ploughshare will then cut the furrow.

Another alternative to tackle the problem of plant residues is to use furrow cleaners. Usually they are star-shaped rotating elements of the sower machine, that are placed just before the ploughshares. There are both single and dual rotor cleaners. It has been observed that the single rotor option works better (especially in wetter conditions) as the reeds and soil tend to get trapped between the two rotors, preventing a good cleaning of the seed furrow.

If you choose a sower machine with chisel ploughshares or a StripTill sower machine, you have to take into account the need for more traction power (+15-20 %) and the problems of working in stony fields. At the same time, these sower machines will never have a problem with the seed being stuck on the reed. For a chisel-type sower machine, it is important to arrange the sowing ploughshares in as many rows as possible so that the distance between the ploughshare in each row is as large as possible. This will ensure a smoother flow of reeds between the ploughshare and prevent a rake effect.

If the field is not perfectly flat (micro-relief), it is preferable to choose a sower machine with a separate suspension system for each ploughshare (preferably a parallelogram mechanism with as much vertical freedom as possible), otherwise the regularity of the sowing depth is likely to suffer. Different sowing depths mean that in the micro-lowland seed will be sown shallower or over the top, while on the micro-hills seeds will be sown much too deep. This will result in an unevenly sprouted field, which will then ripen unevenly and inevitably lead to increased grain loss and increased grain moisture (unripe mixed with the ripe) at harvest.

Direct sowing is characterized by a lot of reeds on the field, which with the soil tends to stick to the working parts of the sower machine – especially StripTill machines. It's important to remember not to drive when it gets wet (evening dew or even a little rain) – evenings and nights are better spent at home, rather than freeing the sower machine from clay and reeds that are stuck to the working parts.

There is a myth that direct sowing requires expensive machinery that is only suitable for large farms. There is one farm owner, who went to England in the first year and bought a second-hand 3 m wide StripTill drill for several thousand euros. It is still in full working order.

One of the advantages of direct sowing, especially in spring, is that the soil will not lack moisture. That's why it's a good idea to wait for the soil to warm up rather than sowing earlier. Otherwise, the seed – especially beans sown at the end of March – will simply settle in the soil and germinate at the same time as beans sown in mid-April. So, take your time, you can't actually miss anything with this technology.

Another advantage is the depth of sowing. While traditional technology recommends sowing beans at a depth of 8 cm to ensure that they have enough moisture, for example, direct sowing is perfectly adequate at 5–6 cm, as during intensive tillage the moisture stays in the soil rather than evaporating. These centimetres also refer to the fuel consumption and the wear rate of the sower machines working parts. The deeper we go, the more we spend. Direct sowing is also more fuel efficient – for example, a 4 m sower machine needs about 19 litres/ha when sowing at 5 cm deep, 39 litres at 10 cm and 58 litres at 25 cm – and of course a more powerful tractor.

On one hand, this technology has a drawback. Because there is a relatively high level of plant residues on the topsoil, the soil dries relatively slower than a field that is traditionally ploughed in autumn and stripped in spring. But this disadvantage is only relative – read what we wrote about carbon losses – 3216 vs. 648 kgC/ha – and in the same section about not hurrying; so, the disadvantage turns almost imperceptibly into a benefit.

Analysis of a direct sowing practical demonstration

During the preparation phase of the project around 2016, only a few "crazies" in Latvia were quietly talking about direct sowing, so it was not easy to find farmers who would be willing to participate in the project. The original idea was to choose farms in a region with a traditional ploughing traditions and particularly difficult soil conditions - a place where the general perception is that it is impossible to farm without ploughing. To our surprise, such group of nine farmers was located in Dobele county, and in 2018 the project was able to start.

The project plan was not to interfere with the farmers' choice of crop rotation, but to change the previous ploughing practice to direct sowing or strip-till on one field per farm, chosen by the farmer. Initially everything was sown with hired sower machines, but later with machines already owned by the owners. The success of the project is well described by the fact that during the project five of the eight farms remaining in the project purchased their own sower machines (one farm already had its own sower machine at the start of the project).

As far as crop rotation is concerned, at the beginning of the project, the farms mainly used the traditional "Zemgale" crop rotation, where winter wheat and winter rapeseed are grown, with occasional sowing of beans for greening. However, as the project progressed, intermediate crops and peas were gradually included in the rotation. They had never been used on these farms before. These changes have reduced the use of synthetic nitrogen fertilizers by 30 %.

As CO_2 reduction is one of the main objectives of the project, the emission reductions from the sowing process were calculated during the project, assuming that the other technological processes in the two technologies are not radically different. As we know, CO_2 emissions are caused by several factors: the amount of C we lose from soil treatment; the amount we lose from running machinery and the emissions from producing fuel. Emissions from machinery manufacturing and fertilizer synthesis were not taken into account in the calculations. To make the calculations, you need to know the basic data: the tractor's fuel consumption in different field operations; the C emissions during fuel production; the C losses depending on the soil treatment. Fuel consumption in traditional technology, where discing, ploughing, cultivating, sowing and rolling are carried out, it is around 65 l/ha, but in direct sowing, where only one operation (sowing) is carried out, around 20 l/ha. The difference is 45 l/ha. Knowing that the combustion of one litre of diesel produces about 2.7 kgC [6], we can calculate that direct sowing reduces C*O2* emissions from burnt diesel by 121 kgC/ha. Adding the approximately 30 % from the diesel production process gives 157 kgC/ha. The second component is C losses from soil treatment technologies. Considering that 134 % of the C surplus of the previous year's harvest is lost in conventional technology (only reeds are used in the calculations), but only 27 % in direct sowing [8], in absolute terms, at the relatively low winter wheat yield of 6 t/ha for Zemgale, the difference between the CO_2 losses from conventional technology and direct sowing is 3216-648=2568 kgC/ha. Adding together the differences in emissions from fuel consumption and soil treatment, direct sowing emits 2.689 kgC less per hectare per year than traditional technologies. At the end of the project, the 200 ha demonstration fields will emit 26 768 kgC/ha less per year than before the project.

Emission reductions are closely linked to the cost of sowing. Taking into account the market prices for technical services in 2022 [11], the cost of sowing in traditional technology is 249.73 €/ha, while based on our calculations (including a profit of 15%) the cost of direct sowing is 92 €/ha. Savings – 157 EUR/ha. Multiplied by the 200 ha of the project's demonstration fields, we get a saving of €31 400 in each year.

To investigate changes in soil bulk density, we sampled five demonstration plots twice a year (spring and autumn). 120 samples per year in each field at three locations, four different depths (5–10, 10–15, 15–20, 20–25 cm) and a total of 480 samples in four years. The main conclusion is that soil density is not increasing over the years. So artificial loosening with a plough is not necessary, as this is done by the life forms living in the soil, which, according to the measurements shown in Figure 2, are increasing in number every year. Soil sampling expeditions also show this: the structure of the soil changes visually over the years – it is easier to dig, tiny roots appear deeper and deeper, there are more life forms, the soil (especially the upper layer) is darker.

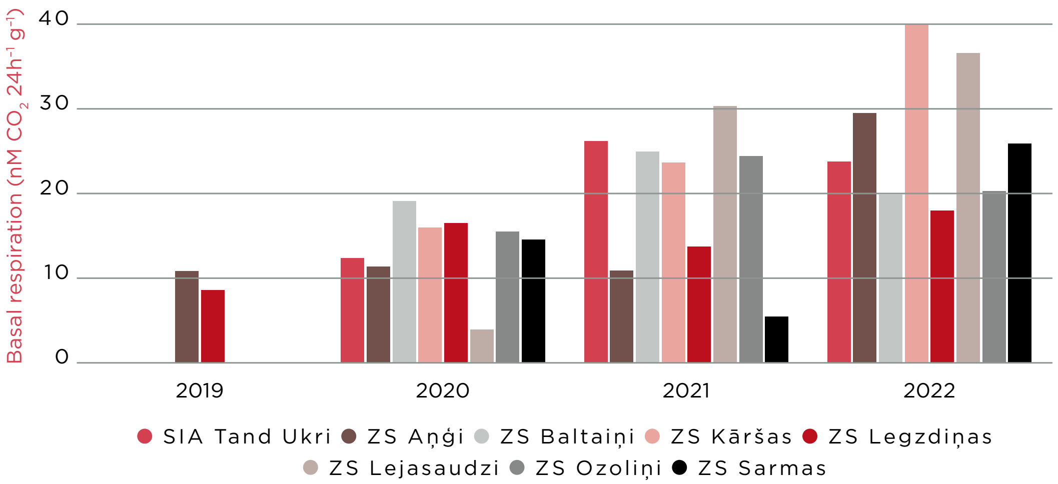


Figure 2. Basal respiration (nM CO_2 $24h^{-1}$ g^{-1}) in direct sowing fields 2019–2022

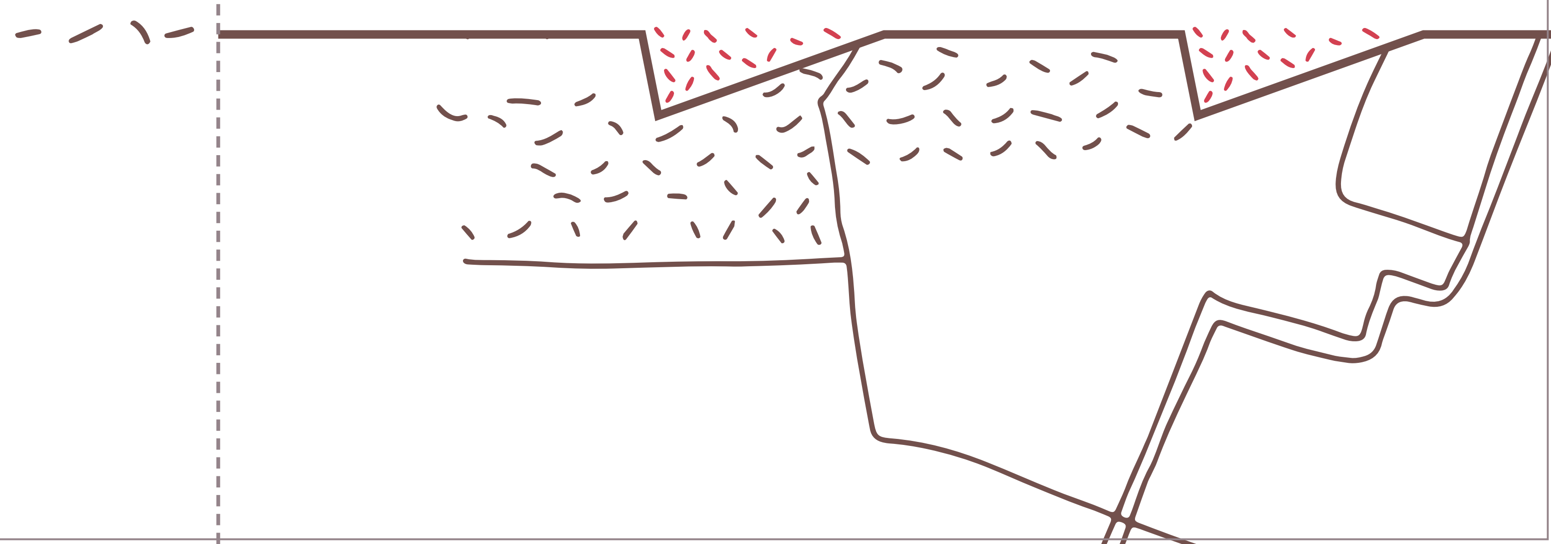
Farmers say that the change from traditional technology to StripTill or direct sowing allows them to get to the field several days sooner after heavy rain than before. This shows that, when worked in this way, the soil better absorbs intense water flow, while at the same time the plant residues on the surface protect the soil from drying out (especially important in spring), rain or wind erosion, and prevent the development of annual weeds (especially if the intermediate crop has done well). A comparative disadvantage is that the soil takes longer to dry out and warms up more slowly. But this is only a partial disadvantage, especially in spring, when there is no need to worry about the seed running out of moisture in May. It is important not to focus on the traditional sowing dates of 15 May and 15 September, but to sow when soil conditions are most favourable. It is virtually impossible to miss something with this technology.

With regard to the capacity of soils to absorb water fluxes from heavy precipitation, it has been scientifically proven that each additional percentage of organic matter in the soil can absorb an additional 25 mm of water.

There is also a public myth about the inevitable increase in the amount of plant protection products (PPL) needed for direct sowing. Our Finnish colleague Timo Rouhiainen from Propax Agro (we visited him in Finland together with the project hosts) with 16 years of trials demonstrates that the consumption of PPL in direct sowing is no higher than in traditional technology. Again, the issue is not about technology, but about sustainable crop rotation, where, in a healthy and living soil, plants fight weeds, diseases and pests on their own.

Conclusions:

1. Compared to traditional technology, direct sowing can reduce CO_2 emissions by 2.689 kgC/ha each year;
2. Direct sowing is 157 €/ha cheaper than traditional sowing;
3. The yields from direct sowing are not significantly different from those from traditional technology;
4. Direct sowing does not lead to long-term soil compaction;
5. Direct sowing improves soil organic matter content;
6. Direct sowing revitalises the soil and improves its microbiological activity;
7. Direct drilling is not a miracle cure for all problems. Direct sowing is an opportunity to farm in a more environmentally friendly way, saving resources, improving soil health, water and air circulation in the soil, reducing costs and making the most of nature's potential. However, the key factor is sustainable crop rotation and not focusing on maximum profit in one year, but on crop rotation combinations that provide plants with airborne nutrients (N and C), protect against diseases and nourish the soil.



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AGROFORESTRY SOLUTIONS FOR ENHANCEMENT OF RESILIENCE TO CLIMATE CHANGE CHALLENGES IN NORTHERN EUROPE

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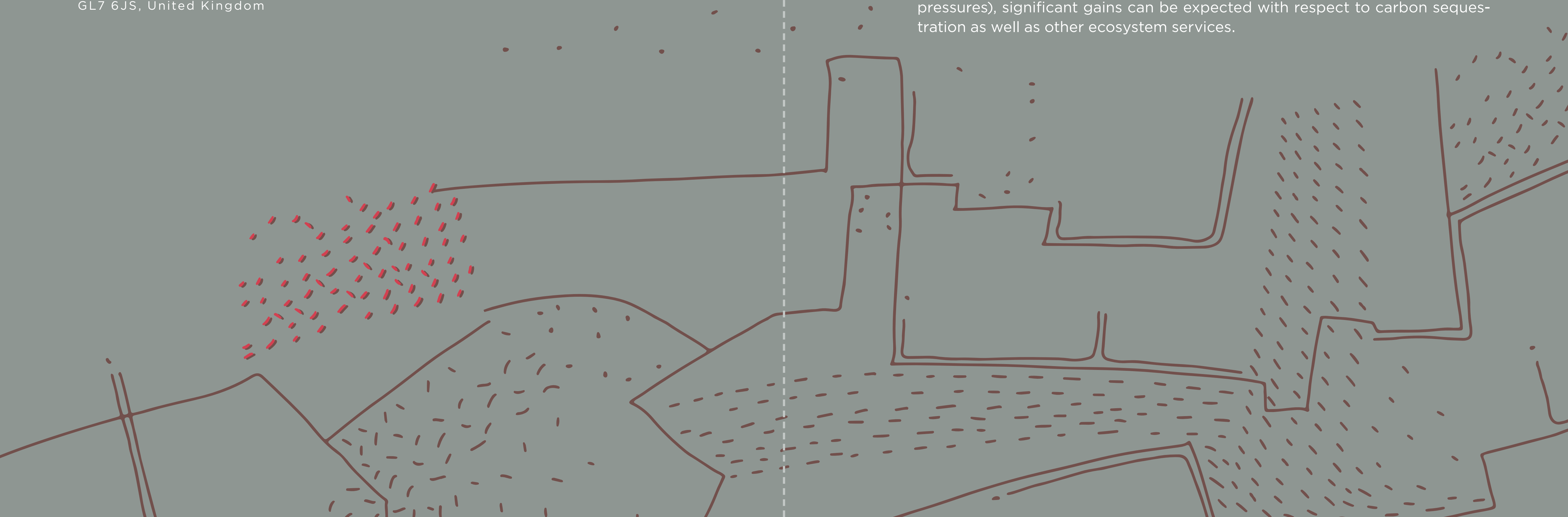
Abstract

Agroforestry, the integration of trees and agricultural systems, can provide a powerful tool in increasing the resilience of our food production systems. As well as mitigating the climate change impacts of the agricultural sector through carbon (C) sequestration, C substitution and facilitating reductions in GHG emissions, agroforestry can play a significant role in helping farmers adapt and become more resilient in the face of climate change through, for example, microclimatic modifications, increased system diversity and a reduction in the risks from flooding and wildfires. In this chapter, we consider the evidence supporting the role of agroforestry in enhancing the resilience of the farming system, as well as impacts on other ecosystem services such as support for biodiversity and soil and water quality. As a diverse system, however, the design, establishment and management of agroforestry can be challenging, and in the second section we outline the key considerations that aim to maximise positive interactions between the trees and crops or livestock that lead to facilitation and minimise negative interactions that result in competition for resources. In the final section, we explore an inspirational example of a highly diverse silvoarable system in the east of England – Wakelyns Agroforestry and detail some of the research evidence that demonstrates how such a system can provide self-sufficiency in energy, higher carbon stocks and higher overall productivity than a monoculture. The potential for increasing the agroforestry area in Europe is considerable, and by targeting agroforestry establishment in high priority areas (i.e. those with multiple environmental pressures), significant gains can be expected with respect to carbon sequestration as well as other ecosystem services.



Introduction

The most recent findings from the European State of the Climate show that Europe is warming at a higher rate than the global average, the temperature increase for Europe is about 0.9°C higher than the global increase and it has also warmed up faster than any other continent in recent decades [1]. Parts of Europe are also warming faster than climate models project and the number of summer days with extreme heat has tripled since 1950 [2].

Agriculture both contributes to and is especially vulnerable to adverse effects of a changing climate. The EU's agricultural sector accounted for 10 % of the Europe's total GHG emissions in 2015 [3]. Reducing the environmental impact of agriculture as well as increasing the resilience of agricultural systems to climate change are fundamental to global sustainability. Agroforestry offers one of the most promising measures to help with both climate change mitigation and adaption [4, 5] as well as having the potential to provide a multitude of other ecosystem services.

Agroforestry can be simply defined as integrating trees and agriculture, including both the establishment of trees on farmland and the introduction of livestock and crops into woodlands. However, successful agroforestry systems are those that are deliberately designed and managed to maximise positive interactions between the tree and non-tree components. The emphasis here is on managing rather than reducing complexity.

Agroforestry systems can be classified according to the components present – silvoarable systems combine trees and crops, silvopastoral systems combine trees and livestock, while agrosilvopastoral systems combine trees, crops and animals. Within these main categories, there are many different types of agroforestry, depending on whether the land use is agriculture or forestry, and whether the trees are located within fields or between fields (Table 1).

Although the term 'agroforestry' has only been in use since the 1970s, integrating trees and agriculture has been practised for thousands of years, evolving from systems of shifting cultivation towards more settled systems involving agriculture, woodland grazing and silvopasture [7]. Since the 1950s, however, trees were increasingly removed from the agricultural landscape as the demand for increased productivity led to crop monocultures, increased mechanisation with a resulting reduction in the agricultural work force and a shift to larger fields and farms with the removal of scattered trees, boundary trees and landscape simplification. These changes in the farming system were supported by policy regimes that favoured single crop systems over crop associations, and removed wooded areas from eligibility for subsidy payments [7].

Table 1.

A TYPOLOGY OF AGROFORESTRY SYSTEMS [6]

	Agroforestry system	Land use classification	
		Forest land	Agricultural land
Trees within fields	Silvopastoral	Forest grazing	Parkland, wood pasture, orchard grazing, individual trees
	Silvoarable	Forest farming	Alley cropping, alley coppice, orchard intercropping, individual trees
	Agrosilvopastoral	Mixture of the above	
Trees between fields	Hedgerows, shelterbelts and riparian buffer strips	Forest strips	Shelterbelts, hedges, riparian tree strips

The environmental impacts of this intensification of agriculture are now well known, ranging from loss of biodiversity, to depleted soils, increased flooding and water pollution. When combined with the predicted impacts of climate change, there is now an increasing interest in agroecological approaches such as agroforestry that combine production with protection of the environment. However, the integration of trees at a low density into agricultural land continues to challenge the conventional specialisation of forestry supported by current agricultural policy mechanisms.

Historically, under the Common Agricultural Policy (CAP), there have been two opposing trends operating with regard to trees and agricultural land. On the one hand, the role of trees has been progressively recognised, and schemes to preserve trees and plant new woodland on farms have been implemented. On the other hand, the main CAP crop and animal support regulations have ignored the existence of trees outside of woodlands and forests and there have been limits on tree densities – if the agricultural area contained trees over a certain density (50 trees/ha within CAP 2005-13 and 100 trees/ha within CAP 2014–2020), the land became ineligible for direct payments. However, within the previous two CAPs, measures have existed within Pillar 2 of CAP that supported the establishment (and more recently, the maintenance) of agroforestry systems, although implementation by member states, and uptake by farmers have both been limited [8]. There seems to be increasing recognition of the potential for agroforestry as a solution to climate change mitigation, adaptation, resilience and biodiversity and organisations such as the European Agroforestry Federation **(www.europeanagroforestry.eu)** are continuing to work hard to promote a joined up approach for agroforestry support in the latest CAP reforms.

Current extent of agroforestry in the EU 27 is estimated at about 15.4 million ha (15.1 million ha of which is livestock agroforestry) which is equivalent to about 3.6% of the territorial area and 8.8% of the utilised agricultural area [9]. The highest abundance is found in the south-west quadrat of the Iberian Peninsula, the south of France, Sardinia, south and central Italy, central and north-east Greece, south and central Bulgaria, and central Romania [9]. The potential for increasing the agroforestry area is considerable, and by targeting agroforestry establishment in high priority areas (i.e. those with multiple environmental pressures), significant gains can be expected with respect to carbon sequestration as well as other ecosystem services [10, 11].

Agroforestry for Climate Change mitigation and adaptation

Climate change mitigation strategies are aimed at tackling the causes, reducing the sources and enhancing greenhouse gas (GHG) sinks to minimise the impacts of climate change, whereas adaptation strategies focus on ways to adjust natural or human systems in order to reduce the negative effects and increase resilience [12].

Mitigation

Agroforestry is recognised as a climate change mitigation strategy under the Kyoto protocol and can play a significant role in mitigating the climate change impacts of the agricultural sector through carbon (C) sequestration, C substitution and facilitating reductions in GHG emissions [13].

Carbon sequestration

The integration of trees into agricultural fields provides large potential for C sequestration. In addition to the C stored directly in the woody biomass of the tree trunk, branches and roots, agroforestry practices can enhance the soil organic carbon (SOC) pool via the addition of leaf, branch and root litter [14]. Agroforestry systems have been shown to be able to store more carbon than conventional farming systems. For example, a 13-year-old alley-cropping system in Ontario, Canada, was found to have 11 % to 41 % more C stored compared to sole-cropping plots [15] and a poplar silvoarable system in the UK was calculated to sequester an average of 2.7–2.9 t C ha^{-1} $year^{-1}$ in the trees [16]. A review of the net rate of change in C stocks in different agroforestry systems from 56 studies worldwide found that agroforestry stands, at an average age of 14 years, sequestered 7.2 +/- 2.8 t C ha^{-1} y^{-1}, with biomass and soil C sequestration contributing about 70 % and 30 % respectively [17].

A review of agroforestry-based solutions to climate change in Europe identified that the adoption of practices to increase SOC pools would have the greatest mitigation potential [18]. However this effect is dependent on the land use prior to agroforestry establishment and the positive impact of afforestation on SOC stocks is more pronounced in cropland soils than in pastures, where there can be a net loss in the years following tree establishment [19, 20]. For example, Upson et al. (2016) observed a reduction in SOC fourteen years after planting a silvopastoral system on existing grassland; the SOC losses were compensated by increased above ground C storage and analysis suggests that the silvopastoral system was storing about 5 % more C than the equivalent areas of woodland and pasture. Significantly higher SOC was found under mature walnut trees in a silvoarable system [21]. The overall C dynamics of agricultural systems are many and complex and only when the C accumulation in a new agroforestry system surpasses the C losses via decomposition or disturbances (e.g. tree planting) will additional C be sequestered within the system [22].

Greenhouse gas emission reductions

The main GHGs are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (including N_2O), and ozone. Large amounts of CO_2, CH_4 and N_2O are released to the atmosphere by the agricultural and forestry sectors. Agroforestry can increase C Sequestration thereby helping to offset some of these emissions. Life cycle analysis of an agroforestry system combining free range poultry with orchards showed significant reductions in overall GHG emissions as well as other environmental impacts when compared to the individual systems [23]. Integrating agroforestry into agricultural operations can reduce N_2O emissions by eliminating nitrogen (N) application on the area occupied by trees together with the absorption of excess N by the trees [5]. Some agroforestry systems may also reduce machinery use, the area of land cultivated and hence reducing CO_2 emissions [24], but equally the addition of trees may make machinery manoeuvres more complex cancelling out any fuel savings from reduction in cultivated area.

There is still a lack of comprehensive studies on the impacts of agroforestry systems on methane and nitrous oxide and other GHG emissions. Data was compared from 15 studies which assessed the net changes in the CH_4 and N_2O emissions from a diverse range of sites and systems and only minor differences in emissions under agroforestry systems compared to adjacent agricultural lands were found [17]. However, recent studies indicate that the foliage of certain trees and shrubs have the potential to reduce ammonia (NH_3) and CH_4 emissions when fed to ruminants, while optimising animal nutrition and improving animal health [25]. Plant secondary metabolites (PSM) such as condensed tannins increase the flow of rumen-bypass protein and essential amino acids to the small intestine, preventing bloat, providing anti-parasitic effects as well as lowering emissions of ammonia and methane [26].

Carbon substitution

Agroforestry systems (e.g. hedgerows, shelterbelts or short rotation coppice (SRC)) can be designed to be pollarded or coppiced for bioenergy production either as woodchip or logs providing an alternative to fossil fuels and a means of C substitution (Figure 1). SRC woody crops such as willow produce between 11 and 16 units of useable energy per unit of non-renewable fossil fuel energy used to grow, harvest and deliver SRC [27]. Research in the UK estimated that approximately 3.6 ha or 5 km of hedgerow would be needed to provide the energy needs for a typical farmhouse [28]. Some of the carbon sequestered in trees can be removed from woodland as timber, which if used in construction can replace fossil fuel intensive materials such as steel. However, both biofuel and timber will release C when the wood eventually decays or is combusted. Woodchip from agroforestry systems can be used as a soil amendment with some potential value as a replacement for fossil fuel derived fertilisers [29], as well as turned into compost, used as an alternative livestock bedding material to straw or as a mulch to prevent weeds in food forests and permaculture systems.

Adaptation and Resilience

Climate change adaption strategies aim to make system changes to reduce the negative effects of climate change and enhance resilience. Agroforestry can play a significant role in helping farmers adapt and become more resilient in the face of climate change through, for example, microclimatic modifications, increased system diversity and a reduction in the risks from flooding and wildfires.

Figure 1. Boundary hedgerow managed for woodfuel. Photo by Jo Smith

Microclimate modifications

A review of agroforestry-based solutions identified planting multifunctional hedges and windbreaks as the solution with the greatest climate change adaption potential [18]. Hedgerows, windbreaks and trees on farmland can alter microclimatic conditions, buffering animals and crops from extreme weather events and helping systems adapt to periods of drought and water stress. When positioned correctly hedgerows, windbreaks and agroforestry alleys can reduce windspeeds in an area up to 30 times their height [30]. Modelled crop yield responses to windbreaks found significant yield benefits in soybeans and to a lesser extent wheat in the areas protected by windbreaks [31]. In exposed areas trees can provide shelter and shade for livestock which can reduce the energy expended for thermoregulation, leading to higher feed conversion, weight gain and higher animal welfare (Figure 2). Provision of shelter has also been shown to reduce lambing losses by up to 50 % [32] and increase sheep live weight gains between 10 and 21 % [33]. Microclimate modifications beneath the tree canopy can also extend the grazing season; using 40 % soil moisture content as a cut off to stop grazing, there was a 17 week longer grazing season within an agroforestry system at Loughgall, Northern Ireland, compared with the grassland system [34, 35].

Diversity

Agroforestry systems can offer greater economic stability. Crop diversification with multiple crops and products reduces the risk of yield loss from a single crop in extreme weather events, creating more diversified enterprises with greater income distribution over time [36]. Diversification can also potentially increase overall system productivity through increased resource use efficiency and the ability of trees to access nutrients and water inaccessible to annual crops.

The establishment of new agroforestry systems can add a high level of diversity to agricultural lands which is important for system resilience against environmental variation [37]. This diversity can also contribute to reducing crop health through improved habitat diversity supporting larger populations of beneficial insects. Significantly higher abundance of beneficial insects (pest predators and pollinators) has been found associated with temperate silvoarable agroforestry systems [38].

Figure 2. The importance of shade. Photo by Jo Smith

Reducing flooding and wildfires

Climate change is expected to result in more erratic precipitation patterns that will ultimately lead to higher soil erosion rates and a greater risk of flooding. Agroforestry increases soil cover and has been shown to increase soil porosity, and reduce surface runoff, which can improve water infiltration and retention in the soil profile thereby reducing moisture stress in low rainfall years [39] and mitigating the impacts of local flooding following heavy rainfall [40]. In New Zealand, 15 year old Poplar trees planted at 20 x 20 m spacing on erodible slopes reduced pasture production losses due to landslides during a cyclonic storm by 13,8 %, with each tree saving, on average, 8,4m² from failure [41].

Research in the Pontbren catchment in mid-Wales demonstrated that strategically positioned shelterbelts effectively capture surface run-off from the pasture land above, infiltration rates inside the strips of broadleaf woodland were 60 times those on the pasture ten metres away [42] and this effect was seen as early as two years after planting [43]. Results suggest that when shelterbelts are positioned correctly reductions in peak flow of around 40 % may be achievable.

Higher temperatures and drier summers have increased the risk of wildfires, not just in Mediterranean countries, but increasingly in Northern Europe. Agroforestry can help reduce the fire risk by removing part of the understorey vegetation whilst also providing revenue from the sale of the biomass as food or fuel, increasing biodiversity, reducing soil erosion and protecting water, and research has identified lower fire frequencies in agroforestry areas in the Mediterranean region [44].

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Agroforestry susceptibility to climate change

Agroforestry systems may themselves be impacted climate change, for example increasing plant stress and shifts in pest and diseases due to changing weather patterns. The timescales for establishment and maturity of trees mean that these may not be predictable at planting. Diversity of tree species along with the consideration of innovative varieties adapted to different climatic conditions should be key principles in developing climate change adapted agroforestry plantings [5, 18].

Agroforestry supports other ecosystem services

There is increasing pressure on agricultural land to meet the growing demand for agricultural commodities while at the same time reducing environmental impacts. Agroforestry offers one solution to maintain agricultural productivity whilst also enhancing the wider ecosystem service provision. Ecosystem goods and services are the economic and ecological benefits that are derived from ecosystem functions [45]. The ecosystem services provided by agroforestry systems can be split into regulation (carbon, soil fertility and erosion control, water quality and conservation), biodiversity (habitat and species), productivity and cultural services [22]. The results of a meta-analysis of 53 individual European studies on the effects of agroforestry on ecosystem services indicate an overall positive effect of agroforestry over conventional agriculture; in particular for improved erosion control, biodiversity and soil fertility [11]. The study also showed that the positive effects of agroforestry on ecosystem services were often more apparent at a landscape and regional-scale than at a farm-scale.

Regulation of Soil and water

Trees can intercept nutrients and sediment washed or blown off farmland, reducing the effects of erosion [46] and improving water quality. Research has found that the presence of trees in short rotation coppice agroforestry and buffer strips in arable systems reduced sediment and nutrient loss compared to conventional agriculture, with the scale of the reduction dependent on site conditions (e.g. slope, vegetation cover, precipitation) [22]. Modelled effects of alley cropping and contour planting in Europe on soil erosion by water indicate that erosion can be reduced significantly, with up to 70 % reduction achieved by a combination of alley cropping and contour planting [47].

Tree shelterbelts can also play a practical role in reducing pollution by capturing ammonia from livestock farms. Modelling has shown that significant amounts of ammonia can be captured by strategically positioned agroforestry systems with up to 27 % captured by tree canopy from the animal housing source, while the livestock under trees attained a maximum of 60 % ammonia capture [48].

Productivity

Well-designed agroforestry systems can be more productive than monocultures. Different components of an agroforestry system can be complementary in their use of solar radiation and water [36] and together with improved shelter and microclimatic conditions this may result in higher overall system productivity. However, competitive interactions between the trees and crops for resources (water, nutrients and light) can also result in overall yield reductions, especially at the interface between the trees and the crop. Field experiments and yield modelling in three European countries indicate that agroforestry can increase overall yields in arable systems by up to 40 % relative to monoculture arable and woodland systems [49]. A comparison of studies found that agroforestry coppice systems have similar biomass yields per area to coppice monocultures [22]. However, dependent on the overall (tree plus crop) yields varied widely depending on species, site and growth conditions, and were between 2 % lower and 140 % higher in the agroforestry system than when the trees and crops were grown separately.

Biodiversity

The results of a meta-analysis of European studies investigating biodiversity changes with agroforestry showed a strong positive effect of agroforestry on biodiversity, the effect size varied depending on the taxa studied, and the strongest positive effect seen for birds [11]. The type of agroforestry system was also significant with the strongest positive impact of agroforestry on biodiversity observed in silvoarable systems.

Planting agroforestry systems alters the landscape mosaic, increasing habitat heterogeneity [22] and increasing soil biodiversity due to the presence of tree roots [e.g. nematodes, 50]. The establishment of trees on farmland provides additional food, shelter and diverse habitats for multiple species. Hedges and shelterbelts are often the sole remaining seminatural habitats in intensively farmed lowland agricultural landscapes and can play an important role in landscape connectivity benefitting movement of wildlife across landscapes [51]. In addition agroforestry systems help to conserve biodiversity via the provision of other ecosystem services such as erosion control, so preventing habitat degradation and loss [39].

Cultural and social Services

Due to their environmental and socio-economic benefits, agroforestry systems represent an important value for society in general. Agroforestry systems can provide recreational opportunities that can benefit the general public as well as the landowner. Activities such as hunting, fishing, mountain biking, equestrianism and rural tourism can diversify income for farmers, while the public can benefit from improved health and enjoyment from agroforestry through sports and wildlife watching [52]. The visual impact of monocultures of crops or trees is unappealing for many people; integrating trees into agricultural landscapes can increase the diversity and attractiveness of the landscape [52].

However the available evidence for the wider societal benefits of agroforestry is fragmented; there is an absence of studies that assessed the cultural ecosystem services associated with agroforestry systems [11] and a critical gap in economic assessments for agroforestry services that fails to account for the social and ecological benefits [10]. At a practical level there remain cultural barriers to wider adoption of agroforestry practices by farmers across Europe. Stakeholder analysis of challenges to adoption carried out found that the most common challenges to farmer uptake are a lack of knowledge and expert support to ensure adequate management and a lack of financial support [18].

Designing and managing agroforestry for maximum, sustainable, production

To provide protection from extreme weather events and other climate change driven impacts, agroforestry systems need to be established several years prior to such an event [5]. Knowledge of the additional benefits of a well-planned agroforestry system are therefore important in encouraging uptake. The Agroforestry Handbook [53] is an excellent resource for detailed guidance on practical management and design considerations for the full range of agroforestry systems.

The productivity of a system is determined by the balance between positive and negative interactions between the tree and agricultural components. The design and management of agroforestry systems should aim to maximise positive interactions that lead to facilitation and minimise negative interactions that result in competition for resources.

System design

Design considerations include the selection of appropriate species, based on a number of criteria, and the spatial arrangement of the system.

Species choice

The selection of tree, crop and livestock species for an agroforestry system is influenced by a number of factors, including the desired outputs, site conditions and climate, species properties, and agronomic factors such as harvest times.

Objectives

The first step in designing an agroforestry system is identifying the primary products required; food (arable, meat and dairy, top fruits and nuts, livestock fodder), high quality timber (walnut, cherry, hornbeam), and/or bioenergy (short rotation coppice (SRC) species such as willow). The woody component of the system may be determined by the periodicity of revenues required, with fruit and nut, and SRC systems, providing annual returns while timber trees are a long-term investment that can be viewed as a 'pension pot' for forward-planning farmers. Government support policies will also influence this decision, with some countries limiting support to certain tree species only (e.g. top fruit, nuts, SRC,). Market forces and marketing infrastructure also need to be taken into consideration.

Site conditions

Tree species selection is dependent on site characteristics such as summer drought susceptibility, and soil properties (stoniness, shallowness, seasonal wetness). The choice of species is also related to site characteristics, for example, poplar can be planted to raise soil pH, willow on wet soils, and fast growing species on erodible soils. The implications of a changing climate also need to be considered, with many species predicted to be affected by rising temperatures and changes to rainfall patterns. Including a range of species is recommended as a means of managing risk, by increasing the range of genetic material in the system, choosing well-adapted provenances and mixing.

Species properties

The ideal species for agroforestry systems should maximise niche differentiation between the tree and other plant components (crops or pasture). This reduces the competition for limiting resources (water, sunlight, nutrients) and maximises overall productivity. For example, ideal tree species will have deep roots to access nutrients and water unavailable to the crop, and either a crown that is in leaf outside the crop's main growing period or that casts a light even shade [54].

Trees

In agroforestry systems, deciduous species are generally favoured over evergreen species which may have a greater impact on crop production through shading, but evergreens may be suitable in exposed upland areas where they can provide shelter for crops and livestock from autumn through to spring. Evidence also suggests that broadleaved tree species may have a greater capacity to accumulate SOC than coniferous species [19].

The size, shape and density of the tree canopy can affect productivity in the understorey. A study comparing pasture production under densely planted young willow and poplar found that willow had a greater effect on understorey plant growth (24 % reduction compared to 9 %) [55]. This is likely to have been due to increased shading and slightly lower soil moisture content under willow. Willow grew faster than poplar, with more shoots, larger stem diameter and a larger canopy diameter.

The distribution of roots and pattern of root activity differs between species; knowing these characteristics may help in avoiding tree/crop competition through suitable spacing [56]. Root systems are determined genetically and modified in response to environmental and management factors.

Differences in timing of peak growing periods or leaf/crop development can be exploited to reduce temporal competition and increase productivity. For example, in southern Britain, ash trees *Fraxinus excelsior* don't come into leaf until late May, therefore avoiding the maximum growth rate period of the adjacent crop or pasture [54]. Winter crops, sown in autumn, have an advantage over spring sown crops in agroforestry systems, as they can get established well before bud break of trees in spring. Conversely, the trees can continue to assimilate carbon into dry mass until leaf fall after crop harvest in mid to late summer, without competition from the crop. In silvoarable systems, timing requirements for harvest of trees and crops need to be considered to prevent damage to either component during harvest operations.

Crops/livestock

SHADE TOLERANCE

The shade tolerance of an understorey species will determine its ability to survive and reproduce in an agroforestry system. Recent research work has aimed to identify high-yielding, shade-tolerant genotypes of pasture and cereal species to improve productivity in agroforestry systems [57, 58]. Mature forest garden agroforestry systems are shadier than silvoarable and silvopastoral systems with lower tree densities. Within forest gardens, a wide range of shade-tolerant species are grown to provide crops and produce, as well as other services such as ground cover and biodiversity support [59].

TREE DAMAGE

Livestock can cause considerable damage to trees, particularly in the early stages of an agroforestry system, and the choice of species or breed may change over the lifetime of the system. Sheep are generally viewed as the best species as the system establishes, with the possibility of introducing cattle at a later stage [60]. Poultry are likely to have less of an impact on tree health, while pigs are more suitable in an established system or for woodland grazing due to their grubbing and bark stripping activity [60].

Arrangement and Density

Tree planting pattern affects productivity (Figure 3). Even distribution of individual trees across a field reduces tree competition but increases tree-crop interactions due to increasing the tree-crop interface zone. In silvoarable systems, the arrangement is usually dictated by agricultural requirements, with the alley width determined by the size of machinery used in arable cultivations. Planting tree rows in a north-south direction is generally accepted as the most efficient orientation to optimise direct sunlight penetration to the crop/pasture. However, if the aim of tree planting is to provide shelter, windbreaks should be sited at right angles to the prevailing wind. Tree densities will vary widely depending on the agroforestry system. In timber systems, initial densities may be higher to allow for thinning while in systems with top fruit, it is likely that trees will be planted at final densities.

Figure 3. Clockwise from top left: (a) Evenly spaced trees at 200 trees/ha; (b) Trees planted in groups to reduce costs of tree protection; (c) Alley cropping design, Apple trees are protected by wore cages against deer damage (d) Scattered individual trees, protected with post and wire against cattle. All photos by Jo Smith

Management

Within agroforestry systems, productivity of each component can be manipulated by management. Thinning and pruning determines tree quality and production, and influences crop and pasture production and therefore animal production. Fertilisation increases production, and alters tree/crop competition dynamics, and stocking density impacts livestock production and impacts tree productivity through reduced competition with pasture or negative impacts of soil compaction through trampling.

Pruning

To produce high quality timber, pruning must be carried out to produce a single straight stem, free of branches and defects, at least 5 m in height, and between 7 and 10 m for poplars. This is particularly important in agroforestry systems where trees are planted more widely-spaced than in plantations, which can encourage poor form. Some tree species, such as poplar *Populus sp.*, ash and sycamore *Acer pseudoplatanus*, exhibit stronger apical dominance and will require less formative pruning than others such as oak and walnut.

In silvoarable systems, regular cultivations within the crop alleys will destroy superficial tree roots and shift the competitive balance in favour of the crops. The cut tree roots decompose and add to the organic matter pool of the soil to release nutrients to the crops [56]. More disruptive management practices such as trenching, knifing, disking or subsoiling can be used where belowground competition between tree and crop roots needs controlling.

Weed control

Weeds, especially grasses, can compete aggressively with newly planted trees, and the vegetated understorey of tree rows may act as a reservoir of weed seeds from where they can infest the adjacent crop alleys. Trees need to be kept free from competition until rooting is deep enough to compete with weeds – this may require weed control for the first three growing seasons [61]. Options for weed control include the use of mulches, herbicides or ground cover plants. Plastic mulching is often used to reduce weed pressure on newly planted trees. Ground cover plants such as clover and lucerne can be established within the tree rows to prevent weed invasion, as long as they have minimum competitive pressure on the trees [61]. Sowing a diverse mixture of flowering species under the trees can also have the additional benefit of attracting pollinators and natural enemies of pests.

Protection from livestock and wild animals

Trees in newly established silvopastoral systems need protection, usually in the form of plastic tree guards or netting, from livestock for up to 5 years for sheep and 12 years for cattle [62]. The animal component of a silvopastoral system can change as the trees mature, with species options increasing once the trees have established. Tree protection depends on the animal and tree species; herbivores such as cattle and horses will not eat species like Eucalyptus globulus or Pinus pinaster, but goats and pigs can cause serious damage to even large trees. Stocking rate is also a factor, and the availability of alternative forage. Young trees in both silvoarable and silvopastoral systems are susceptible to damage by wild animals such as rabbits, hares, and deer. Birds such as pigeons, rooks and crows may also cause structural damage to the trees, being heavy enough to damage branches when perching [61].

Wakelyns Agroforestry: Resilience through diversity

Located in the arable heartland of eastern England, Wakelyns Agroforestry **(www.wakelyns.co.uk)** is an oasis of trees, alive with bird song and insects, surrounded by a sea of large-scale conventional arable production. Integrating trees for timber, energy and fruit production with an organic crop rotation, Wakelyns was established in the mid–1990s by the late plant pathologist, Prof. Martin Wolfe, to put into action his theories of agro-biodiversity being the answer to achieving sustainable and resilient agriculture. For over two decades the farm has been the focus of research into organic crop production and agroforestry.

Diversity at all levels underpins the philosophy and approach to the development of Wakelyns Agroforestry (52.4°N, 1.4°E) which incorporates four silvoarable systems; short rotation coppiced (SRC) willow, SRC hazel *Corylus avellana*, mixed top fruit and nut trees, and mixed hardwood trees with 10–12 m–wide crop alleys between tree rows (Figure 4).

The reasons behind establishing such a diverse system were manifold: to reduce pest and disease pressure by increasing the distance between individuals of the same species; to increase biodiversity including beneficials such as pollinators and natural enemies; to provide resilience to a changing climate; and to diversify production and reduce the risks associated with farming single commodities. Timber trees were planted in pairs of the same species. Lower limbs have been pruned to maintain form, and in recent years, pollarding has been introduced to manage the canopy and facilitate crop management. Coppicing of the hazel and willow short rotation coppice is carried out in winter using a circular saw; cut material is then air dried in the field during summer and chipped. Over the years, a wealth of data has been collected on all elements of the different systems including tree growth and productivity, annual and perennial crop yields, pest and disease incidence, functional biodiversity and whole system sustainability.

Figure 4. Agroforestry systems at Wakelyns, clockwise from top left: Mixed nut and fruit tree system; Hazel SRC system; Mixed timber system; Willow SRC system. All photos by Jo Smith

Decentralising food and energy production

A key element of the research at Wakelyns has been to investigate different approaches to decentralise and localise agriculture, food and energy production and to provide a model to both prove the concept and act as a demonstration for others.

The diverse range of produce that has originated from Wakelyns over the years demonstrates how truly productive a small plot of land can be. Products have included bioenergy from willow and hazel coppice, timber, fruit, vegetables, cereals and pulses, nuts, juice and cider, eggs, venison from the wild muntjac deer and craft materials from the willow and hazel.

Wakelyns has very successfully achieved energy self-sufficiency by using the short rotation coppice (SRC) agroforestry tree rows and traditional field boundary hedgerows to produce woodchip for fuel, as well as the installation of PV panels for electricity production. Woodchip from the SRC and the hedges is used to power a small 20 kW boiler which provides the year-round heat requirements for the farmhouse with additional woodchip left over for other purposes. The coppice species used for woodchip production are hazel, cut on a five-year rotation and willow Salix viminalis, cut on a two-year rotation. Harvesting is carried out in winter using a tractor mounted circular saw and chipped the following summer using a small hand fed chipper.

Biomass production of the SRC willow has been measured since 2011 and the hazel since 2014 [63]. The two species of SRC produce very similar yields under current rotations when converted to annual biomass production (2,87 m^3/100 m/year). This gives two options; a willow system where the canopy is removed every other year so reducing the amount of shade on the alley crops, but requiring more frequent harvest (and potentially more competitive with crops for water and nutrients) versus a hazel system with slower growing trees, potentially casting more shade, but with fewer harvests to achieve the same yield.

How many trees are needed to heat a farmhouse?

A typical 20 kW farmhouse boiler such as the one at Wakelyns uses approximately 80 m^3 of woodchip/year. Therefore, based on the calculations in Table 2:

- 2800 m of Short Rotation Coppice (SRC) – double rows of willow or hazel – is needed to heat the farmhouse. Converting into field area with 3 m wide tree rows and 10 m wide alleys this equates to approximately 3.62 ha of agroforestry.
- 320 m of hedgerow is needed every year to heat the farmhouse; on a 15-year harvesting rotation, a total of 4.8 km of hedgerow would need to be in a coppice rotation to meet this demand.
- Wakelyns Agroforestry has 3.7 km of boundary hedgerow, 2.18 km (3.2 ha) of willow SRC, and 1.5 km (2.4 ha) of hazel SRC as alley cropping agroforestry, so is easily able to meet this need (Table 2).

Table 2.

WOODCHIP PRODUCTION AT WAKELYNS [64]

	Length (m) at Wakelyns	Number of trees per m	Volume of woodchip (m^3/m)	Coppice rotation length (years)	Length coppiced in one year (m)	Annual woochip production (m^3)
Willow SRC	2175	1.65	0.0574	2	1087.5	62.42
Hazel SRC	1500	1.33	0.1432	2	300	42.96
Boundary hedge	3700	variable	0.25	15	247	61.75

Carbon storage and flows

As discussed earlier, agroforestry can increase the amount of carbon sequestered compared to monocultures of crops or pasture due to the incorporation of trees and shrubs. A system combining short rotation crops such as willow for bioenergy production with an agricultural system has the potential to store more carbon than an agriculture-only system with carbon being stored in the willow stools and coarse roots, and an increase in soil organic carbon due to the input of leaflitter and root exudates and turnover [65]. Carbon storage and flows were assessed in the willow SRC system at Wakelyns and compared with a neighbouring field with no trees [66].

Table 3.

C STOCKS AND FLOWS IN THE AGROFORESTRY AND NO-TREE CONTROL AT WAKELYNS

	Agroforestry t/C/ha	Control t/C/ha
C Stocks		
Willow roots	2.22	0.00
Willow stools	2.06	0.00
Soil OC	91.16	62.83
Total stocks	95.44	62.83
C flows out of system		
Willow woodfuel biomass	2.91	0.00
Ley biomass	0.77	1.11
Total flows out	3.68	1.11
C flows within system		
Ley biomass	1.84	2.84
Leaf litter	0.92	0.00
Total flows within	2.76	2.84

The study indicates that carbon stocks within the agroforestry are much higher than in the no-tree control, with most of this difference due to differences in soil organic carbon (SOC). SOC content was higher in topsoil horizon in the agroforestry, translating to an additional 21,11 t/C/ha when compared with the no-tree control. Higher levels of soil carbon were recorded in lower soil horizons (30–40 cm) under the willow tree rows which is likely to be due to the lack of tillage. Carbon flows out of the system were also higher in the agroforestry in 2012/13, due to the export of willow biomass for woodfuel production. While the carbon within this biomass will be released through combustion, this replaces the use of fossil fuels and so can be viewed as a form of carbon substitution. Carbon flows within the system were similar within the agroforestry and control in 2012/13, where the lower productivity of the ley in the agroforestry was offset to a degree by the input of willow leaf litter.

Total Productivity: The Land Equivalent Ratio

As discussed earlier, one of the key attractions of agroforestry is that while productivity of the individual components of an agroforestry system may be lower than in farming systems without trees, overall productivity can be higher due to complementarity of resource use. Modelling allows us to look at the productivity of an agroforestry system over time, by predicting daily growth of the trees and crops in a particular system using local weather, soils and management data. Using a special agroforestry model called Yield-SAFE it was possible to model and thus compare the yields that might be expected at Wakelyns as a pure arable system, a pure willow SRC system and a willow-arable agroforestry system (20:80 willow coppice:crops) for a 10-year period [63]. The modelled rotation for the crops was spring wheat/ley/potato/ley/winter squash/ley (repeated).

Over the course of one full crop rotation (three coppice cycles), total biomass was modelled at 57 t/ha under the agroforestry system (i.e. combining trees and crop biomass), compared to 47 t/ha under pure SRC (i.e. just tree biomass) and 32 t/ha under pure arable (just crop biomass). The model can be used to calculate a Land Equivalent Ratio (LER) i.e. the ratio of productivity under agroforestry versus that in monoculture systems. A ratio > 1 indicates that greater production is achieved under agroforestry than by an identical area of monoculture production. In other words, a greater area of land is needed to produce equivalent yields if arable and coppice are spatially separated than when they are combined in an agroforestry system. The LER was calculated across one full arable rotation (i.e. six years) as 1.36 meaning that there is a 36 % yield advantage for agroforestry compared to when the components are grown separately as monocultures. This suggests that resource partitioning is occurring, and that the net output of the agroforestry system is higher than the monoculture equivalent. This sort of modelling provides the basis for development to compare systems in terms of harvested yields, total profits, and optimal coppice:arable ratios.

Conclusion

Trees store and sequester carbon and planting trees is seen by governments across the world as one of the most cost-effective ways of taking CO_2 out of the atmosphere to tackle the climate crisis. With agricultural land accounting for almost half of the EU area, however, European governments must look to establishing trees on farmland using an agroforestry approach if they are to meet their tree planting targets. In addition to the C stored directly in the woody biomass of the tree trunk, branches and roots, planting trees can enhance the soil organic carbon (SOC) pool via the addition of leaf, branch and root litter. While harvesting products (e.g. coppice) from these 'working trees' mean that the above-ground C store is often temporary, as demonstrated at Wakelyns the greatest long-term gains are to be seen in the below-ground stores, with the biggest positive impact on SOC stocks when trees are integrated into crop-land soils.

The benefits of agroforestry reach beyond its role in mitigating CO_2 emissions, however, by providing alternative product revenues, buffering extremes of climate for improved animal welfare, supporting biodiversity, enhancing the aesthetics of farmland for society and increasing productivity. As a complex system with multiple components, to reach its potential agroforestry needs to be designed and managed to maximise the positive interactions between the trees and crops or livestock, while trying to minimise competition for resources. Clever selection of suitable species, planting designs and management techniques can help achieve this balance, while new research into crop breeding for agroforestry conditions is also underway to enhance productivity further. Although agroforestry systems currently cover just under 9 % of the UAA of Europe, farms such as Wakelyns Agroforestry play an important role in inspiring others to integrate trees as well as provide a research platform for investigations into the impact on productivity and the environment.

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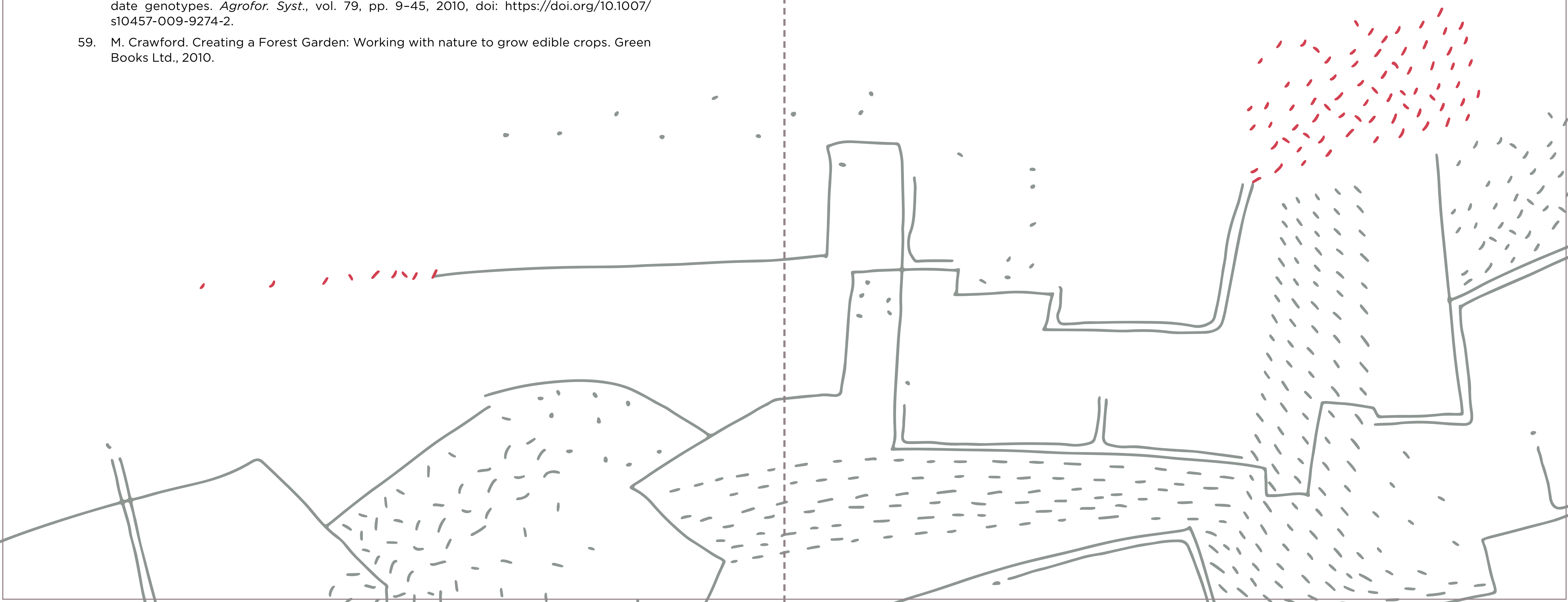

BIOCHARS – A CLIMATE SMART SOLUTION IN AGRICULTURE?

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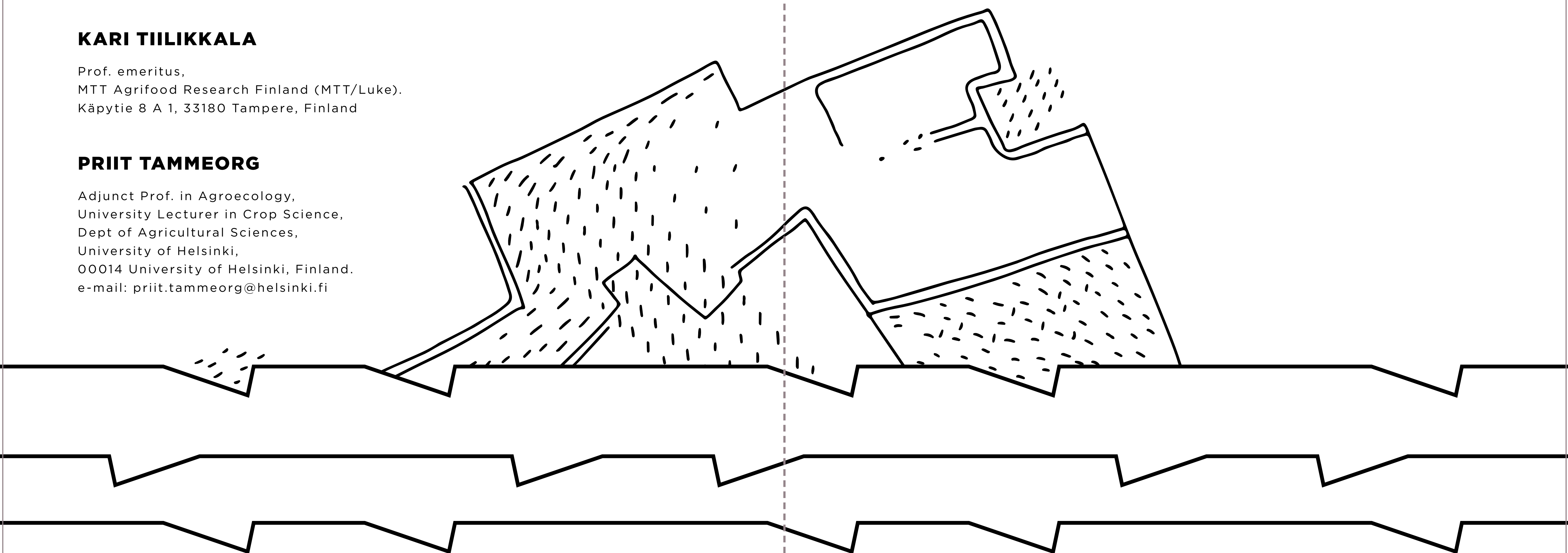

Introduction

There is an urgent need to develop climate smart agriculture and to change food and farming systems more sustainable globally [1, 2, 3]. Use of biochars has become one of the technologies, which offers many possibilities to improve soil fertility and to create long-term carbon sink. Addition of some biochars to soils can simultaneously improve soil health and contribute to climate change mitigation. Most soil-added biochars are a long-term storage of carbon [4, 5, 6, 7] with stability of hundreds to thousands of years [8, 9]. History of the use of biochars as soil amendment is millennia long [8] but their use as a part of modern agriculture and carbon farming is relatively short [10, 11] with earliest experiments started in 2006 (12).

Very often the application of a biochar in agriculture is based on limited practical knowledge about long term impacts of biochar in soil ecosystems. Functions of a biochar amendment depend very much on the soil type, its initial carbon content and fertility [13]. Thus, commercial scale biochar field trials are urgently needed to get more information about long-term impacts of biochar on soil health and productivity [14].

Aim of this article is to help farmers to learn: 1) what are biochars and 2) how to start using them. Importance of the quality of biochars will be presented and needs to develop regional collaboration for biochar production and use are discussed. The third aim 3) is to encourage advisors and consultants to establish regional pilot projects for development of biochar-based farming systems and to collect data of the long-term impacts on soil health and fertility. And finally, this article aims also to 4) encourage policy makers to speed up shift from industrial agriculture to carbon farming and climate smart-agriculture in Europe.

What are biochars?

A lot of definitions for the word "biochar" can be found in the literature. There might be differences between languages how it is understood or defined. In some cases, biochar is used as the generic term to describe any thermally treated biomass despite its application purpose. One of the most established is the definition published in the European Biochar Certificate (EBC): *"Biochar is a porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation"* [15]. In addition to EBC, also several other highly valuable information about biochars and their use is available on the Foundation Ithaka Institute website http://**www.ithaka-institut.org/en/**.

In practice all kinds of biomass can be pyrolysed or thermo-chemically processed to biochars plus pyrolysis gas and liquids. Many European biochar scientists, stakeholders and producers have voluntarily agreed list of proper feedstocks for production of certified biochar. The list and quality requirements have been published in the EBC. In addition, the European Commission has published quality criteria for biochar used in fertilising products [16].

Food safety authorities in every member state of the European Union have their own regulations, which define legal quality standards for biochar and products consisting of biochar components.

Every biochar is different if compared to another (Figure 1). The quality depends on feedstock, pyrolysis technology, process temperature and time as well as on post-treatment technologies. It is crucial to know the properties of the biochar in question before using it, as some biochars may contain high amount of hazardous substances like polycyclic hydrocarbons. Also aging of biochars changes their properties during storage and transportation- and even more significantly in soil.

Figure 1. Biochar made of spruce (left) and birch (right) look different because of the wood species specific growth rings and compactness of the wood cells. Photo: Kari Tiilikkala

Production of biochar

History of the biochar production is long and development of the pyrolysis technology has been documented since 1600 [17, 18].

Production of biochar can be based on a decentralized system (Figure 2) or on production of char in large scale biochar pyrolysis plants. There are a vast number of existing pyrolysis technologies and new systems are developed every year. Slow pyrolysis is one of the most suitable for biochar production out of dry plant biomass. About 30 % of the feedstock material can be converted to biochar.

Figure 2. Two types of batch retorts suitable for decentralized biochar production. Photos by Tuomo Leppänen

Farm scale batch retorts have capacity to produce about 1 to 8 m^3 biochar per run. In the thermochemical process one day is needed for heating up the system and the second day for cooling down the retort. Batch retort can be filled with many kinds of biomass (dry) with different particle size. Pyrolysis is an excellent technology to produce high value products out of plant waste which is often burned causing greenhouse gas (GHG) emissions and local air quality problems [19]. Many of the small batch retorts are relatively easy to move from one place of feedstock storages to another. Semi-batch retorts are normally not mobile and have capacity to produce about 5 000–10 000 m^3 biochar per year. Continuously running pyrolysis plants produce biochar on industrial scale, 20 000 m^3/year or more. All the technologies can be used for production of pyrolysis gas as bioenergy and pyrolysis liquids for replacement of petroleum-derived chemicals. Large scale pyrolysis plants need more standard feedstock than the small batch retorts.

One of the easiest and cheapest ways to produce high quality biochar (EBC premium grade is well possible) on farm is to use flame-curtain kilns (Kon-Tiki or similar) or even just conical soil pits [20]. Such simple kilns can be used to pyrolyze various types of biomass, including long branches or waste wood and reach pyrolysis temperatures as high as 650–800 C degrees and if maintained well, produce hardly any smoke or gas emissions [20, 21]. The pyrolysis gases there are almost completely burnt thanks to the vortex system on top of the kiln and carbonization occurs under the flame curtain [20]. The main drawback of such system is the high continuous need for labor in running the pyrolysis as well as loss of heat energy and pyrolysis liquids. In large-scale settings the need of manual labor can greatly be reduced by using front-loader tractors (see Figure 3 and link of Terra Magica farm-scale device in operation[1]).

1 https://www.youtube.com/watch?v=w0s0dOZ-U6w

Figure 3. left: Kon-Tiki kiln in Tasmania by Frank Strie, one of the first models for activating the hot biochar by bottom-up quenching with water. Photo from [20] . Right: Large-scale pyrolysis in soil pit is an efficient way of getting biochar on farm- it is though crucial to have good set of long tools to arrange biomass in even layers to avoid smoke emissions. It is also recommended to have the walls of soil pit covered by clay plaster to facilitate easier collection of liquid-activated biochar after quenching. Farm-scale pyrolysis event in Liperi, Finland in October 2019. Photo by Priit Tammeorg

Selection of proper technologies is important to be done regionally in order to optimize logistics of all materials. Transport distance of feedstock and biochar are important factors of the biochar life-cycle assessment and carbon neutrality of the carbon chain starting from biomass collection until the end use of a biochar product.

The price of biochar is very variable in Europe because of quality differences and unstable market of biochar. The certified biochars, particularly the ones with special functions are more expensive than uncertified biochars with basic quality. In long run the price for farmers will be reasonable if the biochar can be produced using local plant biomass as feedstock. Also opening the market of plant-based pyrolysis liquids in Europe could lower the price of biochar considerably.

BEST PRACTICES TO FOLLOW WHEN RUNNING A FLAME-CURTAIN KILN:

- **Use dry biomass not thicker than 10 cm;**
- **Add new biomass in thin layers every time the top surface of biomass turns grey (ash);**
- **have appropriate tools for arranging the top biomass layer evenly (especially in large-scale soil pits);**
- **avoid any smoke emissions;**
- **Quench the still-hot biochar with water or water-slurry mixture for increased surface area and porosity.**

Application methods are in development phase

During the long history of biochar many kinds of biochar application technologies have been developed but mostly for small scale farming systems. Guidelines for use of biochar in large scale agriculture are diverse and based either on historical procedures or on short term experiences of farmers or research groups. Thus, knowledge about application technologies and long-term impacts of biochar must be learned during the coming years in good collaboration among farmers and advisers.

Several studies have shown positive effects of biochar application on crop yields at rates of 5–50 tons per hectare, but only if applied with appropriate nutrient management. It is relevant to remember that most of non-nutrient-loaded biochars are not fertilizers, with perhaps the only exception being potassium in wood biochars. So, adding biochars without necessary amounts of nitrogen (N) and other nutrients cannot be expected to provide improvements of crop yields. Use of nutrient-enriched biochar is the best way to start with. However, the most important impacts of biochar amendments are linked to soil physical properties like porosity and water retention capacity or synergies with soil biota and not on yield increase of plants due to added nutrients.

Biochar should ideally be applied near the root zone, where nutrients are cycling and uptake by plants take place. Certain cropping systems may benefit from the application of biochar in layers below the root zone, for example during landscaping for carbon sequestration or if using biochar for moisture management. If the biochar is applied to soil especially for carbon sequestration purposes or for growing deep rooted trees, placement deeper in the soil is needed. In agriculture often used application methods are:

- Broadcasting;
- Traditional banding;
- Mixing biochar with other solid amendments;
- Mixing biochar with manures or liquid slurries;
- Targeted biochar applications in precision agriculture or horticulture.

Single application of biochar can provide beneficial effects over several growing seasons. Therefore, biochar does not need to be applied every year on a field. Splitting applications over time is possible depending on the crop and farming system [22].

Machinery of a normal farm is sufficient to handle and apply biochar (Figure 4 and 5) and there is no need to make high price investments b cause of use of biochars. Biochars are generally light materials with dry bulk density 250–320 kg/m^3, depending on the moisture content and particle size of the char. Before applying biochar to the field, it is very important to moisturize the

material well to about 20 % to 50 % moisture content to control dust. Water makes handling of the char easier, and can be required in some markets for safety. Application guidelines and market prices are based either on weight or volume of the biochar. In practice the volume is often better because then the water content of char does not change the price. Also measuring biochar for application is easier by volumes in practice. It is also relevant to consider that the fluffiness of biochar causes relatively big requirements for space for storing and transporting the biochars [23]!

Figure 4. A field application of manure biochar mixture. Photo: Jarmo Pudas

Figure 5. Using sand-spreader to apply pure softwood biochar (about 30 % moisture content) to the field in Helsinki long-term field experiments. Note the preciseness of application due to minimal dust. Photo by Priit Tammeorg

Use of biochar products in field crop production

In arable farming biochars can be used in many ways and to target different issues in soil. **The first step** is to define the reason why biochar should be used in every case and place. The reason could be just to create a carbon sink and reduce nutrient losses via leaching and GHG emissions from soil [24]. If so, the normal dose is 10–25 t ha^{-1} (the more the soil contains native carbon, the more biochar is needed for notable improvement) and application technology should be selected to fit to the farming system.

Very often farmers have many other and practical reasons for biochar use such as: 1) to improve soil structure and hydraulic conductivity in compacted parts of a field 2) to improve water holding capacity and plant-available water content of soil 3) to add stabile and porous carbon material to soil improving bioactivity and function of the beneficial soil biota, like arbuscular mycorrhiza, 4) to improve nutrient cycles via improved fertilizer use efficiency and limited leaching of plant nutrients from a field, 5) to eliminate impact of toxic chemicals of a soil. **The second step** is to select the biochar which has been made for the desired purpose. **The third step** is to decide how to get proper biochar and how to use it. The proper timing is often before a rainy period of growing seasons, or even in the autumn before to avoid the initial immobilisation of nitrogen by freshly-applied biochar. In practice the use of nutrient enriched biochar (composted or mixed with manure etc.) is often the most profitable way if used before a growing season. Application of biochar could also be linked with liming applications because of the similarity of impacts and application technology [25].

The particle size of biochar should be 2 mm or more. Dust is a problem for user and small particles are spread by wind or leach after a heavy rain if there is no time to be mixed into soil immediately after an application. On high-carbon (more than 2 %) and nutrient rich soils in the Northern Europe there generally is no significant improvement of crop yields to be expected, the yield responses are more pronounced in low C soils [26]. Also, if biochars with high liming capacity (non-wood biochars) are applied to acid soils, their liming effect is often responsible for improved crop yields [27].

However, the most important impacts should be measured from the soil ecosystem of a field within several years after applications. If positive changes have been noticed, applications can be repeated every third or fourth year [28]. Recently decision support tools have been developed for farmers to help to assess the need of biochar on their own lands or as a new product of the farming system [29].

Because of many multifunctional impacts of nutrient-enriched biochar, it is highly recommended that cereal and field crop grower increase networking with livestock farmers. Nutrient enriched biochar can be produced regionally in a cost-effective way. As one example, in 2023, the Agri-Char research group of University of Helsinki started testing out the best practices for farm-scale activation of spruce biochar, the treatments included treating the biochar with nitric acid following with different nitrogen-rich liquids, including effluent from dairy manure separation. The first results were rather promising as the moist and N-releasing biochar was able to attenuate the effects of drought in loam soil.[1] The collaboration will enable carbon farming and climate smart agriculture as well as improve the resilience of food systems.

Composting

From practical point of view use of biochars in composting is one of the most reliable technologies to get many benefits out of one application. It is the easiest way to load biochar with nutrients and microbes. Enriched biochars improve soil productivity almost in every place. Aged and loaded biochars are better soil health enhancers than fresh and dry biochars [30].

The first step is to make a small-scale experiment with own biomass of the farm in order to get correct ratio of carbon and nitrogen (C/N) in the composted mixture. The ratio should be about 100:1. Biochar content ranges from 3 % to 25 % (volume) depending on the nitrogen content of the biomass. Monitoring water content of the compost (squeeze test) is always needed.

One could take handful of the compost and squeeze. No water should come out, but there should be water enough to hold the material together, when one opens the hand. Measure the temperature daily during the first week and then weekly about one month. It should be 55°C at least for 14 days before the cooling and curing phases of composting. Take samples of the biochar compost mixture after three months for laboratory analysis. Nutrient profile, C:N ratio and compost stability test (CO_2 respiration) should be measured. Nitrate (NO_3) content should be higher than ammonium (NH_4) content before use of the compost.

Bioassay test for compost quality should be done before scaling up the biochar based composting system and the test is valuable always before use of a new compost mixture [31]. Application rate of the biochar compost should be calculated based on the fertilizing need of the crop and nutrient content of the compost.

1 http://biochar-hy.blogspot.com/2023/07/added-value-in-activating-already.html

Animal husbandry

A great part of biochars produced in Europe are used in livestock farming. Biochars can be mixed with feed, added to litter or used in the treatment of slurry and manure [32]. Mixing biochars into cattle feed has been recommended already long ago. Long lists of positive impacts have been published, but good and livestock species specific guidelines on use of biochars as feed additive are slight. [33]. No negative effects have been reported with biochars used as a feed additive [34].

The most important step in the beginning of the biochar use as a feed component is to make sure that the quality of char is good enough for use as animal feed. Biochars used as a feed ingredient is subject to strict food quality rules under EC Regulation 178/2002 and to the strict regulations for organic livestock feed under EC Regulation 834/2007. The EBC certificate include specific quality criteria for biochar used as feed additive [15].

The percentage of biochar in feed varies between 0.5–2 % and daily dose depend on livestock species. For getting information about the use of biochar in animal husbandry consult always local advisers before starting the use.

An easy and practical way to use biochar is with bedding material (straw or saw dust). 5–10% of char (volume) reduce odors and nutrient losses [35]. Accordingly, adding 0.1 % biochar (m/m) in a liquid manure reduced odors, surface crust and nutrient losses [36]. Biochar can be applied at 13 % to a cattle slurry and subsequently applied to a field at 4 m^3 biochar ha^{-1}, It has been proved, that this procedure decrease total NH_3-emissions, N_2O-emissions and CH_4-emissions effectively [37]. Biochar can be also added to manure after it is cleaned from barns. The most efficient process is to use biochar directly in the barn where it can capture nitrogen from urine and manure as it is generated. One of the potential ways of using biochar for nutrient recovery is using biochar bed on sedimentation lagoons and to recover nutrients from dairy wastewater [38]. A new option is to use biochar in bio gas production in order to control moisture content of the raw material and to adjust C/N ratio to be optimum for the fermentation process [39, 40]. Digestate-enriched biochar is beneficial in sustaining soil fertility through maintaining high soil organic matter and gradual release of micronutrients [41].

Horticulture

It is impossible to give a common advice on how to apply biochars in horticulture in general. Number of vegetable crops is huge and all plant species need different amount of water and nutrients. Also, every soil and growing media is different with the overall rule of thumb being that the poorer the soil initially, the better the effect.

It has been reported that in vegetable production biochars, 20 t per ha, has given a very positive yield response if used in combination with N fertilizer [42]. In the Nepalese trials, good effects have been achieved by applying biochar close to the plant roots, not broadcasting to overall field (Figure 6). This is making the practice also more cost-efficient [43].

Figure 6. Manure biochar mixture application to row crops in North Sinai. Photo: Magdy Maher Mohamed

In addition, biochars can be used in greenhouse production to replace peat and perlite in the growing media [44, 45, 46] and the char can be used in hydroponic vegetable production [47, 48]. In perennial horticulture use of biochar has been valuable only if low soil fertility or water deficiency is limiting plant growth. Some biochars help to control problems associated with salinity stress. There is little information about impacts of biochars on the root development when trees have been growing several years after use of biochar [49, 50, 51]. Application of biochar products on soil surface around trees cannot be recommended as a way to increase yields [52].

Numerous positive Impacts

Biochars can be used in many ways and thus a lot of variable impacts have been reported. A part of the impacts has been scientifically justified but many are commercial claims and functions which have noticed by farmers during the long history of biochar use in agriculture. It is evident that adding biochar to soil is an effective technology to use fields as a carbon sink for a long time [53].

One kilogram of a biochar corresponds to about 3,5 kg CO_2 eq net negative carbon removal depending on the quality of biochar [54]. Production and use of biochar are climate positive technologies [55, 56, 57] especially if all products of the pyrolysis of biomass can be utilized [58]. In addition to the carbon sequestration, biochar amendments to agricultural soil mitigate climate change because of the reduction of greenhouse gas emissions from soil [24, 59, 60].

Yield responses differ case by case

Yield responses of biochar (without added nutrients) in field use are very variable and depend very much on the soil type and initial C content and nutrient availability. Both negative and positive impacts have been reported. Positive yield responses are possible on fields where the soil fertility is limited because of low soil organic matter, lack of water, on arid soils and on soils where salinity or toxic chemicals cause plant stress. On acid soils the yield increases with high liming capacity biochars are evident [61] and positive yield impacts are usually more obvious in tropical farming conditions with low C soils and in vegetable production [62].

The first short-term (up to four years) results from scientific field experiments in Nordic countries have started to emerge [63, 64, 65], but the long-term effects are still scarce. The first years' results from long-term field experiments with biochar from Helsinki, Finland, found that on boreal soils with initial C content of more than 3 %, there were signs of improved availability of soil water and potassium content which supported plant yield formation under drought- yet the effects to the grain yields were not significant [26, 63, 64]. The only well justified impact of biochar on fertile soils is the carbon capture, one application of biochar 10 t ha^{-1} can increase the net ecosystem C-budget about 5 Mg C ha^{-1} [66].

Hagner et al (2016) [67] have proved in short-term greenhouse experiment that use of dry biochar may decrease yields of the crops grown immediately

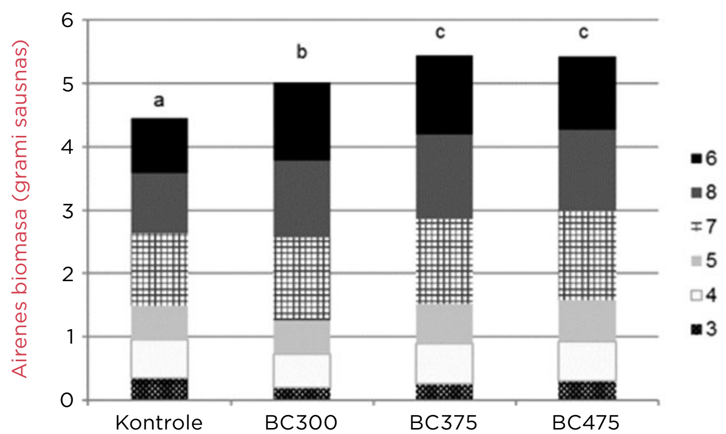

Figure 7. Cumulative biomass of ryegrass (g dry weight/pot) in the control, BC300, BC375 and BC475 treated pots at separate harvests (3, 4, 5, 7, 8 and 10 weeks after sown) at 80 tn/ha biochar addition. The biochar BC300 was produced at 300 °C, BC375 at 375 °C and BC475 at 475 °C.

after an application of biochar, but may increase the yields of the crops which are grown after an incubation period of several weeks or months. Aging of biochar and synergism among soil organisms improve soil health and fertility over time. The figure (Figure 7) of the Hagner et al paper showed that biochar increased cumulative sum of ryegrass yield (six harvesting times) even though yields of the first two cuts were lower than in the untreated control pots. (Figure 7). Pyrolysis temperature of the biochar had also an impact on the yield response. Temperature 300 C is too low for production of high-quality biochar.

Very often positive yield increases have been reported if nutrient-enriched biochar has been used [41, 43]. In addition, enriched biochar increase soil organic matter effectively, it is a slow release fertilizer, and the char immobilize heavy metals. In many cases nutrient-enriched biochar could reduce the need for mineral fertilizers and promote organic farming. Natural aging of biochar in soil may increase soil enzymatic activity and thus nutrient availability in long run [68].

In Composting

Positive impacts of biochar on composting process and compost quality are well justified by many research publications. Biochar speed up the composting process and decrease GHG emissions of the process. Biochar can be loaded with nutrients and microbes which finally improve soil health and fertility [69; 70, 71]. It is widely known, that bacterial community of composted material can be improved effectively [72]. In greenhouse production it is important to know that peat and perlite can be replaced with biochar as a component of growing media [45].

To Improve Water holding and Water Use efficiency

One important impact is the improvement of water holding capacity and water use efficiency of biochar amended soils- and again more in soils that have originally low C content (less than 1 %). This will be very important in the climate with more frequent drought periods [73, 74, 75, 76]. In many cases use of biochar lower need of irrigation water [77] and improve soil health, fertility and structure as long-term impacts [78, 79, 80].

Biochars may improve stimulate the activity of beneficial micro-organisms in soil [81; 82] by allowing for favorable habitats for bacteria and fungi [83]. Biochar can be used as carrier for beneficial micro-organisms and to increase the role of arbuscular mycorrhizae around root systems. All these organisms improve root health and nutrient and water uptake. This is a very important impact in organic farming and in every case where heavy use of synthetic fertilizers will be limited [84].

Sorption of pesticide residues from polluted soils has been justified widely. This is one important reason for the global interest on use of biochar in agriculture [85, 86]. Biochar improve soil cation exchange capacity, nutrient sorption and can be used to capture nutrients from dairy wastewater. New technologies can be developed to lower nutrient leaching from "nutrient hot spots" to water systems [87].

Health and environmental impacts in Animal husbandry

Use and impacts of biochar in animal husbandry have been well described by Schmidt et al. 2019 [88]. Biochar can be used in many ways in the chain of biomass from feeding animals until application back to soil ecosystem. The authors listed a list of the positive impacts as follows:

- Generally improved health and appearance;
- Improved vitality;
- Improved udder health;
- Decreased cell counts in the milk (interrupting the administration of biochar leads to higher cell counts and a drop in performance);
- Minimisation of hoof problems;
- Stabilisation of post-partum health;
- Reduced diarrhoea within 1–2 days, faeces subsequently generally more solid;
- Decline in the mortality rate;
- Increase in milk protein and/or fat;
- Combining biochar and sauerkraut brine has proved worthwhile;
- Marked improvement of slurry viscosity, with less stirring needed and less scum on the surface;
- Slurry not smelling as bad as it used to.

Feed supplementation with biochar reduce animal pathogens [89, 90, 91], incidence of parasites [92] and enable toxin sorption from feed [93]. Even risks of pesticide residues and mycotoxins can be lowered [94, 95]. In development of climate smart agriculture, the impact to decrease methane emissions in animal husbandry is very important. In practice it is also important that the liquid manure viscosity can be improved and the odor load of the manure can be decreased [96].

From environmental point of view, it is important that the feed additive not only increase feed efficiency but also increase nutrient availability of the manure, protect ground and surface water, and sequester carbon in the soil [97]. Cascading approach of using biochar in animal husbandry will maximize the impacts of the char-based technologies and improve economic efficiency [98].

Multiple functions in Manure treatment

Use of Biochar in barns has many functions such as effective capture of nitrogen that is otherwise lost to ammonia volatilization. The application of biochar to manure either via feed or via bedding materials is a potent technology to reduce manure related greenhouse gas emissions [99, 100]. Biochar spread on tillage soil lower nutrient leaching from the field to water systems [101, 102, 103].

It can be concluded based on the combination of the known impacts that biochar is plant growth enhancing soil amendment, that improves the recycling of nutrients from organic residues of animal farming and will be an important part of carbon farming systems.

Uncertainties still exist

The cumulative number of publications on charcoal and biochar from 1998 to 2024 exceeds 45 000 as of 10 April 2024 and in recent years has stabilized at around 10 000 papers per year.[1] Most of the papers are based on scientific work done on laboratory or experimental plot scale. The data has been recorded within a short of time if compared to time what is needed for recording measurable changes in soil ecosystem. Very often quality parameters of the used biochar are missing or reported in a minimal way. From practical point of view uncertainty in moderate for making decisions on farm level.

The most reliable results are related to carbon sequestration, GHG emissions, water use efficiency and improvement of soil bioactivity and organic matter. Also, the result about improving of composting process are very reliable.

1 https://www.sciencedirect.com/search?qs=biochar

The most variable are impacts on crop yield because of the fact that plant growth depend on a huge number of abiotic and biotic factors in every case and place. Long-time changes of soil ecosystems after biochar applications are almost unknown (with just first papers emerging of the effects on decadal scale [12] and based mainly on unvalidated models and historical data. Thus, farm scale pilots are urgently needed to fill the knowledge gaps so that practical guidelines will be evidence based practices in the future.

Regional concepts – the basis of development

Before scaling up production and use of biochar regionally it is very valuable to make a masterplan or concept how to organize production and use of biochar as a part of carbon farming systems. There should be good knowledge in: 1) plant material available for pyrolysis in the region 2) logistics capacity needed for transportation of the feedstock and pyrolysis products, 3) pyrolysis technology available in the region, 4) potential users of biochar in the region 5) type and quality of biochar needed, 6) potential investors and political drivers for development of carbon farming and climate smart agriculture, 7) support of the regional market chains for development of food systems and carbon farming.

Good collaboration among farmers and other key players may lead to a permanent change in use of plant biomass regionally and development of novel bioeconomy. One important impact is related to the use of pyrolysis technology as waste management technology and production of biochar as climate positive alternative to burning of biomass [104, 105].

Agricultural systems in Europe face raising concern about resilience to many types of shocks and stresses [106]. Production and use of biochar could be a part of the system level transformation from fossil oil-based food production to a system which enable regional food security in long run. Global warming will continue many decades in every case and climate change migration will make the resilience issues increasingly important also in the Europe.

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USING BIOCHAR IN CLIMATE-FRIENDLY AGRICULTURE – EXPERIENCES AND CHALLENGES

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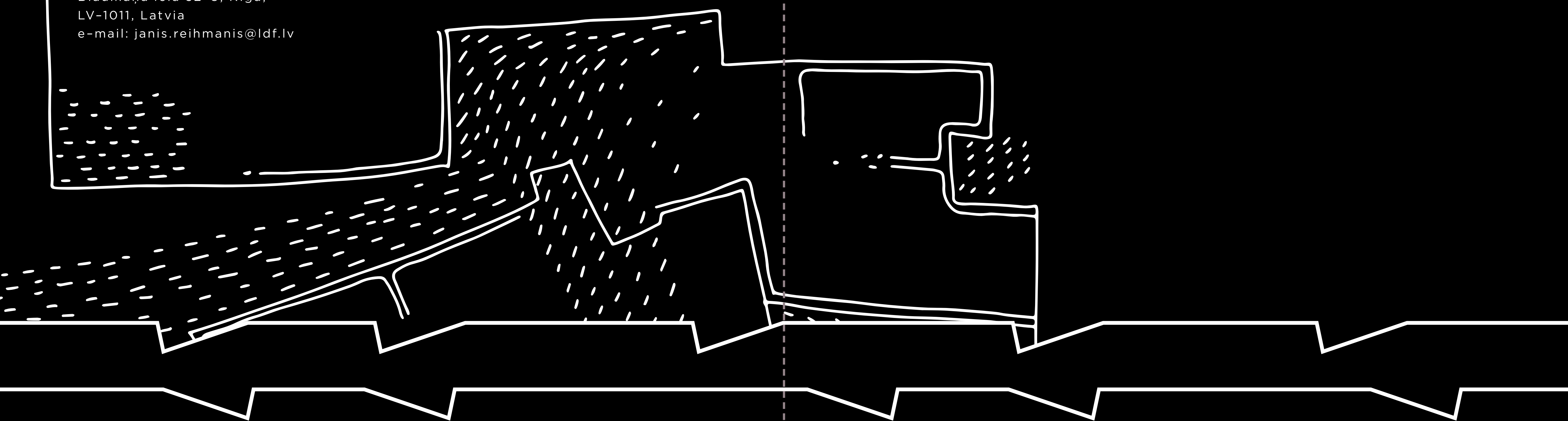

Introduction

Agriculture significantly contributes to global greenhouse gas emissions (GHG) and consequently to anthropogenic climate change. At the same time, agriculture also has a huge potential to contribute to climate change mitigation, as it has a strong impact on climate change. Agriculture's direct impact to total global greenhouse gas emissions is around 10–15 %. Indirect emissions, including those from land-use change (LULUCF - land use, land-use change and forestry), such as deforestation and peatland development, increase to more than 30 % [1].

Agriculture is the second largest sector in terms of total GHG emissions after fossil energy use. This sector is the largest contributor to global emissions of non-CO_2 greenhouse gases, accounting for 54 % of total methane (CH_4) and nitrous oxide (N_2O) emissions in 2005 [2]. Solutions are being found to tackle climate change and its impacts on agriculture, which would both benefit climate change mitigation and adaptation and enable sustainable food production.

In the last decade scientific research and practical trials on the use of biochar in agriculture have gained considerable popularity. This is linked both to the identification of more climate-friendly farming methods and to the potential of biochar to facilitate carbon sequestration and thus mitigate climate change. However, from a farmer's perspective, the main motivation for using biochar is its ability to improve nutrient availability and yield. This was also the approach of the LIFE CRAFT project - to test the effectiveness of biochar in the context of producing farms [3], to assess its practical application in Latvia.

Impact of biochar application in agriculture on the climate

Biochar is not a new concept in agriculture. It dates back to ancient farming civilizations. The best-known example is in the Amazon Basin, where a biochar-rich soil horizon was discovered, Internationally it is often referred as *Terra preta*, which is the original Spanish term for Internationally itis dark land/soil of Indians – *Terra preta de Indio*.

Biochar incorporation affects soil structure, texture, porosity, particle size distribution and density. The main physical characteristic of most biochar is its highly porous structure and large surface area. This structure can provide a habitat for beneficial soil micro-organisms such as mycorrhizae and bacteria, and influences the accumulation of plant nutrients. Evidences shows that biochar application improves the availability of key nutrients to plants, especially when it is incorporated with additional nutrients. Biochar incorporation has also been found to reduce ammonium leaching and N_2O release from soil [4]. It can therefore be stated, that originally biochar was used as an agrotechnical tool to improve soil and to secure better yield, but today this approach has been extended to climate change mitigation and adaptation.

A large meta-analysis study showed that the impact of biochar on climate is not only in the context of N_2O emissions, but can also reduce nitrate (NO_3^-) leaching. This study concluded that use of biochar reduced N_2O emissions by 38 % and NO_3 leaching by 13 % [5]. In Finland, under climate conditions similar to Latvia, and at a rate similar to the LIFE CRAFT project – 21 t/ha – it was found that biochar from spruce wood reduced NO_3^- leaching by 68 % during the growing season compared to the control [6]. However, this study found no yield increase associated with biochar application and no effect on ammonium (NH_4^+) leaching from the soil.

Carbon accumulation in soil by biochar also occurs at a finer particle scale. In a study carried out in a Mediterranean climate, it was found that biochar incorporation contributed to the retention of soil organic matter particles smaller than 53 µm as particle-bound on the mineral surface [7].

Looking at the effect of biochar application in agriculture on climate of carbon in the soil is undeniable. As pyrolysis converts the biomass carbon into stable carbon compounds, its incorporation ensures long-term carbon storage in the soil. Even for millennia, as the *Terra preta* example shows.

Practical aspects of biochar incorporation in soil

Note that biochar is not a fertilizer. Therefore, if biochar is derived from low-nutrient biomass (e.g. wood, reeds, etc.), it is unlikely to incorporate additional plant nutrients into the soil. Its physical properties can improve soil structure, texture, porosity, particle distribution and density. However, the material from which biochar is produced can also have a significant impact on its effectiveness. For example, a study at Hokkaido University in Japan showed that biochar made from poultry or dairy cow manure contains more plant nutrients than if biochar is made from wood. Although some nutrients are released during pyrolysis, the remaining concentrations may be available to plants as additional nutrients [8].

One of the key conditions for making the most of biochar is its pre-treatment before use. This means it needs to be incorporated with or pre-soaked with plant nutrients and/or micro-organisms. Such pre-soaking is called inoculation. This pre-treatment makes biochar a carrier for plant nutrients and/or micro-organisms and ensures their gradual and long-term availability to plants.

The LIFE CRAFT project experience in biochar use

Within the LIFE CRAFT project there were three organic farms selected specializing in vegetable production. The selected farms were located in Daugmale, Tirza and Dāviņi parishes (pilot areas are marked according to the name of the nearest populated place). A 0.4 ha plot was established on each farm to carry out practical trials on the impact of biochar from 2019 to 2023. On all farms, this plot was divided into four equal parts (0.1 ha each) – three of which were treated with biochar at different concentrations 2.5, 10 and 20 t/ha, but the fourth served as a control, where biochar was not incorporated, but the same crop was grown as in the biochar areas. At the start of the project biochar was incorporated into the soil together with manure, green manure or a complex mixture of microorganisms (see Table 1). Subsequent soil treatment resulted in biochar being incorporated and mixed into the arable layer.

Crop choice to be grown each year was not restricted in any way on the project farms. It was the owner's free choice. The only condition from the project was that each crop had to be grown in all biochar concentration zones. In most cases, farms grew one crop per season in all four biochar concentration field strips. However, in some cases, several crops were grown within the same season. In these cases, the vegetable crops were arranged perpendicular to the biochar concentration field strips, so that each crop was in both the control strip and three different biochar concentration strips. In the 2020 season, turnips, onions, radish and kale were grown perpendicular to the biochar concentration field strips in the Daugmale plot, while in 2022, different varieties of pumpkins were grown in the Lambārte plot (Table 1).

Table 1.

BIOCHAR INCORPORATION TYPE AND THE CROPS GROWN IN LIFE CRAFT PROJECT PILOT

Pilot area	Date of biochar incorporation	Biochar incorporation method	2019	2020	2021	2022	2023
Tirza	21.11.2018.	Incorporated with green manure (lucerne)	Soya	Soya	Potatoes	Soya	
Daugmale	24.04.2019.	Incorporated with manure	Oats and peas in green manure	Turnips, onion, radish, kale	Onions, winter vetch and rye green manure	Potatoes	Green manure – rye with vetches
Lambārte	07.05.2019.	Incorporated in combination with the Bioeffect preparation "Biomix"	Carrots	Onions	Potatoes	Pumpkins	Green manure – oats with clover as intercrop

To detect the effect of biochar on vegetable yield, each harvested crop from biochar concentration field strips was weighed separately. In some years above-ground vegetation weight and vegetation height measurements were also taken. To assess the impact of biochar, only per farm per year data were compared. To determe effect of biochar concentration the Spearman's Rank correlation coefficient was applied for log-transformed yield (t/ha), above-ground vegetation mass (t/ha) or vegetation height (cm) and biochar concentration (t/ha) values.

In general, the results do not show a persistent positive correlation between incorporated biochar amount and vegetable yields [9, 10]. No statistically significant ($p > 0.5$) correlation was found between above-ground vegetation mass and vegetation height in any of the measurements made and the amount of incorporated biochar. Positive effects of biochar concentrations during the whole project were found only in two years in the Lambārte pilot area – for the year 2020 onion harvest (rs=0.8; p=0.333) (Figure 1) and for the year 2022 pumpkin yield (rs=0.8; p=0.333) (Figure 2).

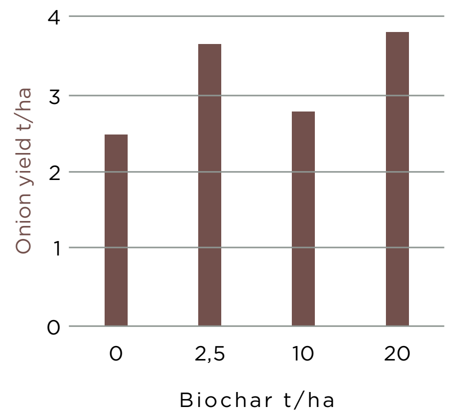

Figure 1. Onion yield in the Lambārte pilot area in the 2020 growing season

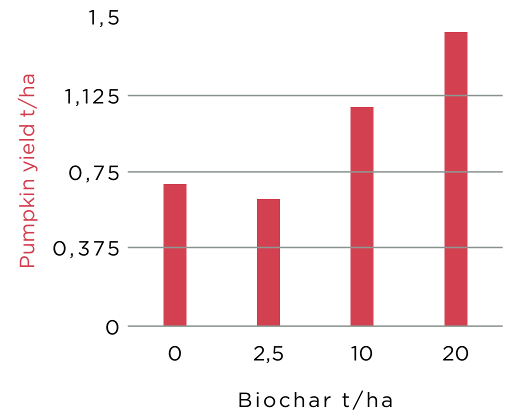

Figure 2. Pumpkin yield in the Lambārte pilot area in the 2022 growing season

In the Tirza pilot area, a statistically significant negative biochar concentration effect on soybean yield was found in three years: 2019 (rs=-0.8; p=0.333), 2020 (rs=-0.6; p=0.417) and 2022 (rs=-0.8; p=0.333) (Figure 3).

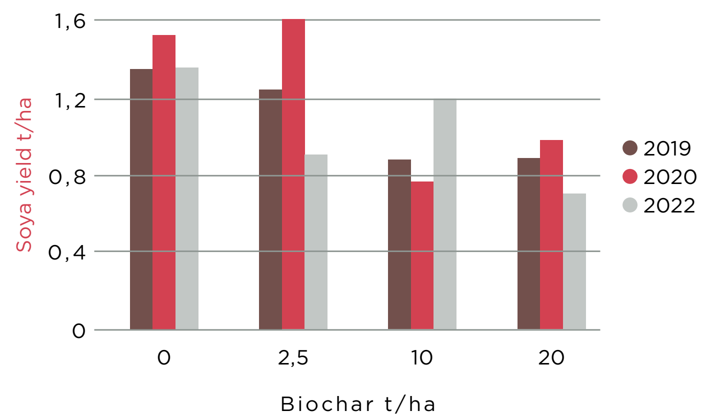

Figure 3. Soybean yield in the Tirzah pilot area in the 2019, 2020 and 2022 growing seasons

Interestingly, there are studies that have shown the opposite patterns to those found in soybean field during the LIFE CRAFT project [11]. This study, however, used biochar from bird droppings made from poultry manure. It also served as a fertilizer, as the measurements showed an increase in soil organic matter, total nitrogen, total phosphorus and available potassium of 43.53 %, 36.97 %, 22.28 % and 4.24 % respectively. In contrast, the fields in the Tirza pilot area were fertilized only with green manure in biochar incorporation year and during the rest trial seasons relied primarily on the ability of soya itself to accumulate atmospheric nitrogen via rhizobium bacteria. In this study [11], soybean growth was assessed by measuring the length and weight of the plant and its roots. Plant length measurements were also carried out during the 2019 growing season as part of the LIFE CRAFT project, but did not show a statistically significant correlation with incorporated biochar amount. As biochar concentrations increased, the yield of harvested and dried soybeans decreased over the three years of cultivation.

Monitoring scheme of the LIFE CRAFT project showed that biochar incorporation had a significant impact on soil properties such as organic matter content, total soil carbon, soil pH, phosphorus pentoxide, zinc and manganese content. Biochar incorporation resulted in an average increase in soil organic matter, soil carbon content, soil pH and plant available phosphorus, while plant available zinc and manganese decreased. For a number of soil properties significant differences were observed between the project farms, which can be explained by differences in soil composition, field topography, agronomic practices, fertilizer application rates and crops grown in the pilot areas. A particularly strong effect on the increase of organic matter content and plant available P_2O_2 and the reduction of soil acidity was observed in the Daugmale pilot area, where 30 t/ha of manure was incorporated together with biochar.

Biochar incorporation had no significant effect on any of the parameters reflecting microbiological activity. There were significant seasonal differences in dehydrogenase activity, ammonium oxidation potential and Shannon diversity index, which can be explained with differences in meteorological conditions and nutrient availability to micro-organisms, but not to biochar application and its amount in the soil.

During the LIFE CRAFT project monitoring period, a significant biochar effect on soil organic matter and total carbon accumulation was observed, indicating CO_2 accumulation in the soil.

Other surveys have also reported that yield response to biochar has varied from negative to positive due to interactions between soil properties, biochar properties and complex interactions among soil, biochar, crops, climate and management [12].

In the Netherlands, field experiments showed no significant biochar effect on sandy soil (which could potentially benefit the most) water retention and hydraulic conductivity or on aggregate stability. Applied biochar amount in these experiments even exceeded the maximum amount applied in the LIFE CRAFT pilot areas, i.e. used biochar in the Netherlands was up to 50 t/ha [13].

A remarkable finding from the LIFE CRAFT experience is that even at the highest biochar concentration (20 t/ha), after biochar mixing into the arable layer there was no visual change to the soil. On closer inspection, biochar particles were easily detectable even in the fifth year after incorporation. However, the total amount was not close to that shown in the images from the *Terra preta* examples. Thus, increasing the incorporated biochar concentration is a possible solution to achieve a persistent positive result. However, as it is seen in the LIFE CRAFT project, this option would no longer be economically viable, as the price of feedstock materials per hectare would significantly increase, while the financial benefits for the farm would remain uncertain.

As it has been shown above, further research and systematic reviews are needed to comprehensively assess the biochar impact on GHG emissions, carbon sequestration into the soil, productivity and the mechanisms underlying these processes. There are studies that have shown that the biochar use can give different results depending on the feedstock material, pyrolysis temperature, soil characteristics, climate and other conditions.

Conclusions

1. LIFE CRAFT project experience shows that, unlike tests carried out under strictly controlled laboratory conditions, yields on a producing farm can be affected by a variety of other factors including uneven growing conditions and soil properties within a field, where the impact of these conditions may be locally more significant than the impact of incorporated biochar;
2. Despite the growing evidence of the positive effects of biochar, further research is needed on possible factors that could weaken or hinder its ability to address climate change and ensure crop productivity;
3. Before biochar methods have been developed and tested in the field with lasting positive results, it would be premature to recommend such practices as economically viable for large agriculture farms;
4. On smaller scale farms, where biochar production using own labour and biomass is possible, biochar has a greater potential to become economically viable. Especially when used in combination with other environmentally friendly practices (permaculture, agroforestry, agroecological farming, etc.);
5. In the context of climate change mitigation and adaptation, biochar still retains high potential as a tool for carbon sequestration into the soil. However, its application on a purely market-based basis is hampered by high costs. Such instrument would require additional support mechanisms.

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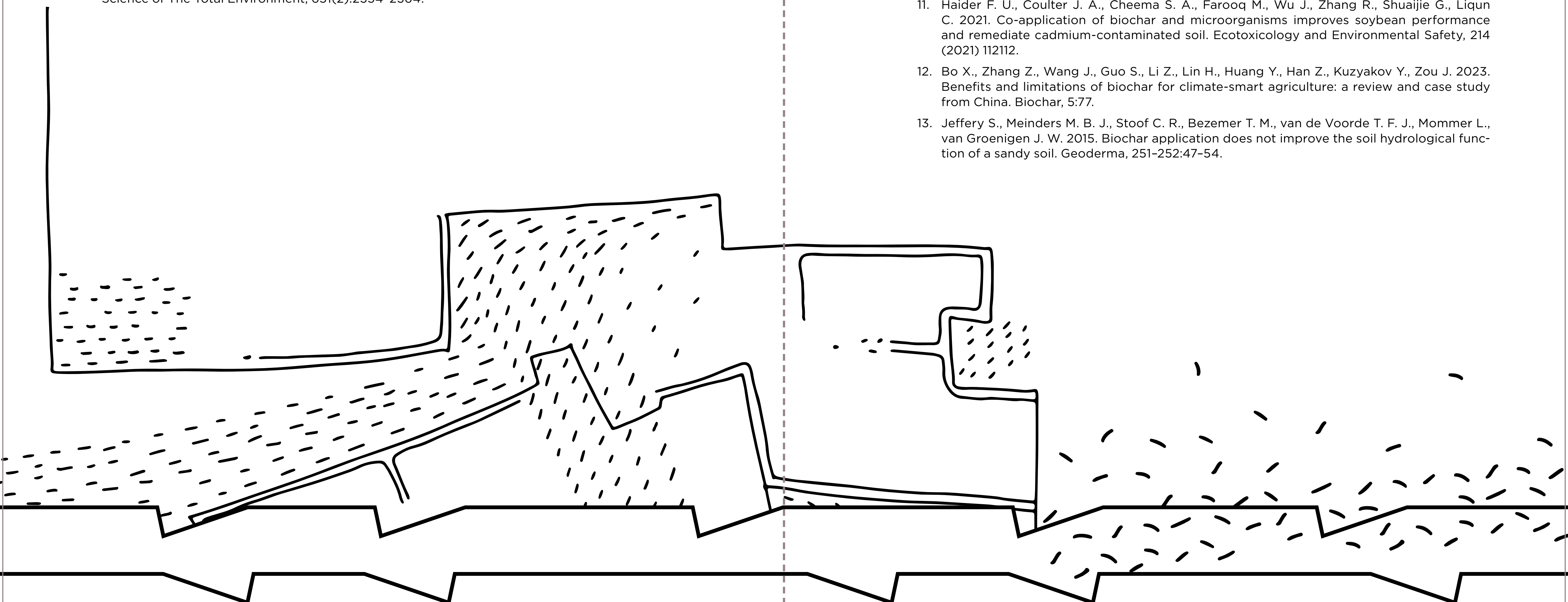

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