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Master Thesis

Evaluation of measures to increase organic carbon contents in agricultural soils

submitted by

Jonathan Sorger-Domenigg, BSc

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Supervisor:

Univ. Prof. Dipl.-Ing. Dr. Dr.h.c.mult. Martin Gerzabek

Institute of Soil Research
Department of Forest- and Soil Sciences

Affidavit

I hereby swear that I have compiled this Master Thesis without external help and without using sources and aides other than those permitted and that the sources have been cited verbatim or quoted textually in the places indicated.

This work has not been submitted in the same or similar form to any other examiners as a form of examination.

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21.12.2022

Date

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Abstract

As organic carbon, whether as soil organic matter or as a greenhouse gas, has become a global issue in the environmental debate, the amount of literature on the subject has skyrocketed. As with any topic receiving increasing attention worldwide, the quality and practicality of published content varies, underscoring the need for summarized and evaluated research that assesses the current literature on measures to increase organic carbon in agricultural soils. Six measures, aiming to increase soil organic carbon (SOC) stocks, have been defined and selected to match the European agricultural practice. These include agroforestry, agricultural extensification, cover- and intercropping, erosion control, tillage and fertilization and soil melioration. Additional assessment point are detection methods for long-term carbon storage and a comparison of the organic and conventional agriculture and their impact on SOC. This work presents a collection of relevant scientific papers and case studies selected thorough a process that ensures appropriate comparison and analysis. After selection, the measures are rated to produce information on both qualitative and quantitative aspects of their influence on SOC stocks. Given the current trend to monetize soil organic carbon increases through carbon credits, the results of this study should serve as indicators if the above measures are appropriate for long-term carbon increase and storage. Examples of highly rated agricultural measures include cover- and intercrops, biochar and agroforestry measures such as alley cropping. Measures that could only increase SOC contents under highly specific conditions or under high risk are conversion of cropland to grassland, tillage and silvopasture. Detection methods for carbon storage presents a current and relevant challenge, as there is a large gap between technological advances and viable in-field measurement methods.

Zusammenfassung

Organischer Kohlenstoff, ob als organische Bodensubstanz oder als Treibhausgas, ist ein zentrales Thema in der Debatte um Klima und Umwelt geworden. Doch wie bei allen Themen in globalen Fokus, schwankt die Qualität der stetig wachsenden Zahl an neuen Publikationen. Dadurch entsteht ein klarer Bedarf an zusammengefassten und systematisch ausgewerteten Literaturstudien zu Maßnahmen, die den organischen Kohlenstoff in landwirtschaftlichen Böden erhöhen. Sechs Maßnahmen, die auf die Erhöhung des Bodenkohlenstoffes abzielen, wurden, der europäischen landwirtschaftlichen Praxis entsprechend, ausgewählt und definiert. Diese beinhalten: Agroforst, Extensivierungsmaßnahmen, Deck- und Zwischenfrüchte, Erosionsschutz, Bodenbearbeitung, Düngung und Bodenverbesserungsmaßnahmen. Zusätzliche Themen sind Detektionsmethoden von Langzeit-Kohlenstoffspeicherung und ein Vergleich zwischen dem Einfluss von biologischer und konventioneller Landwirtschaft auf den Bodenkohlenstoff. In der folgenden Arbeit wird eine Sammlung an relevanten, wissenschaftlichen Publikationen und Fallstudien präsentiert, die nach einem Prozess, der den Vergleich und die Analyse erlaubt, ausgewählt wurden. Nach der Auswahl werden die Studien bewertet, um Information zu qualitativen und quantitativen Aspekten der untersuchten Maßnahmen und ihres Einflusses auf Bodenkohlenstoffvorräte zu ermitteln. Angesichts des derzeitigen Trends, Kohlenstoffzunahme im Boden durch „Carbon-Credits" zu monetarisieren, sollen die Ergebnisse dieser Studie als Indikatoren dafür dienen, ob die oben genannten Maßnahmen für eine langfristige Kohlenstoffzunahme und -speicherung geeignet sind. Beispiele für hoch bewertete landwirtschaftliche Maßnahmen sind Deck- und Zwischenfrüchte, Pflanzenkohle und agroforstliche Maßnahmen wie „Alley Cropping". Maßnahmen, die den SOC-Gehalt nur unter sehr spezifischen Bedingungen oder unter hohem Risiko erhöhen könnten, sind die Umwandlung von Ackerland in Grünland, Bodenbearbeitung und Hutewald. Nachweismethoden für die Kohlenstoffspeicherung stellen aktuell eine große Herausforderung dar, da eine große Lücke zwischen technologischen Fortschritten und praktikablen Messmethoden im Feld besteht.

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1. Introduction

1.1. Rationale

Carbon can be considered one of the most essential building blocks of all life on earth. Since its recognition as an element during the 18th century, it has become something like a celebrity beneath the elements in recent times. And rightfully so. Due to its role in agricultural soils, be it in the build-up of soil organic matter (SOM), which is crucial for healthy and fertile soils, or as its gaseous form, carbon-dioxide (CO_2), a driving member of the greenhouse-gases (GHG), carbon has shifted into the centre of today's scientific focus (Wiesmeier et al. 2021; Don, 2022). While climate-warming is no new phenomenon, there has been serious concern of the scientific community since the late 20th century (WMO, 1989), the private- and public sector involvement has only recently picked up its pace. With the common goal of reducing, mitigating, and reversing the damage that half a century of wildly unhindered emissions has caused and will cause, governments, non-profits, and private companies alike, are putting their heads together to come up with ways to successfully motivate the industry to stop polluting, the farmers to start sequestering and the people to reduce their ecological footprint. In short: a global race to counteract the effect of GHG on the ozone layer has begun.

With agriculture accounting for 18,4% of global GHG emissions in 2016 (Our World in Data, 2020) and 11% of European emissions (EEA, 2021), it represents one of the sectors with lots of room for improvement (Foereid and Hogh-Jensen, 2004; Seitz et al., 2021; Rosinger et al., 2022). Since the industrial revolution, the discovery of synthetic fertilizers and the development of heavy machinery towards the end of the last millennia, CO_2-emissions have risen to 40% above their long-term pre-industrial average (Henriques and Borowiecki, 2014). But while the goal is relatively clear, the way to reach it remains cause for discussion and dispute throughout the world.

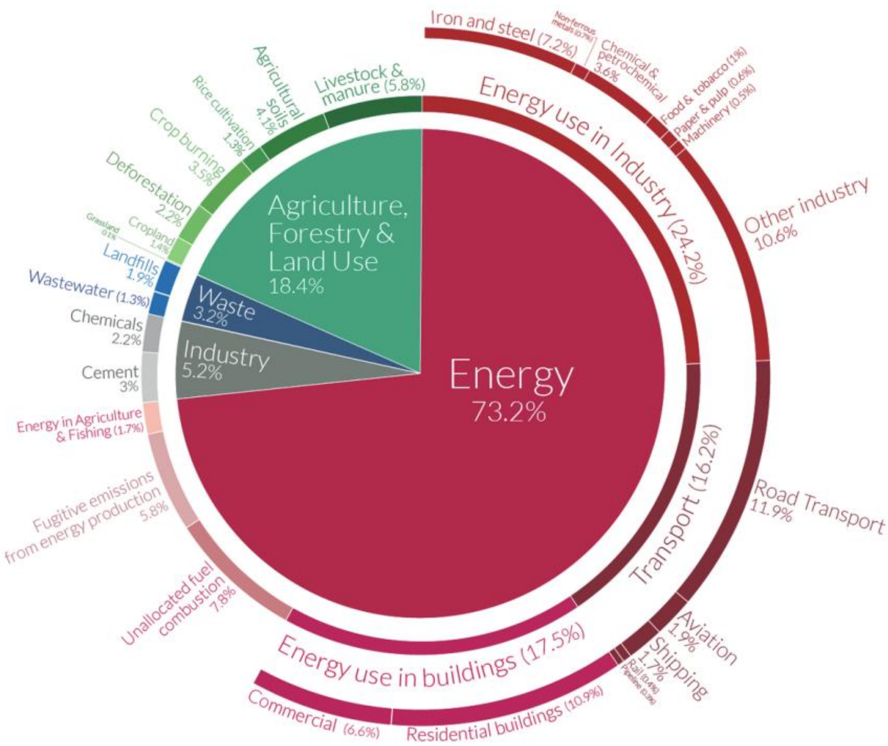

Figure 1: Global greenhouse gas emissions in 2016, 49.4 billion tonnes of CO2 eq.; Source: Climate Watch, the World Resources Institute, 2020; Our World in Data, 2020

While larger emitters, such as the fossil fuel industry, which is currently responsible for 86% [+/-14%] of all anthropogenic CO_2 emissions (IPCC, 2021), are not yet properly held accountable, short-term solutions, easier and faster to execute, are being developed to reduce the carbon already in the atmosphere. One of the suggestions, is increasing the carbon content in agricultural soils (Farelly et al., 2018; OECD, 2022). From a scientific point of view, doing so only makes sense. Carbon is an essential component of organic matter, better known as humus, which directly and indirectly (positively) influences many soil properties (Gerzabek et al., 2022). Yet from an economic point of view, in many cases, it is the opposite. Building carbon stocks means either increasing input of organic matter, like manure or compost, or decreasing output by reducing cash crops in the rotation, cut frequencies or cattle grazing, for example (Freibauer et al., 2004; Smith, 2000). Both things, a farmer, trying to make a living, does not necessarily want. This is where the newly developed carbon economy should come in. Essentially, the carbon credit system wants to reward farmers taking an extra step, or giving up on additional yield, to increase their organic carbon content. To do so, they need to identify extra steps a farmer can take, to reward where deserved.

Emission trading started 1997, when 180 countries signed the Kyoto protocol (Kumar, 2016; UNFCC, 2008), but the criticism, especially from the scientific community, remains high (Böhm et al., 2012; Coelho, 2015). Inaccurate measuring and short-sighted measures, such as the arbitrary planting of trees, whose carbon-sequestration potential is monetized before it was even achieved (IPCC, 2019; OXFAM, 2021), not only cause further environmental issues, but have also led to a reduced credibility in emission trading. The aim of this research is therefore, to take a closer look at selected agricultural measures, practiced to increase and sequester carbon into the soil, and analyse them on their effectivity and feasibility to create a reliable basis for further work and research.

1.2. Theoretical Background

In the following chapter, the theoretical background for this research is covered. An initial overview of the basic physical and chemical properties of the element carbon is given, followed by an explanation of the carbon cycle and a description of the most important roles of carbon in agricultural soils.

Next, the agricultural measures analysed in this study will be described and their impact on soil organic carbon stocks explained. The seven sub-chapters each represent a measure to increase soil organic carbon stocks and give scientific and practice-oriented background.

Finally, a brief sub-chapter will focus on carbon trade and economy and discuss the underlying application of this study.

1.2.1. Carbon basics

Carbon is an essential element and the underlying source of all life on earth. While organic matter in topsoil usually only accounts for a few percent of its mass (Brady and Ray, 2008), it fulfils essential soil functions and takes up a major role in the global carbon cycle (Janzen, 2003). It is this soil organic matter (SOM) that acts as a sorbent for inorganic and organic substances in the soil solution, offers charges to increase the cation-exchange capacity as well as hydrophobic zones for insoluble organic substances and takes up a central part in creating and stabilizing the soil aggregates and structure (Gerzabek et al., 2022). Soil temperature and mineralisation rate of plant residues depend on it, much like the soil fauna and micro-flora (Gonzáles-Pérez, 2003).

1.2.1.1. Soil organic matter and carbon

Soil organic matter describes a heterogeneous mix of decaying plant and animal matter, the living biomass of microbes and the decomposition-resistant carbon polymers, known as humic substances. It includes all organic molecules, like carbohydrates, proteins and fats, and all organic materials added through anthropogenic activity, such as compost, synthetic organic fertilizers, or biochar (Lavelle et al., 2005; Scheffer and Schachtschabel, 2018). Fundamentally, SOM is therefore built up through two sets of factors: natural ones and anthropogenic ones. Natural factors, such as climate, pedogenesis and vegetation cover play an important role, especially when it comes to initial build up and natural equilibria of SOM. Human-induced factors such as the type of land-use and soil management and the overall degradation rate of the soil have the potential to greatly affect SOM content (Piccolo, 2012).

Soils hold roughly 80% of terrestrial organic carbon reservoirs, while vegetation only accounts for around 20% (Scheffer and Schachtschabel, 2018). Yet, the two are tightly interlinked, providing each other with the necessary means to produce and sustain life.

1.2.1.2. The carbon cycle

CO_2 is assimilated into the vegetation via photosynthesis and integrated into soil as plant residues and root-exudates. Inside the soil, the organic material then goes through mineralization, which is the process of microbial deconstruction of organic into inorganic components (CO_2, H_2O) and the release of the contained nutrients (Mg, Fe, N, S). With constant environmental and vegetational conditions, an equilibrium between carbon input and output develops, characterized by a typical humus pattern. The plant-residues and the carbon they contain re-enters the atmosphere as CO_2, through respiration (Fig.2; Naylor et al., 2020). Whatever amount of carbon stays behind in the soil, without being mineralized, will be permanently bound to the OM through stabilisation processes that protect it from microbial decomposition/degradation. This is the reason SOM is regarded as highly heterogenic (Scheffer and Schachtschabel, 2018).

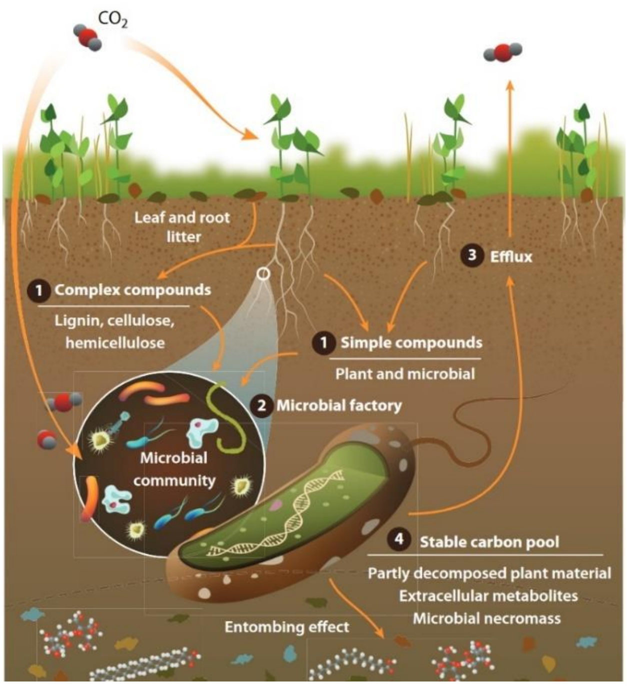

Figure 2: Soil carbon cycle through microbial loop; Source: Naylor et al., 2020

1.2.1.3. The role of carbon in agricultural soils

A soil's main functions, seen in an agricultural context, are the production of biomass, storage and filtration of water, nutrient cycling, and storage, providing habitat for biological activity and carbon storage. Carbon storage can be seen as an underlying function, as it greatly impacts the others (Wiesmeier et al., 2018). Besides these physical and chemical functions of carbon in agricultural soils, climatic aspects, such as the driving role of carbon as a greenhouse gas (CO_2), have caused a recent rise in interest in carbon sequestration and storage as a soil function.

Taking a closer look at the described functions and how they are influenced by carbon:

i. Production of biomass: Carbon is the base element for our most important organic compounds. Be it carbohydrates, lipids, proteins or nucleic acids, carbon is their common denominator, as the bonds between carbon atoms are particularly stable and therefor allow for the construction of long chains (Fig. 3). Through this, carbon can take on many shapes and forms, creating an incredible variety of organic compounds (Fullick, 2018).

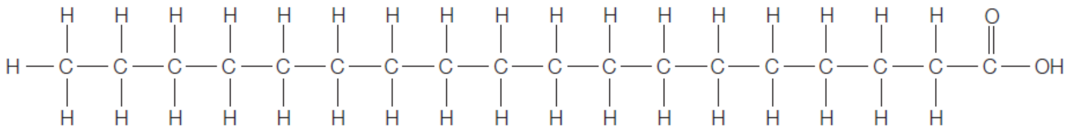

Figure 3: Stearic Acid, Source: Fullick, 2018

ii. Water storage and filtration: As established above, carbon is an essential building block of organic matter, such as the one in fertile, agricultural topsoil. SOM influences the soils' ability to store, retain and filter water in various ways such as the increase of the field capacity (FC), plant available water capacity (PAWC) and the reduction of erosion or evaporation potential. On the other hand, many factors, such as the soil texture, management type and initial SOM content influence a soils ability to store water (Lal, 2020).

iii. Nutrient cycling and storage: When it comes to nutrient cycling, the role of organic matter is crucial. Most labile nutrients are contained in organic compounds, and as plants almost exclusively take up nutrients in inorganic form, the energy provided to microorganisms by organic matter, allowing them to mineralize these nutrients is essential (Lavelle et al., 2005).

iv. Soil as a habitat: A gram of soil inhabits around 10 million, partly unidentified, microorganisms, that are responsible for making the soil a reactive, highly efficient bioreactor, that sustains life on earth (Scheffer and Schachtschabel, 2018). Many of these microorganisms take part in decomposing and deconstructing dead plant and animal matter, therefor providing plants with new nutrients, and creating and strengthening the soil structure.

v. Carbon storage: As demonstrated by the previously listed examples, carbon has an impact on all other soil functions. Naturally, this works the other way around as well, whereby carbon storage is influenced by a variety of soil functions and properties. Carbon storage is closely linked to soil texture and clay content, as clay minerals can potentially bind organic matter and therefor keep carbon from being mineralized (Wei et al., 2013; Kucerik, 2019). When carbon enters the soil as plant litter or dead organic matter, decomposition is heavily dependent on the soil fauna, so called destruents.

The complexity and sheer variety of abiotic and biotic interactions between climate, carbon and the different soil organisms is high (Fig. 4; Hancock et al., 2019). Regardless, the need to act and interact with the carbon in our soils is undisputed. Since the dawn of agriculture, over 10000 years ago, humans have changed SOC-stocks through their practices (Weisdorf, 2005). This next chapter will list a few examples, on how certain agricultural measures do that today.

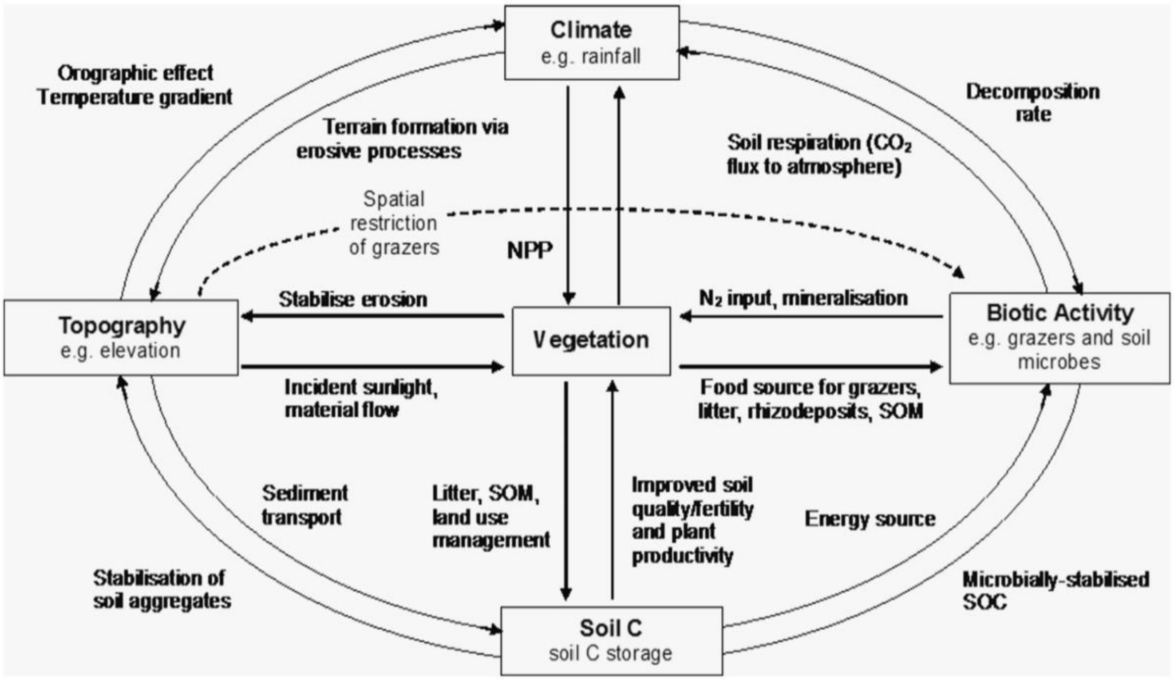

Figure 4: Abiotic and biotic control of soil organic carbon; Source: Hancock et al., 2019

1.2.2. Impact of agricultural measures and management on soil organic carbon stocks

In the following paragraphs, six agricultural measures are defined and described. Since this study focuses on central and western Europe, the measures are selected according to a geographically and culturally relevant context.

1.2.2.1. Extensification

Agricultural extensification describes the reduction of in- and/or output of a farming system. This might be a decrease of fertilizers or pesticides used in crop production, reduction of livestock density on pastureland, reduced cut frequency on grassland, changes in crop rotation or even extensification of cropland to grassland (Eurostat glossary, 2017; Tupek et al., 2021).

Extensification itself can be achieved through a variety of ways. The most common are listed below:

i. Conversion of cropland into grassland: All thoughts of feasibility left aside, converting highly productive cropland into extensively managed grassland/meadows presents a promising way to build up soil carbon stocks, as croplands often show the lowest SOC-stocks (Poeplau, 2021).

ii. Reduction of cut frequency: Depending on the current cut frequency, reduction can lead to changes in SOC stocks. Cutting frequency, paired with the right fertilizer management plays an important role in determining a grasslands potential for carbon sequestration (Poeplau, 2016).

iii. Reduction of grazing intensity: Grazing intensity, under influence of a variety of abiotic and biotic parameters, can shape a grasslands or pastures soil structure and species composition and therefor its capacity to sequester and store carbon (Abdalla et al., 2018).

1.2.2.2. Cover- and intercropping

Cover- and intercropping are two different forms of utilizing additional plants in a crop rotation for a variety of benefits:

i. Cover crops: Cover crops are used between main crops, during winter and on fallows. Depending on the choice of cover crops, this creates benefits, such as the reduction of erosion potential, increase of organic matter in- and on the soil and in case of legumes, the fixation of the essential plant nutrient nitrogen. Cover crops can increase SOC-stocks, as they not only decrease emissions by covering the soil, but also add carbon, photosynthesized into their biomass, back to the soil (Seitz et al., 2022; Poeplau and Don, 2014).

ii. Intercropping: As opposed to cover crops, intercropping describes the practice of cultivating more than one crop at the same time. This can be done in different ways and designs, such as the use of perennial crops throughout the field, or agroforestry systems. There are several benefits derived from intercropping, with the most prominent being the increase of biodiversity above and below ground, which generally strengthens a farming system by reducing pest and weed pressure and increasing output variety and therefor the yield security (Cong et al., 2014). Further, a soils natural resources can be utilized more efficiently and sometimes, allelopathic interaction between crops can have positive effects. Concerning the increase of SOC, intercropping provides promising results, especially from studies in agroforestry systems (see chapter 1.2.2.7.).

1.2.2.3. Erosion control

Soil erosion describes the displacement of soil, mostly through rain and wind, but also through landslides, earthquakes, and other natural phenomena. Intergovernmental, environmental institutions such as the FAO, the IPCC or the UNCCD have identified erosion as a major threat to global soil health (Pennock, 2019; Olsson et al., 2019; UNCCD, 2022). Through the massive quantities of soil being relocated, erosion plays an important role in soil organic carbon dynamics. Through the detachment of soil mass, SOC is transported and buried, leading to changes in mineralisation and impact on net primary production (Fig. 5; Kirkels, 2014). In 2012, the European Soil Data Centre (ESDAC) estimated global soil erosion to amount to 35,9 Pg (1 Petagram equals 1 billion metric tons) of soil displaced through water erosion (Borelli et al., 2013). Nature is only partly at fault when it comes to soil erosion. In many cases, land-use change, mismanagement, and excessive exploitation of agricultural soils lead to increasing

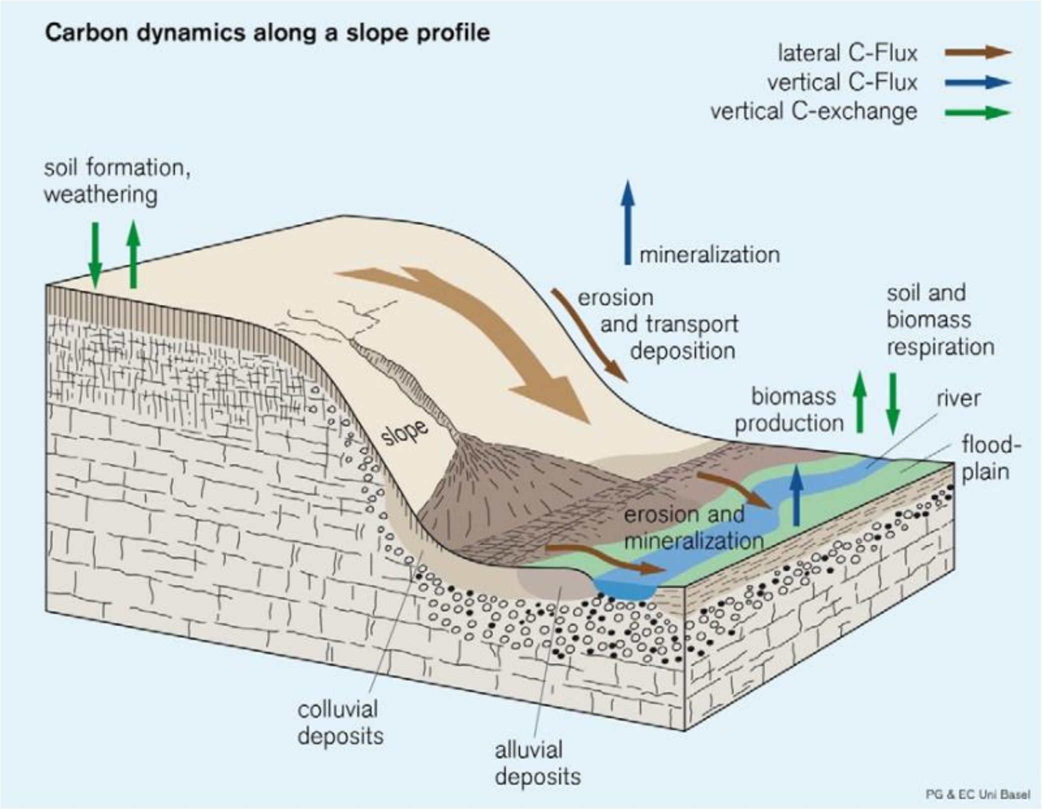

Figure 5: Carbon dynamics along a slope profile, including interaction between biomass production, erosion, deposition and carbon fluxes; Source: Kirkels et al., 2014

erosion. Intensive tillage and soil management result in soil compaction, which in turn can increase the soils erosion potential (UNCCD, 2022).

To combat these issues, several measures can be undertaken by farmers to counteract or prevent soil loss through erosion. The following will be used in the subsequent analysis:

i. Erosion control through cross-seeding: cross-seeding is a seeding technique where half the seeds are planted in conventional order, while the other half is planted at a specific angle, to achieve broader root spread throughout the soil, which in turn can help to protect the soil from erosion and reduce weed pressure (Reimer et al., 2019).

ii. Windbreaks: Linear, woody vegetation grown to reduce wind speed and therefore protects the soil from erosion. Additional benefits include positive impact on a farm's microclimate, production of food and/or timber and increase in local biodiversity by provision of habitat for beneficial animals (Řeháček et al., 2017). Carbon can be sequestered into the shrubs and trees, and the additional biomass can be composted and utilized to increase SOC-stocks on-field.

iii. Permanent planting: Exposed and bare soil is highly susceptible to erosion; thus, permanent vegetation cover provides efficient protection (Rivas, 2006). And while permanent plant cover might not be an option for arable land, field edges and slopes can be stabilized through planting of suitable, permanent vegetation. Depending on vegetation type and management, permanent planting provides an additional method to sequestering carbon into a farming system (Marques et al., 2020).

iv. Hedges: Hedges were historically introduced to mark territory. Today, they are a common form of erosion prevention, applied all over Europe, with a variety of additional ecosystem services. Aside from shielding arable land from wind and water erosion, they create multiple benefits for the farmer, such as providing habitat for beneficial animals, thus increasing the biodiversity around the farm, or creating additional biomass to re-enter the farming system, therefore increasing the organic carbon input (Lacoste et al., 2016; Hombegowda et al., 2020).

1.2.2.4. Tillage

Tillage, the mechanical management of soil, has major impacts on SOM (Krauss et al., 2021). However, which form of tillage, be it conventional, conservational or no-till, is most suitable for sustainable soil management is still heavily debated.

Due to the complexity of the topic, tillage practices have been simplified and reduced to 3 measures, defined as follows:

i. Conventional tillage: The 2001 OECD definition, states that conventional tillage is when tillage is used as main form of seedbed preparation and weed control. It typically includes soil management forms such as ploughing, harrowing and the removal of plant residues of previous crops. Conventional tillage has been shown to impact SOC, as open soils are prone to increased emissions (Reicosky, 1997). High tillage intensity can lead to compaction of soil bellow the tillage depth, increase erosion risk and cause additional emissions through the use of fossil fuel (Haddaway et al., 2017).

ii. Conservation tillage or reduced tillage: Conservation tillage is defined by reduced tillage intensity, to allow the soil to better retain water and nutrients. Often plant residues are left on the field (OECD, 2001). It can include ploughing or non-inversion tillage, at overall shallower depths. Reduced tillage can increase SOC content at different soil depths, greatly depending on a variety of soil parameters (Krauss et al., 2021).

iii. No-Till: As the name suggests, no tillage is applied in no-till systems. The crop is sown into covered fields, benefiting from high OM and water retention, but potential competition for nutrients through increased weed pressure. Converting from conventional to no-till systems can lead to an increase in SOC, if biomass is kept on-field (Badagliacca et al., 2018).

1.2.2.5. Fertilization and soil melioration

Another broad, but relevant topic, is plant fertilization. Not only between organic and conventional farmers, but globally, the use of synthetic mineral fertilizers is thoroughly discussed, the amount of published literature is high. Conversely, application of organic matter, such as animal manure or plant residues is increasingly recommended, causing further debates on what achieves the best results.

In the following analysis, three types of fertilization will be included:

i. Synthetic or mineral fertilizer: The classical mineral fertilizers, such as NPK fertilizers, provide a quick and efficient boost to plant growth, by supplying the essential plant nutrients nitrogen, phosphorus, and potassium directly into the absorption zone of the crops root system. They are highly water soluble, allowing quick absorption, at the risk of high leaching rates (Rashidzadeh and Olad, 2014).

ii. Organic fertilizer: As a result of decomposition of organic material, organic fertilizers take a more indirect route to supply plants with nutrients. They include animal and plant waste, compost, and other by-products of living organisms (Sabry, 2015).

iii. Mixed fertilization: Often, non-organically certified farmers tend to utilize a mixture of both organic and mineral fertilizers. It must be noted that the large amount of different fertilization approaches cannot be fully represented in the following evaluation.

iv. Biochar: A form of soil melioration, which has recently seen increasing attention. Biochar is a product created by pyrolysis (thermal decomposition in absence of oxygen) of biomass, with high carbon contents and various beneficial functions (water and soil quality) for agricultural soils. Biochar presents a promising tool to sequester carbon into soils, as carbon bound in it becomes extremely stable, with a half-life of hundreds, possible thousands, of years (Rittl et al., 2018; Laird, 2008).

1.2.2.6. Agroforestry

Agroforestry describes land-use systems, where woody perennials are integrated into the agricultural production (Nair, 1985). Two or more crops are included in a dynamic farming system, where efficient utilization and reproduction of farm resources are key. The whole system benefits from both, species, and farm output diversification, thus increasing the farm stability and sustainability (Lorenz and Lal, 2014). 2008, Nair classified key practices for Agroforestry in temperate climate zone such as follows:

i. Alley cropping or hedgerows: A practice that shows promising results for the adaptation of agroforestry into European agriculture. Through parallel rows of trees, planted throughout the crop fields, farmers can continue the mechanization of their crop management (harvest, soil management, etc.). Carbon can be stored in the trees themselves and re-enters the soil as plant litter. Especially in combination with permanent plant-cover and/or adapted tillage, carbon sequestration can be maximized in alley cropping systems (Fig. 6; Cardinael et al., 2015).

Figure 6: Alley cropping agroforestry system with walnut and durum wheat; Source: Cardinael et al., 2015

ii. Forest farming: Forest farming described the cultivation of non-timber products under a tree canopy. It differs from wild harvesting, as crops are actively managed and maintained in their natural forest habitat (Trozzo et al., 2021). Impact of forest farming on SOC-pools strongly depends on a variety of factors, such as the prior land-use type, the forest and crop management and the general farming system.

iii. Riparian buffer stripes: Buffer stripes, meaning stripes of un-managed vegetation between either two different forms of vegetation, two different fields, or between agricultural land and a body of water, are a common sight in our agricultural landscape. Riparian buffer stripes are commonly used for nutrient, but also pesticide or herbicide retention, preventing agrochemicals from leaching into natural ecosystems. Riparian buffer strips fulfil a variety of ecosystem services, from erosion control to nutrient and pesticide retention to a habitat for beneficial fauna and flora, and likely a high potential to sequester and store carbon (Stutter et al., 2012).

iv. Silvopasture: The combination of livestock and forage production with forestry systems, called Silvopasture, has been practiced for thousands of years, but has recently seen a new rise in attention. It consists of complex management of both spatial and temporal factors and when carefully planned, can provide impressive system productivity. Especially when compared to conventional livestock management, Silvopasture presents promising results when it comes to carbon storage (Jose and Dollinger, 2019).

1.2.2.7. Detection methods for long-term carbon storage

One of the biggest challenges for both scientists, researching carbon increasing measures and politicians and entrepreneurs, trying to establish systems to support farmers trying to increase their SOC-stocks, is the detection of carbon. SOC has a very high spatial variability (Zhang et al., 2015), making accurate measurement a complicated issue. Since the recent introduction of financial value to the topic, questions like the where, when how much and how deep are no longer debates exclusive to the scientific world.

This chapter will focus on carbon detection, with the aim of supporting the subsequent evaluation and discussion, by shining a light on how the success of agricultural measures is and could be measured. The basics are listed below:

i. Carbon mass based on equal soil mass: When extracting OM from soil samples, bulk density plays a crucial role, as it directly correlates with the soil volume. If between two soil samples bulk density has decreased for example, this means volume has increased and therefore, soil must be sampled deeper to produce an equal amount as the previous sample (Gerzabek et al., 1997).

ii. Loss on ignition (LOI): Through burning of soil mass, the lost biomass can be calculated by through weight loss after ignition. A common method of carbon measuring, although factors such as the furnace type, sample mass and clay content and temperature and duration of ignition (Hoogsteen et al., 2015).

iii. Further detections methods: Results will include further detection methods found in literature used for the evaluation.

When it comes to carbon detection, a variety of factors are decisive of the outcome, such as the timing, depth and sample size and number. Sampling needs to be precise and replicable, to allow analysis, comparison and in the end, monetisation through carbon credits or other forms of carbon-based subsidies.

1.2.3. Carbon trade and economy

In this last theoretical chapter, a brief overview of the underling mechanics of carbon economy and trade are given.

1.2.3.1. Carbon trade & CO_2-certification

A carbon market is defined as a market, where greenhouse gases (GHG), in form of CO_2-equivalent (CO_2-eq) are commodified as a tradable unit (Betz et al., 2022). Over the past decade, carbon trade has grown to a massive market worldwide. In their 2021 Report on the state of carbon pricing, the World Bank reports 127 countries currently committed to some form of decarbonization scheme, with a global revenue of USD 53 billion created from carbon trade through initiatives around the world, covering 21,7% of global GHG emissions (World Bank, 2021).

The world bank describes carbon pricing as an instrument that covers external costs of carbon emissions, such as health and environmental damage, and redirects it to those responsible (World Bank, 2021; Carbon pricing dashboard, World Bank, 2017). To do so, carbon pricing makes use of multiple tools:

i. Emission trading systems (ETS): Emitters can trade emission units to meet their national or international emission goals. ETS are executed in two manners:

   1) Cap-and-trade system: A cap for maximum emissions for a country/ETS system are set and emission allowances are distributed. Those polluting above the cap can then buy additional allowances from those polluting under the limit.

   2) Baseline-and-credit system: A baseline emission level is defined, and credits are issued to those producing underneath it. Those credits can then be sold to those producing above it.

ii. Carbon tax: A definite price is set on the carbon content of fossil fuels (price per tCO_2e). Unlike the carbon price, emission reduction outcome is not defined.

iii. Offset mechanisms: Emission reductions from project- or program-based activities can be sold nationally or internationally in form of carbon credits. These carbon credits can be used to achieve emission goals set in international agreements.

iv. RBCF: In short for result-based climate finance, as the name suggest, are funds paid after the achievement of prior defined emission goals. RBCF often include poverty alleviation and community benefit programs (?).

v. Internal carbon pricing: Is a tool used by companies, governments and organisations, to guide their decision-making process in accordance to environmental risks, impacts and opportunities.

2. Objectives

The fundamental objective of this study is to identify and analyse the impact of land use and soil management on soil organic carbon contents. To do so, the seven previously described (1.2.2.) sub-categories of agricultural measures are analysed through an evaluation process, defined in chapter 3.

Specific questions to be addressed in this literature review include:

- What is the influence of extensification (conversion from cropland to grassland, multi-cut grassland to fewer cuts, grazing...)?
- What is the contribution of cover- and intercrops (intercrops after harvesting the main crop, but also undersown crops)?
- How is the OC of organic farms compared to conventional farming?
- What is the positive influence of erosion control (e.g.: cross-seeding, windbreaks, permanent planting) on OC contents?
- What is the influence of tillage on OC levels (grubbing versus tillage, cover cropping, minimum tillage)?
- What is the influence of fertilization (mineral fertilization versus organic fertilizers)?
- What is the influence of agroforestry on SOC?
- What are the detection methods for soil organic carbon stocks?

3. Materials & Methods (Literature collection & evaluation method)

This chapter will describe the research and evaluation process of this study. Starting with the literature search an explanation on how and from where literature was acquired is given and the in- and exclusion criteria and moderators used to determine suitable scientific literature are identified and explained.

After having both given scientific background and a precise description on the literature selection, the evaluation system, after which the six measures will be analysed and rated on their effectivity in soil-carbon increase, will be constructed and explained.

3.1. Literature search

86 relevant publications were collected from various databases, over the period of 01.05.2022 until 25.11.2022. The acquired literature used for evaluation had to fulfil several requirements regarding their sampling method, study design and study duration, to fit into the final evaluation of SOC-increasing, agricultural measures. Chapter 3.2. contains the in- or exclusion criteria, after which the literature was selected. Databases used for literature search are: BOKU LitSearch, Google Scholar, ScienceDirect and ResearchGate.

Keywords used for literature search included following combinations:

(Extensification OR grazing OR pasture management OR cutting frequency OR cover crops OR cover cropping OR intercropping OR crop rotation OR crop management OR Erosion OR wind-erosion OR tillage OR no-till OR reduced tillage OR conservation tillage OR Fertilizer OR nutrient management OR manure OR organic matter application OR agroforestry OR hedges OR silvopastures) AND (Carbon OR Carbon sequestration OR Soil organic carbon OR C-Sequestration OR SOC OR SOC-storage OR SOC-stocks)

Grey literature refers to online journals, unpublished studies, policy reports and other, non-peer reviewed publications (Conn, et al., 2003). Since the aim of this thesis is to combine both scientific and practical points of view, to accurately depict the status quo of European agriculture, some forms of grey literature have been included in the study.

3.2. Inclusion and exclusion criteria

To ensure a systematic review process, the studies, chosen for evaluation, have been selected through a set of inclusion and exclusion criteria.

These consist of the following:

- Geographic relevance: As this master thesis focuses on European agriculture, studies conducted in Europe, or places of similar climatic conditions are given priority in the evaluation process. Studies conducted in other climatic conditions may be included for additional information.

- Recentness: Studies conducted before 2000 will not be included.

- Practical: Studies of practical availability are given priority, meaning highly theoretical or experimental measures, with no current, practical feasibility, will only be included for additional information.

- Bias: Studies conducted by or for political and/or commercial entities cannot be included. This is to avoid including results which are at a high risk of being altered to favour a specific sponsor.

- The land-use and management or treatment of arable land must include at least one pair of data – control and treatment, clearly described management/treatment method, including duration and a sufficient set of moderators (3.3.)

3.3. Moderators

Moderators are covariables that change the effect-size of the management/treatment outcome. Influence of management practices on SOC-content will vary since it depends on many other factors, such as the ones listed below. To be able to compare different management practices, these so-called moderators must be taken in account and their influence must be rated.

Example: Surface decomposition of plant residues depends on precipitation levels and temperature (Wiesmeier et al., 2019). Therefore, when comparing SOC-increase or decrease after conventional tillage, reduced tillage and no tillage, the temperature and the amount of rainfall during/after the treatment must be considered, as it will alter the outcome.

If said variables (precipitation and temperature in this example) have a significant effect on the measure's effectivity on SOC-stock in- or decrease, it will in turn be identified as a key-moderator.

Essential covariables are identified, following the SCORPAN-approach, a method that McBratney et. al developed in 2003, based on the research of Hans Jenny (Wiesmeier et. al, 2019). In the following section, the seven SCORPAN variables are defined, and their most important factors explained.

$$S = f(s, c, o, r, p, a, n)$$

Soil (mS):

- Soil type: Soil types differ in their percentage of minerals, water, air, and organic matter. The carbon storage potential is therefore heavily dependent on the soil type. Factors such as clay and silt content, which have bigger surface areas to absorb and hold carbon (Zhou et al., 2019), or general organic matter content play important roles in estimating a soils potential to sequester additional carbon.

- PH-value (acidic, neutral, alkaline): Soil carbon is negatively correlated with pH-value, meaning lower pH-values tend to favour higher carbon accumulation of organic matter and therefor carbon (Zhou et al., 2019).

- Soil texture (clay, loam, sand, etc.): In 1997 Bosatta and Agren did a study to demonstrate the relationship of organic carbon storage and clay content of soils (Fig. 7). They concluded, that with higher clay content, mineralisation rates decrease, while C and N contents increase. In a more recent study, Schweizer et al., explain this by the reduced accessibility of the OM for degraders, although they conclude that clay content is not necessarily a limiting factor when it comes to OC uptake and storage (Schweizer et al., 2021).

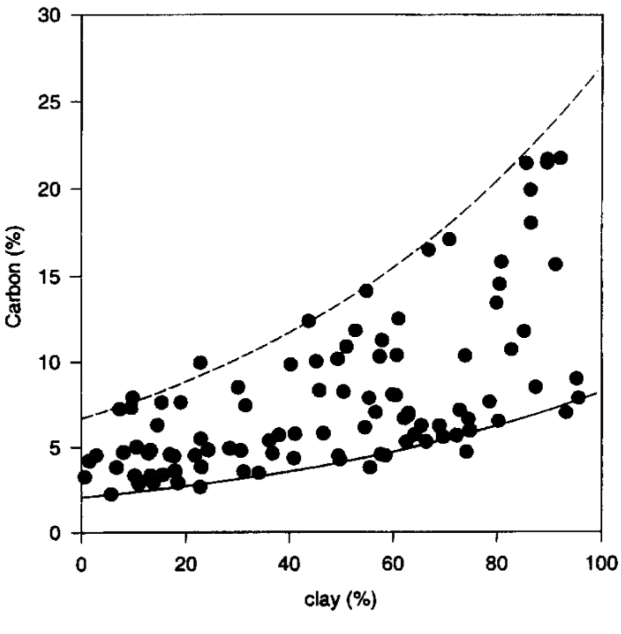

Figure 7: Soil organic carbon concentration at a steady-state against clay content; Source: Bosatta and Agren, 1997

- Soil aggregation: As with the texture, aggregation provides protection of SOM, and therefore carbon particles against degradation. It is often assumed that OM sorption increases with the mass of fine particles of a soil.

- Bulk density: Is the dry weight of soil divided by its volume (Scheffer and Schachtschabel, 2018). When it comes to measuring carbon, bulk density (BD) is essential, as it ensures that factors such as sampling depth or soil compaction are accounted for, when comparing samples.

- Water filled pore spaces (WFPS): Is the ratio of soil water content to total soil porosity (Scheffer and Schachtschabel, 2018).

Climate (mC):

Especially through precipitation, heat, cold or drought periods and general seasons, climate is an essential, highly complex, variable, when comparing the impact of different agricultural measures on SOC. To allow rating of sufficient fulfilment of the moderator, Climate (c) has been simplified as follows:

- Climate types, according to Köppen-Geiger climate classification (Kottek et al., 2006; Köppen, 1936):

    1. Csa; Temperate with dry, hot summer (Mediterranean climate)
    2. Cfb; Temperate without dry season and warm summer
    3. Dfb; Temperate continental climate/humid continental climate without dry season and with warm summer
    4. Dfc: Cold, without dry season and with cold summer

- Precipitation, according to Köppen-Geiger classification (Köppen, 1936; Kottek et al., 2006):

Table 1: Temperature and precipitation under C and D climates of the Köppen-Geiger classification. (Tmin= temperature minimum, Psmin= precipitation minimum summer, Pwmin= precpiation winter minimum, Psmax= precipitation summer maximum, Pwmax= precipitation summer maxumum); Source: Kottek et al., 2006

Climate type	Description	Criteria
C	Warm temperate climates	$-3\,^{\circ}C < T_{min} < +18\,^{\circ}C$
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warn temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	Snow climate	$T_{min} \leq -3\,^{\circ}C$
Ds	Snow climate, dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate, dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw

Organisms (mO):

- Land-use: An essential moderator when it comes to comparing different measures and their impact on SOC-storage. In temperate zones, cropland is often named as the least SOC rich land-use type, while forests and grassland have significantly higher values (Martin et al., 2011, Wiesmeier et al., 2019).

- Vegetation cover: SOC-stocks are strongly affected by the vegetation on top, with estimations by Wiesmeier et al. 2019, that its impact on SOC declines with increasing soil depth.

- Microbial biomass: Plays an important role through stabilization of organic matter in the soil (Poeplau, 2020, Wiesmeier et al., 2019). Impacts SOC dynamics through heterotrophic respiration (Gross et al., 2022).

Relief (mR):

- Topography: Can influence SOC through its control of water flow paths, water accumulation and discharge. Inclination can have drastic impacts on the general SOC-storage potential of soils, through the concomitant erosion potential (Wiesmeier et al., 2019).

Parental material (mP):

- The influence of the parent material on soil organic carbon functions is rather indirect through clay and silt or Fe-Al oxides contents, resulting from the withering of different minerals in the parent material. The effects of parent material on SOC storage although have been found to be rather minor (Araujo et al., 2017, Gray et al., 2009).

Age (mA):

- While not as significant as other moderators listed above, the age of a soil does influence a variety of soil parameters (Gerzabek et al., 2022; Delgado-Baquerizo et al., 2020). With the effect being relatively hard to measure, they are unlikely to be considered in field tests.

Spatial information (mN):

- Since spatial data can include a broad range of factors already listed, such as topography, land-use, climate, and soil type, it will not be named as individual moderator, as its application is a given.

3.4. Evaluation

The evaluation follows two steps. First, in chapter 4., the included literature for each measure is listed in individual tables, which include study name, location, and size (consistent of number of treatments or study sites and replicates), as well as a short summary of the main findings and comments on their evaluation-input and their fulfilment of the previously listed criteria (3.1., 3.2., 3.3.).

In the second step (chapter 5.) discusses the studies outcomes and the impact of the measure on SOC, with additional information on which moderator (3.3.) are most influential on the overall efficiency and probability of said measure to increase SOC stocks.

4. Results of the literature review

In the following chapter, the literature, selected for the evaluation of measures are presented in their individual tables. Aside from the title and authors, location, and study size (number of treatments and number of repetition), a short summary of the results, as well as comments and notes on their fulfilment of the previously defined in- and exclusion criteria and their strongest arguments. In the subsequent chapter, these studies then flow together, and through discussion form a holistic evaluation of their respective measure.

4.1. Extensification

Table 2: Literature selection for extensification measures

Study	Study Location	Study Size	Results	Rating/Notes
	Slovenia			

The effects of cutting frequencies at equal fertiliser rates on bio-diverse permanent grassland: Soil organic C and apparent N budget (Kramberger et al., 2015)		6 treatments, 4 replicates	Long-term effects (19 years) of different cutting frequencies (12-14 cuts, 6 cuts, 4 cuts, 3 cuts, 2 cuts per year) under the same NPK fertilisation. Results showed significant effects of cutting frequency on soil parameters and plant diversity. Low cutting frequency showed highest SOC, but not all fertilised nitrogen was taken up by plants and lost from the system.	Measuring depth at 0-10cm and 10-20cm (bulk density considered). Strong argument for cutting frequency as tool for grassland management. Highlights interaction of nitrogen with SOC.
Converting highly productive arable cropland in Europe to grassland: –a poor candidate for carbon sequestration (Gosling et al., 2017)	England	14 treatments, 2 replicates	No discernible differences in SOC found in 30cm depth between 17-year-old grasslands and 14 arable land sites. Loss of crop residues balances gains of permanent vegetation cover. Conversion led to increase in soil microbial population.	Unclear study design. Missing climatic factors such as precipitation. Differences in soil microbial communities explained through tillage, but pesticide-use might also have an impact. Strongest argument against extensification/ conversion of cropland to grassland.
Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands (Abdalla et al., 2018).	Global	83 studies, 164 sites	Grazing intensity, SOC (until 30cm) and total nitrogen were normalized for this study. Climatic zones were separated into dry warm (DW), dry cool (DC), moist warm (MW) moist cool (MC). Across all climatic zones, grazing intensity led to a decrease in SOC, with exceptions and under influence of climatic parameters. Under MW climate, grazing intensity increased SOC stocks. Under DC and DW climate, low and medium grazing intensity increased SOC stocks. High grazing intensity significantly increased SOC stocks for C4-dominated grasslands compared to C3 and C3-C4 -mixed grasslands. Grazing intensity was also associated with increase in total nitrogen and bulk density.	Global review of studies with focus across climatic sections. Argument for low to medium grazing intensities in temperate climates, for C3-grasslands. Grazing intensity impact on bulk density, nitrogen and other grassland parameters must be considered. When increasing grazing intensity in MW climates and under C4-dominated grasslands, SOC might be increased, but so might be N2O or CH4 emissions.
Grassland soil organic carbon stocks along management intensity and warming gradients (Poeplau, 2021)	Southern Germany	Review, With 16 treatments (3 cutting frequency, 7 fertilizers, 6 cover crops)	Intensification in form of cutting frequency and increased mineral fertilisation and cover crop use can have positive effects on SOC stocks. Cutting frequency in urban lawns: Results showed, that compared to meadow like lawns (1 cut per year), the short utility lawns (8 times per growing season) showed significantly higher SOC-sequestration, likely since clippings were not removed. Fertilisation: Higher SOC-sequestration through higher NPP, at the risk of increased emissions from fertiliser production. Perennial cover crops: High belowground C-inputs favours SOC storage.	This study is a literature review for different extensification measures and their impact on SOC-stocks. It has a large scope but does not go into detail on moderators included in the reviewed studies.
Sustainable Extensification as an Alternative Model for Reducing GHG Emissions from Agriculture. The Case of an Extensively Managed Organic Farm in Denmark (Bluwstein et al., 2015)	Denmark	1 study farm	GHG emissions of an organic farm under extensification. Reduction of livestock density with simultaneous increase of cropland leads to equal kcal/person/day production as Danish standards, with less GHG emissions. Conversion of cropland into grassland leads to an increase of CO2 emissions of 5 tons per year.	Carbon sequestration standards used for calculation of carbon stocks under land-use change on a national level, might not be suitable for small-scale carbon calculations. Data used to estimate soil carbon fluxes were based on Danish National Inventory Report, which relies on C-Tool, a model that quantifies carbon turnover. Similarly, as the Gosling study, it estimates carbon loss when converting cropland to grassland, although the reason for this is not discussed in this study.
Impact of a conversion from cropland to grassland on C and N storage and related soil properties: Analysis of a 60-year chrono sequence (Breuer et al., 2006)	Germany	2 study sites	No clear dependency of soil property on grassland age. Sampling fixed soil depths instead of fixed soil mass did not mask potential effects of land use change on soil C storage.	Very thought through, logic, lots of moderators, arguing for careful interpretation of results.

			Soil C more dependent on soil type than land use. Different results when using chrono sequence analysis as to paired site surveys.	
Effects of grazing on grassland soil carbon: a global review (McSherry and Ritchie, 2013)	Global	17 studies	Hypothesis: grazer effects shifts from negative to positive with decreasing precipitation, increasing fineness of soil texture, transition from dominant grass species with C3 to C4 photosynthesis, and decreasing grazing intensity. Strong interaction between precipitation and soil type in their influence on grazer effect on SOC. Increase in mean annual precipitation of 600 mm resulted in a 24% decrease in grazer effect size on finer textured soils, while on sandy soils the same increase in precipitation produced a 22% increase in grazer effect on SOC. Strong interaction between grazing intensity and grass type on grazer effect on SOC. Increasing grazing intensity increased SOC by 6–7% on C4-dominated and C4–C3 mixed grasslands but decreased SOC by an average 18% in C3-dominated grasslands. Significant interaction between sampling depth and study duration. Short-term studies, sampling to deeper depths (>40 cm) tended to result in positive effects of grazing, while sampling to intermediate (15–40 cm) depths produced more negative effects. Changes of up to 1.6 kg C/m^2	Variables (moderators): soil texture, precipitation, grass type, grazing intensity, study duration and sampling depth. Only studies comparing grazed sample plot to ungrazed plot, with effects reported in either soil carbon density (mass per unit area) or %C together with bulk density, were included. CEC, pH and total nitrogen were not included.
Effect of grassland harvesting frequency and N-fertilization on stocks and dynamics of soil organic matter in the temperate climate (Nüsse et al., 2018)	Germany	4 treatments, 3 replicates	Treatments included 3 and 5 cuts per year with and without N-fertilization. In the first 0-10cm, SOC and soil microbial biomass carbon were significantly higher under the 5 cut regime. N-fertilisation was found to have negative effects on MBC. Cutting frequency also positively influenced amounts of large macroaggregates. Explanations might be the promotion of tiller and leaf growth, which can stimulate biomass production and stimulated root exudations, both caused by the increased cutting frequency.	Argument for increased cutting frequency. Sampling at 0-10-, 10-30- and 30–60-centimetre depth. With no fertilisation, 3 cuts had higher SOC stocks at 10-30cm and 30-60cm depth. This must be considered as well, as synthetic n-fertilisation might not be an option when it comes to extensification of grassland for mitigating climate change.
Effect of grassland cutting frequency on soil carbon storage – a case study on public lawns in three Swedish cities (Poeplau et al., 2016)	Sweden	3 study sites	Frequently cut lawns (average of 8 times per season) compared to meadow-like lawns (once per season). Significantly higher SOC contents in frequently cut lawns. Cutting frequency only affects SOC when cuttings are left on the surface.	Important argument for cutting frequency. More cuts favour carbon sequestration, C:N ratio plays an important role.
Estimated soil organic carbon change due to agricultural land management modifications in a semiarid cereal-growing region in Central Spain (Boellstorff, 2009)	Spain	1 study site,	Results show extensification using longer-term pasture rotations (e.g., 5-year) could increase SOC levels and have an impact on soil restoration important in maintaining productivity.	Climate, precipitation, topography, soil type, land—use, sample depth (0-10cm)

4.2. Cover- and intercropping

Table 3: Literature selection for cover- and intercropping measures

Study	Study Location	Study Size	Results	Rating/Notes
Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis (Poeplau and Don, 2014)	Global	30 studies, 37 sites	Significantly higher SOC stocks under cover crops than reference croplands. Linear corelation of introduction of cover crops and increase in SOC stock of 0.32+-0.08 mg/ha/yr in 22cm mean soil depth over a period of 54 years. Use of cover crops as green manure as an important management option to increase SOC-stocks, with maximum estimates of 16.7 Mg/ha/yr over estimated periods of over 100 years (50% of effect in first 20 years). Additional benefits such as reduced nutrient leaching and erosion and increased biodiversity and nutrient efficiency.	Only 76% of studies in temperate climate, rest form tropics. Moderators (sampling depth, MAP, MAT, soil type and treatment) included. 13 out of 139 plots showed C-depletion. Explained to either priming or high spatial heterogeneity of SOC.
Cover crop functional types differentially alter the content and composition of soil organic carbon in particulate and mineral-associated fractions (Zhang et al., 2022)	Pennsylvania, USA	4 treatments, 4 replicates	Study includes 3 different cover crop plant functionality types (Legumes, Grass, Brassica). Result show higher bulk SOC content in all 3 treatments compared to fallow, but mixture of all three plant functionality types showed highest short and long-term SOC persistence due to shifted SOC formation pathways impacting the short and long-term SOC stabilization and stocks. Highest C input in mixture (39.4 Mg C/ha) followed by monoculture of brassica and grass, then legumes and least fallow (27.8 Mg C/ha).	Understanding of where the additional carbon gained through cover crops is stored. Particulate organic matter vs mineral associated organic matter, meaning short vs. long term carbon storage. Both pathways can complement each other. Study highlights importance of species selection for cover crop mixtures.
Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem (Steenwerth and Belina, 2008)	California, USA	3 treatments, 6 replicates	Comparison of rye and triticale cover crops to a vineyard cultivation showed consistently higher MBC, DOC and CO_2 efflux in the cover crops. Slightly higher soil c in triticale compared to rye. Evaluation of effects of temperature, water content and precipitation on C dynamics showed responses of DOC and CO_2 efflux, not in MBC.	Californian Mediterranean climate includes heavy winter rains at 8°C average daily temperature to summer drought conditions at 19°C average daily temperature. Soil water content as most important climatic condition influencing soil C dynamics and CO_2 efflux.
Interactive Effects of Subsidiary Crops and Weed Pressure in the Transition Period to Non-Inversion Tillage, A Case Study of Six Sites Across Northern and Central Europe (Reimer et al., 2019).	Europe	6 treatments, 4 replicates	This study researches the effect of subsidiary crops on weed pressure when used with non-inversion tillage. Results showed a significant reduction of weed cover throughout the intercrop period, but only slight reduction when using it under main crops. Overall, weed pressure was higher under non-inversion tillage with subsidiary crops than under inversion tillage without the cover crops.	Study makes argument for use of cover crops for additional weed control but highlights the challenge of increased weed pressure as well. Experimental design with N-fertilization and for 2 years.
Intercropping enhances soil carbon and nitrogen (Cong et al., 2014)	China	6 treatments, 3 replicates	Wheat, maize and faba-bean as intercrop or sole crop in 2-year rotation. SOC content in top 20cm was found to be 3-5% higher in intercropping systems than in sole crop systems. Soil organic nitrogen was 10-12% higher in intercropping systems than in sole crop systems. Total root biomass in intercrops 23% higher than in sole crop systems.	Authors state that benefits of intercropping for improving long-term soil fertility might outweigh the contribution to GHG mitigation. Regardless, intercropping compares to other measures such as zero tillage, cover cropping and complex rotations. Long term experiment of 7 years.
Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis (McClelland et al., 2021)	Global	40 studies	Overall, the analysis found a strong positive effect on SOC stocks, showing a 12% increase, which equals around 1.11 Mg C/ha more than a no cover crop control. Strongest predictors were found to be planting and termination date, annual cover crop biomass production and soil clay content.	Focus on 0-30cm soil depth in temperate climates. Robust inclusion criteria and moderator control. Study states importance of including growing windows, climate and soil factors in decision making tools for application of cover crops. High biomass production is key, combination of cover

			Continuous planted and autumn planted and terminated cover crop showed 20-30% higher total SOC stocks than other cover crop growing windows. Findings for annual C sequestration under cover crops on par with conversion of cropland to grassland or forest, alley cropping and improved grazing practices.	crops with other measures such as no-till and perennial plants recommended.
Real cover crops contribution to soil organic carbon sequestration in sloping vineyard (Novara et al., 2018)	Italy	2 treatments, 3 replicates, 39 studies	Comparison between two paired sites with one sloping area and one flat, one under cover crops, the other under conventional tillage. For both cases (sloped and flat), cover crops showed higher SOC (9% higher in sloped, 6% higher in flat) after 5 years of treatment. Higher SOC under cover crops could be attributed to less soil and therefor nutrient erosion in sloped areas.	Comparison with 39 other studies on C-sequestration in olive and vineyard systems resulted in identification of strong correlation of C-input to slope gradient (moderator R). C-input by cover crop is described as overestimated.
The potential of cover crops to increase soil organic carbon storage in German croplands (Seitz et al., 2022)	Germany	2171 studies	Cover crop area could be tripled to 30% of arable land in Germany. This could lead to 12% increase of total carbon input and could lead to increase of 35 Tg over 50 years, assuming an annual increase of 0,06 Mg C/ha. Even after realisation of full potential of cover crop use for C-sequestration over 50 years, croplands in Germany would still be a source, not a sink, and declines in general SOC stocks would not be halted.	Very large study size (2,171 study sites, 1267 included in simulation) with high spatial variabilities, but main moderators were included. Main crops were not changed under cover crop scenarios. Importance of subsidies and farmer know-how emphasized.
Cover crops and carbon sequestration: Lessons from U.S. studies (Blanco-Canqui, 2022)	USA	35 studies	Only in 22 of 77 comparisons, significant SOC accumulation due to cover crops was found. Accumulation of 0,2-0,92 Mg C/ha/yr where cover crops increased SOC. Accumulation mostly correlated to biomass production and years under cover crop treatment.	Emphasis on biomass production of cover crops, management needs to be adapted to achieve most efficient C-sequestration.

4.3. Erosion control

Table 4: Literature selection for erosion control

Study	Study Location	Study Size	Results	Rating/Notes
Application of a modeling approach to designate soil and soil organic carbon loss to wind erosion on long-term monitoring sites (BDF) in Northern Germany (Nerger et al., 2017)	Germany	2 study sites	Measure of wind erosion impact on arable, sandy soils in Northern Germany through combination of long-term data on soil and farm management and a wind erosion model. Soil mass loss of 49.4 kg/m2 and SOC stock decrease of 2.44 kg/m2 from 1999 to 2009 through wind erosion.	Moderators well listed. Complicated monitoring of SOC loss through wind erosion. Measured soil loss corresponded to the modelled one in both sites. Applicability to similar sites, where SOC loss through wind erosion are likely.
Differences in soil organic carbon and soil erosion for native pasture and minimum till agricultural management systems (Wells et al., 2019)	Australia	2 study sites	Comparison of two neighbouring sites (SOC, soil nitrogen [SN] and erosion), one under minimum tillage, one under grazing on native pasture. SOC and SN both found 50% higher at grazing site than under MT, while erosion was significantly higher at the MT site. No link between erosion and SOC, SN and C:N was evident.	Geographically relevant? Link between erosion and SOC missing. Extensification: Even after long term conservative management and stubble retention cropping, native pastures show higher SOC content. Inclusion of perennial pastures in rotations with cropping recommended. Case study for MT vs. grazing.
Rebuilding soil carbon in degraded steppe soils of Eastern Europe: The importance of windbreaks and improved cropland management (Wiesmeier et al., 2018)	Moldova	8 study sites, 5 treatments,	Comparison of OC storage potential under windbreaks, cropland with improved crop/rotation and manure application and cropland with cover cropping to natural grassland and conventional cropland. Sequestration rates for topsoil until 30cm under windbreaks was 0.9 t C/ha/yr, under	Argument for windbreaks and cover cropping, and combination of measures! Good moderator fit and use.

			improved crop rotation with manure application 1.3 t C/ha/yr and cover cropping 1.9. t C/ha/yr. The study concludes that cultivated chernozems lost 50% of their SOC stocks in the last century. Windbreaks help accumulate SOC stocks, yet not all carbon is stabilized in the fine mineral fraction.	
Soil-erosion and runoff prevention by plant covers. A review (Zuazu and Pleguezuelo, 2008)	Global	Not clear how many articles reviewed.	This review focuses on 3 research questions: 1. Impact of eroding soil productivity with climate, soil seal, crust development and C-loss focus. 2. Erosion and land use in agricultural lands, focus on shrub and forest lands and Mediterranean terraced lands. 3. Impact of plant cover on soil erosion with focus on Mediterranean factors affecting vegetation, plant roots as erosion control and biodiversity. Results show that erosion might be more affected by changes in plant cover and rainfall than runoff. Plant cover has bigger impact on runoff and erosion than changes in canopy alone. Inappropriate removal of plant cover, especially in mountain areas threaten land conservation.	Not a case study, but interesting research questions. Useful for building arguments for erosion measures.
Global soil organic carbon removal by water erosion under climate change and land use change during AD 1850–2005 (Naipal et al., 2018)	Global	1 model	Land surface models in combination with Revised Universal Soil Loss model to represent links between soil erosion by rainfall and runoff and carbon dynamics. From AD 1850-2005 a total potential of 74 ± 18 Pg C loss was estimated, form which 79-85% concurred in agricultural land. Through this additional loss of SOC through erosion, an estimated 2 Pg C was lost in the period of 1850 to 2005.	Strong arguments to include and further study erosion impact on SOC stocks. Study suggests erosion has similar impact on global SOC stocks as climate and land-use change.
Soil organic carbon and soil erosion – Understanding change at the large catchment scale (Hancock et al., 2019)	Australia	2	Study found stable spatial SOC distributions in two separated water catchments over a period of 8 years. Measurement by environmental tracker element caesium-137. Significant correlation of SOC change, erosion, and deposition. Results suggest SOC can be translocated by heavy rainfall events and provides insight how catchments may respond to more frequent extreme weather events.	Geographically relevant? Study design well done. Very clear evidence of erosion impact on SOC. Not case study
Hedge row intercropping impact on run-off, soil erosion, carbon sequestration and millet yield (Hombegowda et al., 2019)	India	10 treatments, 3 replications	4-year field experiment to research effect of hedgerow intercropping on soil erosion and nutrient dynamics. Different hedge row tree species (*Leucaena leucocephala* and *Gliricidia sepium*) in combination with trench planting were tested to measure reduction in soil runoff. The treatment *Gliricidia* + Trench planting reduced run-off by 29%, soil loss by 45–48%, and loss of soil organic carbon (SOC) by 42–47% respectively over control. Similarly, for *Leucaena* + Trench planting, run-off was reduced by 17–19, soil loss by 27–40, and SOC loss by 28–37%, over control.	Geographical differences such as precipitation, temperature or soil parameters might make it hard to include in study. Plant choices for hedge rows might not be representative for European alternatives. Still, study shows clear potential of hedge row intercropping.
Soil-resistant organic carbon improves soil erosion resistance under agroforestry in the Yellow River Flood Plain, of China (Pan et al., 2022)	China	4 treatments, 3 replications	Soil erodibility under 4 different agroforestry systems (Chinese ash (Fraxinus chinensis Roxb) forestland (CK), Chinese ash forestland and soybean (Glycine max (Linn.) Merr.) farmland (AS), Chinese ash forestland and peanut (Arachis hypogaea Linn.) farmland (AP), and Chinese ash forestland and chrysanthemum (Arachis hypogaea Linn.) farmland (AC)). These systems were ranked for SOC fractions (dissolved organic carbon, microbial biomass carbon, non-easily oxidizable carbon and mineral-associated carbon) as follows: AS > CK > AP > AC	Agroforestry to reduce soil erodibility. Geographically relevant? Plant wise? Moderators well accounted for.

The Effects of Soil Improving Cropping Systems (SICS) on Soil Erosion and Soil Organic Carbon Stocks across Europe: A Simulation Study (Baartman et al., 2022)	Europe	4 (scenarios)	Simulation of four different scenarios consisting of different levels and combinations of cover crops, mulching, soil compaction alleviation and minimum tillage until 2050. Impact on two factors: soil health (SOC) and soil degradation (erosion) measured. Model used: PERSEA Soil Improving Cropping Systems (SICS) showed overall SOC increase under high level of SICS application and significant decrease of erosion.	Is there a sacrifice of parameters for the sake of large-scale applicability? Are measures sufficiently and realistically defined? Which measure strongest impacts?
Changes in deep soil organic carbon and soil properties beneath tree windbreak plantings in the U.S. Great Plains (Khaleel et al., 2020)	United States	8 study locations	Quantification of SOC stocks underneath windbreaks until a depth of 1.25m. Average SOC stocks across sites were 16% higher beneath the windbreak trees than in the adjacent fields. Subsurface soil (30-125cm) under the trees stored 7% more SOC than the upper 30cm.	This study emphasizes the importance of measuring SOC at greater depths underneath tree systems. Building arguments for windbreaks, but not necessarily strong connection to erosion.
The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes — A review of different concepts (Kirkels et al., 2014)	Global	Nr of articles reviewed not included	This review describes the fate of SOC upon erosion, highlighting the different relations governing C dynamics, such as detachment of sediment and SOC, net primary production resulting in dynamic replacement and changes in mineralisation upon transport and deposition due to aggregate breakdown and deep burial.	Not case study but important to highlight the complexity of the issue of soil erosion and SOC loss. Discussing if arable land is a CO2 sink or source.
Three years of management with cover crops protecting sloping olive groves soils, carbon and water effects on gypsiferous soil (Sastre et al., 2018)	Spain	4 treatments, 3 replications	Experiment with cover crops under rainfed olive grove in semiarid conditions in Central Spain. Study of a variety of parameters (plant cover, root density, organic carbon, organic nitrogen, aggregate stability, porosity, infiltration, water storage and soil penetration resistance) under 3 different cover crop treatments and minimum tillage. They conclude on a period of minimum 3 years for cover crops to improve named soil parameters.	No direct link to erosion. Better for cover crops?
Model-based evaluation of impact of soil redistribution on soil organic carbon stocks in a temperate hedgerow landscape (Lacoste et al., 2016)	France	1 study site, 2 models,	This research focuses on soil redistribution effect on SOC in temperate hedgerow landscapes via a modelling approach. Simulation of SOC dynamics over 90 years, with climate and land-use scenarios as business as usual, in a dairy farming, mix of cropping and grassland system. A net decrease of SOC stocks 2kg C/ha/year was predicted, by soil exportation out of the study site and increased mineralization. Hedgerows and woods were only area of where soil redistribution induced SOC storage. Tillage was main factor when it came to soil redistribution within cultivated fields, whereas erosion was relatively small, due to protective role of hedgerow network.	Strong argument for hedgerows, and interesting argument for tillage. Interesting that SOC under trees and hedgerows was initially not higher than under cultivated land.
Effects of a Permanent Soil Cover on Water Dynamics and Wine Characteristics in a Steep Vineyard in the Central Spain (Marques et al., 2020)	Spain	3 treatments, 5 repetitions	2-year trial for comparison of tillage to permanent plant cover with Brachypodium distachyon (L.) P. Beauv. (Bra). Seeded once in first year and then allowed to self-seed. Tillage was performed twice in spring (10-15cm) and once in autumn (20-35cm). In 3 different moments of cultivation, rainfall simulations were performed, 1 in summer with dry soils, 2 in early autumn with moderate soil moisture and 3 in autumn with wet soils. The till treatment had more soil moisture in the upper layer (0-10 cm, 14.1% ± 2.4%) compared with the cover crop treatment (12.3% ± 2.0%). Runoff was 11% higher under cover crops in summer, which can be attributed to the higher	2 years might be too short for cover crops to create enough root mass and density to further reduce runoff. Study recommends cover corps for soil protection in semi-arid environments. Link from runoff to SOC displacement must be made.

			soil porosity in shallow tilled soils, but lower (3%) than tillage runoff in wet soils (22%), where cover crops had increased the infiltration potential of the soil.	
The role of dissolved organic matter in soil organic carbon stability under water erosion (Zhang et al., 2019)	China	60 soil samples (2 sites, 3 transects, 10 sampling depths)	Two sampling sites in a typical watershed area were researched to understand dissolved organic mater dynamics under water erosion. The study found that the light and fine fractions from the upslope site, were transported to the downslope site, with the eroded SOC (staying behind) being more stable than the deposited one.	Not case study, no measures researched. Argument for importance of water erosion but very difficult study.
The stability and fate of Soil Organic Carbon during the transport phase of soil erosion (de Nijls and Cammeraat, 2020)	Global	Reviewed nr. Of articles not named	Stability of SOC during transport phase of erosion is an interplay of presence of decomposers, SOC accessibility and suitable abiotic conditions. Protection mechanisms (chemical/physical) of SOC against mineralization are disturbed through erosion, although level of impact on these mechanisms is yet to be researched. Erosion favours disaggregation, which releases previously protected SOC.	Argument for why erosion is important. Not a case study for evaluation of measures.

4.4. Tillage

Table 5: Literature selection for tillage methods

Study	Study Location	Study Size	Results	Rating/Notes
Characterization of the heavy, hydrolysable and non-hydrolysable fractions of soil organic carbon in conventional and no-tillage soils (Ramnarine et al., 2018)	Canada	2 treatments, 192 samples, 32 repetitions	Comparison of no-till (NT) to conventional tillage (CT) and their effect on the heavy fraction (HF), the hydrolysable fraction (HYF) and non-hydrolysable fractions (NHF) of SOC after six years of treatment. Results showed significant increase of carbon only in the first 0-10cm of depth, but when looking at the entire 0-30cm profile, no significant increase in carbon sequestration potential was found in the short term.	Emphasis must be put on short term. Further advantages of no-till for carbon sequestration and retention? For example, reduction of erosion, therefore C-loss. Other agronomic practices not listed.
Effect of tillage and crop management on runoff, soil erosion and organic carbon loss (Chowaniak et al., 2020)	Poland	2 treatments, 4 plots,	Comparison of NT to CT under different plant covers. Runoff was 4.3 ± 0.6% higher under NT than CT, soil loss was 66.8 ± 2.7% lower under NT than under CT. NT limited the total organic carbon losses by an average of 46.0 ± 2.9% and sediment bound organic carbon loss by 53.2 ± 0.7%. There was no significant differences for DOC.	Great study description. Fertilizer and herbicide use. Why higher runoff in first years in NT? How solid is the argument that runoff is lower in CT? Because of lower soil permeability in NT systems in the first years of application. After accumulation of roots, and formation of new pores, permeability increases again, differences decreased. Also, differences of runoff very small compared to the soil loss differences. Long term effects!
Evaluating storage and pool size of soil organic carbon in degraded soils: Tillage effects when crop residue is returned (Zhang et al., 2019)	China	3 tillage treatments, 4 replications	Tillage treatment: NT, ridge-tillage (RT) and moldboard plow (MP). In comparison to degraded soils, all 3 tillage systems increased SOC, but no differences between the tillage forms when looking at 0-30cm. Tillage had no effects on soybean and maize yields. Under NT and RT higher SOC storage in the plow layer (0-20cm) than MP.	Continental monsoon climate. Another argument for 0-30cm equality.
Increasing soil organic carbon sequestration and yield stability by no-tillage and straw-returning in wheat–maize rotation (Shi et al., 2022)	China	6 treatments, 4 replications	The 6 treatments consist of: control, no-till and rotary tillage, each with and without straw return. Highest SOC increase (34.1%) under NT with straw return (SR), which was found as best strategy for yield amount and stability.	Again, climate. Straw return as a method for C increase.
	Italy			

Long-term no-tillage application increases soil organic carbon, nitrous oxide emissions and faba bean (Vicia faba L.) yields under rain-fed Mediterranean conditions (Badagliacca et al., 2018)		3 vertical and 3 horizontal treatments, 2 replications	Under a long-term tillage experiment (23 years), a 2-year experiment with faba beans was conducted. While yields where significantly higher in NT (23%), so were N2O emissions (2.58 vs 1.71 kg N2O-N ha−1). This was explained due to higher bulk density and WFPS, and higher abundance of bacteria and N cycle genes.	Increase of N2O emissions compared to CT, study says these need to be taken in account, although, the total emissions were similar to the ones measured in other N-fertilized crops.
Microbial-derived carbon components are critical for enhancing soil organic carbon in no-tillage croplands: A global perspective (Li et al., 2021)	Global	95 Studies	NT effect on different SOC fractions (DOC, particulate organic C [POC], easily oxidizable organic C [EOC], microbial biomass C [MBC], and mineral-associated organic C [MOC]). NT increased SOC concentrations (7.4% higher than in reduced tillage). Compared with CT, NT significantly increased DOC (17.6%), POC (11.7%), EOC (14.8%), MBC (33.1%).	This meta-analysis shows that increases in SOC concentrations under NT correlate with MBC and POC, therefor creating a strong argument for the importance of microbial activity.
Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe (Krauss et al., 2022)	Switzerland, Germany, France, Netherlands	9 treatments, 66 samples	Comparison of mouldboard ploughing with reduced tillage in nine organic farming field trials. 66 soil cores to a depth of 100cm were sampled in field experiments ranging from 8 to 21 years, with clay contents from 10-50%. Reduced tillage in comparison with ploughing increased SOC in the first 10cm (by 20.8% or 3.8 Mg/ha), depleted SOC stocks in the intermediate layer, until 50cm, with maximum depletion happening at 20-30 cm, but increased SOC in the deepest layer, at 70-100cm. Cumulative SOC increased by 1.7% (1.5 Mg/ha) until first 50cm and 3.6% (4 Mg/ha) for the whole 100cm. Biomass production was 8% lower, which lead to a reduction of crop C input by 6% under reduced tillage. This was outbalanced by the C input through weed biomass increase.	Interesting study for its sampling depth and organic field trials, meaning no application of agrochemicals. Interesting to see effects of that (long term trials with 21 years) on SOC. Carbon calculated by loss-by-ignition method, bulk density was accounted for.
Short-term Response of Chickpea Yield, Total Soil Carbon, and Soil Nitrogen to Different Tillage and Organic Amendment Regimes (Naderi et al., 2021)	Iran	3 fertilizer treatments for 2 ploughing treatments, 2 repetitions	The two tillage systems each were tested under 3 different fertilizer treatments, cattle manure, nitrogen fertilizer, the two of them combined and no urea N or manure added control. Highest SOC was found in manure treated plots, as well in manure plus N treated plots. SOC was significantly higher in reduced tillage plots. Highest yields in N+manure plots, but not much higher than only N fertilized plots. Tillage did not affect yield.	No bulk density used. Interesting about C: N. Sampled until 0-30cm. They say reduced tillage reduces runoff (contrary to Chowaniak et al., 2020)? Reduced is not no-till?
Straw amendment and soil tillage alter soil organic carbon chemical composition and are associated with microbial community structure (Li et al., 2022)	China	6 treatments, 3 repetitions,	Comparison of NT to CT (until 20cm) and deep tillage, DT, to 35cm. Evaluation of straw amendment and soil tillage interrelations with soil microbial communities. Results showed that tillage practices. Coupled with straw amendments can improve the microbial community and enhance the SOC stocks.	Temperate, continental monsoon climate. Strong argument for tillage influence on soil microbial community and their effect on SOC stocks!

4.5. Fertilization and soil melioration

Table 6: Literature selection for fertilization and soil melioration

Study	Study Location	Study Size	Results	Rating/Notes
Simulating soil carbon sequestration from long term fertilizer and manure additions under continuous wheat using the DailyDayCent model (Begum et al., 2017)	United Kingdom	4 treatments,	Comparison of control, mineral nitrogen fertilizer, farmyard manure and a combination of N and manure. Use of ecosystem model DailyDayCent to predict SOC sequestration and yield. Management practices of test site documented over the past 170 years. Model results agree relatively well with test site observations. The model predicted highest SOC sequestration under farmyard manure, observations at site showed highest SOC sequestration under combination of mineral fertilizer and manure.	What is the reason for the discrepancy between model and onsite? Potential argument for combination of manure and synthetic fertilizers.
Carbon fractions and stock in response to solid and fluid organomineral fertilizers in highly fertile soils (Corrêa et al., 2019)	Brasil	5 treatments, 4 replicates	Only little changes in total organic carbon (TOC) was observed. In the soil type Inceptisol, TOC increased with fluid mineral fertilizer, at 0-5cm and 0-20cm depth. In both experiments, the resulting surface layer SOC increase are explained by no-till application rather than fertilizer application.	Climatically not suitable for evaluation. Better argument for no-till than fertilizer use.
Soil organic carbon stock in grasslands: Effects of inorganic fertilizers, liming and grazing in different climate settings (Eze et al., 2018)	Global	341 studies	This meta-analysis tested management effects on grassland SOC stocks under different climatic conditions. Management practices tested: 1) Fertilizer application (N and P) 2) Liming 3) Grazing regime Global reduction of SOC stocks in grassland found (-8.5%), mainly due to grazing (-15%). Fertilizer and liming slightly increased SOC stocks (+6.7% and +5.8%) but not enough to balance the C loss through grazing. Management effects were greatest in the tropics but had the least effect in temperate zones, which suggests temperate grasslands as potential carbon sinks.	Accuracy of results dependant on use of climatic parameters in analysis. Connection to extensification.
Impacts of organic amendments on carbon stocks of an agricultural soil Comparison of model-simulations to measurements (Karhu et al., 2012)	Sweden	8 treatments, 4 replicates	The authors tested the ability of the model Yasso07 to measure changes in SOC by comparing modelling data to actual data from 1956-1991. They found that the model was able to accurately predict the in- or decrease in carbon stocks. Further, farmyard and green manure showed great results increasing SOC stocks. Peat + N fertilizer and straw + N fertilizer showed strongest results.	Pointing towards moderator C as important parameter influencing fertilizer impact on SOC. Most important factor in SOC prediction was accurate, high-quality data on C in- and output.
Why does mineral fertilization increase soil carbon stocks in temperate grasslands? (Poeplau et al., 2018)	Germany, Netherlands	7 treatments, 4 replicates	Seven long-term experiments (16-58 years) were sampled to determine the effects of mineral fertilization (N, P, K, PK, and NPK) on SOC stocks, in comparison to unfertilized plots. Soils were sampled to 100cm depth. All fertilizers had significantly positive effects on SOC stocks in topsoil (0-30cm). 1.15kg N fertilizer needed to sequester 1kg of SOC.	CO2 costs of fertilizer production need to be considered when using fertilizer to mitigate climate change.
Aggregate mass and carbon stocks in a paddy soil after long-term application of chemical or organic fertilizers (Qiu et al., 2022)	China	4 treatments, 3 replicates	Four treatments of fertilizer application (control, NPK, NPK plus straw return, NK plus pig manure). Mass of soil aggregates and carbon stocks were determined, which showed that organic carbon in bulk soil and aggregates decreases with increasing soil depth (measured until 40cm), the exception are free microaggregates.	Climate/geography Tillage effects. Argument for application of organic fertilizers, such as manure and straw return.

			Compared to control or chemical fertilizer only, fertilizer combinations with manure or straw significantly increased the mass and carbon concentration in small macroaggregates (2000–250 μm) and small macroaggregate fractions, while the opposite was detected for large macroaggregates and large macroaggregate fractions. In general, small macroaggregates were found to bind most SOC.	
How do nitrogen fertilization and cover crop influence soil C-N stocks and subsequent yields of sugarcane? (Tenelli et al., 2021)	Brazil	4 treatments, 4 replicates	This study focuses on the impact of 4-year N fertilization on SOC stocks in sandy and clayey soils and considers the potential use of legume cover crops to reduce the necessary N fertilizer amount. Treatments consisted of control, 60, 120 and 180 kg N/ha. No effect of N fertilizer rates on SOC and N stocks was found. Cover crops increased N storage and microbial biomass carbon and positively influenced yields.	Climatically not applicable to Europe. SOC measured once before trial and after – variability very high. Sandy vs. clayey soil samples included.
Soil phosphorus (P) mining in agriculture – Impacts on P availability, crop yields and soil organic carbon stocks (Vandermoere et al., 2021).	Belgium	2 treatments, 3 and 4 replicates	Study on Phosphorus problematic in north-west Europe (Flanders, Netherlands). In these areas, 4 years of 0 P fertilization showed no effect on crop yield or P uptake. Grass as green manure or main crop only partially maintains SOC levels in absence of organic fertilizers.	P overfertilization only partly a problem in Europe. Regardless, clearly points to an important problem: eutrophication.
Soil Organic Carbon, Nitrogen, and Phosphorus Levels and Stocks After Long-Term Nitrogen Fertilization (Zhon et al., 2015)	China	10 treatments, 3 replicates	Research on long-term effects of N-fertilization on SOC stocks and distribution (and N and P stocks and distribution). Results showed that N-fertilization affected C and N distribution over 0-120cm soil depth. The effects on P was mainly in the first 30cm. The influence of N fertilization on C, N and P levels varied for different wheat cultivars. Wheat cropping at fertilizer rates below 240kg N/ha resulted in C fixation, but when N was applied over the crop requirements, the soil became a C source.	Definite argument for careful fertilization planning.
BIOCHAR				
Effect of Woodchips Biochar on Sensitivity to Temperature of Soil Greenhouse Gases Emissions (Criscuoli et al., 2019)	Italy	3 treatments, 3 replicates	This study investigates the role of temperature when it comes to biochar effect on soil GHG emissions. A pot experiment was set up to measure all three GHG emissions (CO2, N20, CH4). The results showed no effect on N20 and only slight impact on CO2 emissions, but a negative impact on soil uptake of CH4.	While not directly about building up SOC stocks, this study emphasizes the need for precise research to maximise biochar efficiency. With warming climate, temperature effect on biochar amendments must be considered to avoid unwanted side effects.
Stability of Woodchips Biochar and Impact on Soil Carbon Stocks: Results from a Two-Year Field Experiment (Criscuoli et al., 2021)	Italy	6 treatments, 4 replicates each	This experiment tests the stability of biochar in the field, including its impact on the total SOC stocks and the priming effect over a period of two years. The 6 treatments were 25 and 50 t per ha biochar amendment, with or without combination with compost, one with only compost and one control. The 50t/ha biochar showed significant SOC increase, with no effect on the degradation of SOM-C. The study concludes that the use of woodchip biochar can increase soil C content in the medium term.	Experiment proving the two-year stability and effectivity of woodchip biochar in the alpine region, providing an argument for biochar as a mitigation tool for climate change. Combination with compost could have a high potential as a great measure to increase SOC stocks and improve soil health.
Sustainable agronomic practices for enhancing the soil quality and yield of Cicer arietinum L. under diverse agroecosystems (Dubey et al., 2020)	India	3 treatments at 3 different locations,	Study of effect of agro-waste derived biochar and vermicompost on soil quality and yield of *Cicer arietinum* L. (chickpea). Both showed significant increase of total organic carbon and available N, P and K. Vermicompost also increased the microbial biomass carbon significantly. Although vermicompost showed higher impacts on soil quality and yield, biochar was	Great showcase of the power of vermicompost and biochar. Also highlights the importance of precise goals, as vermicompost can increase CO2 emissions, and therefor might not always be suitable as a sustainable measure. Climatic differences to Europe must be considered.

			found to have higher potential as a practice to mitigate climate change, as it reduces the CO_2 efflux from agroecosystems, which vermicompost increased.	
Global soil organic carbon changes and economic revenues with biochar application (Han et al., 2022)	Global	70 studies	Response of SOC to biochar amendment in 389 paired field measurements showed biochar addition significantly increased SOC by 45.8% on average, with large regional variations. Response of SOC to biochar dependent most on biochar application rates, initial SOC, edaphic and climatic variables. The study also did a economic assessment of idealized biochar addition scenarios to identify location with highest potential for new pyrolysis plants.	Methodology must be carefully examined when comparing biochar effects on a global scale. Moderators identified provide valuable input for evaluation.
Effect of biochar and biochar combined with N-fertilizer on soil organic carbon content (Horák and Šimanský, 2016)	Slovakia	9 treatments, 3 replicates	The different treatments consist of 0, 10 and 20 Mg/ha biochar application each paired with 0, 40 and 80 kg/ha N. Biochar plots always showed higher SOC content at beginning and end of trial, compared to control plots. Statistically significant effects only showed at beginning and end of biochar 20 Mg/ha and 40 kg/N/ha application.	Very short study, not all moderators presented. Methodology needs to be carefully looked at. Long-term effects unclear.
Biochar amendment increases tree growth in nutrient-poor, young Scots pine stands in Finland (Palviainen et al., 2020)	Finland	3 treatments, 4 replicates	The 3 treatments consisted of 5 Mg/ha and 10 Mg/ha, plus control without biochar. Diameter growth of dominant trees increased 25% under 10 Mg/ha biochar amendment compared to control.	Clear evidence of biomass increase under biochar amendments, especially in nutrient poor soils. Experiment in young pine forest, so not totally applicable to agriculture. No direct measurement of SOC.
Temperature sensitivity of soil organic matter decomposition varies with biochar application and soil type (Rittl et al., 2018)	Brazil	24 treatments, 4 replicates	Experiment of 4 (rates of biochar amendments) x 3 (temperatures) x 2 (soils) treatments. Results showed that biochar addition decreased soil CO_2 emissions compared to untreated soils. CO_2 emissions from biochar-treated soils also had higher temperature sensitivity than those of untreated soils and soil texture influenced the temperature sensitivity. Biochar addition seemed to decrease the native SOM decomposition. The study concludes with the need for region- and soil specific biochar schemes to achieve SOC stock increase.	While the temperatures (up to 40°C) in this study might still not apply to Europe, it still makes a strong argument for precise biochar application planning. Study of 144 days, so no long-term conclusions.
Soil greenhouse gas, carbon content, and tree growth response to biochar amendment in western United States forests (Sarauer et al., 2018)	USA	3 treatments, 5 replicates	Biochar effects on GHG emission in temperate forest soils. Application of 0, 2.5, or 25 Mg/ha to the forest soil surface. C_2O and CH_4 fluxes varied by season but did not show any impact of biochar addition. No N_2O was detected, since forest soils were not fertilized, and nitrogen limited. Increase in soil C content by 41% compared to control, but no effect on tree growth.	Might not be applicable to agriculture and arable land. No impact on GHG, contradicting Criscuoli et al., 2019?
Potential of sawdust and corn cobs derived biochar to improve soil aggregate stability, water retention, and crop yield of degraded sandy loam soil (Shaheen and Bukhari, 2019)	Pakistan	7 treatments, 3 replicates	Treatments: 1. control 2. NPK 3. sawdust biochar (SDB) 4. corn cobs biochar (CCB) 5. SDB + CCB 6. SDB + NPK 7. CCB + NPK Biochar increased plant available water content, water contents at field capacity and PWP, soil porosity and decreased bulk density.	Climatic conditions might differ to Europe. SOC not directly researched, yet a indirect argument for biochar can be made form its effect on soil structure. Results of biochar in combination with NPK fertilizer interesting, yet to be taken cautiously because of CO_2 cost of fertilizer production.

			The most stable aggregates were in SDB+CCB, therefor biochar application a useful tool to increase soil structure.	
Soil organic and inorganic carbon sequestration by consecutive biochar application: Results from a decade field experiment (Shi et al., 2020)	China	3 treatments with 3 replicates each	Treatments consisted of control, 4.5 Mg/ha/year (B4.5) and 9.0 Mg/ha/year (B9.0). Results showed biochar significantly increased soil inorganic carbon (3.2%–24.3%), POC (38.2%–166.2%) and total organic carbon content (15.8%–82.2%). Silt-clay associated carbon was significantly decreased under B9.0. The study concludes that soil inorganic carbon contributes to carbon sequestration after biochar application, and that carbon was mainly allocated in the POC fraction. The decreased silt-clay associated carbon suggests a positive priming effect of the biochar on the native SOC.	10-year field experiment produces valuable long-term data for biochar experiments. Study says priming effect of biochar might be underestimated. Closer look on most important moderators necessary.
Biochar stability and impact on soil organic carbon mineralization depend on biochar processing, aging and soil clay content (Yang et al., 2022)	China	4 treatments, 3 replicates	4 treatments with biochar pyrolyzed at 300, 450 and 600°C (M300, M450, M600) + control. Priming effect on 2 soils with different clay content was tested. Results showed that: Aged biochar showed negative priming effects for both soils. Biochar was more stable in clayey soils. Biochar pyrolyzed at higher temperatures showed higher carbon sequestration potential.	Experiment under controlled conditions, might not accurately reflect field conditions. Biochar-induced priming effect?

4.6. Agroforestry

Table 7: Literature selection for agroforestry

Study	Study Location	Study Size	Results	Rating/Notes
Agroforestry perennials reduce nitrous oxide emissions and their live and dead trees increase ecosystem carbon storage (Gross et al., 2022)	Canada	10 study sites	3-year assessment of GHG emissions and SOC stocks under different agroforestry systems. Systems studied include hedgerows and shelterbelts with component land-use types, such as annual cropland, newly planted saplings and perennial vegetated area with or without trees (woodland or grassland). Results showed 89% lower N2O emissions under perennial vegetation, a between 1.9-2.55 times higher total ecosystem C under woodland than all other land uses. Shelterbelts and hedgerows contained 2.09 and 3.03 times more C than cropland.	Study points out importance of microorganisms (mO) and their influence on SOC stocks. Strong arguments for agroforestry and especially woodland. Temperate climate zone.
Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes, and future potentials (Shi et al., 2018)	Global	76 studies	427 soil C stock pairs grouped into four main agroforestry (AF) systems (alley cropping, silvopasture, windbreaks, homegardens). Mean SOC stocks in AF-systems (1m depth) were 126 Mg C/ha (19% more than cropland or pasture). Highest C stocks in subtropical homegardens, AF with younger trees and topsoil (0-20cm). Potentially, AF could store 5.3 x 10^9 Mg additional C in soil on 944 Mha globally (mostly in tropics and subtropics).	Climatically focused on tropics and subtropics. Very large scope, for very theoretical assumptions. Good use of moderators.
Forest land-use increases soil organic carbon quality but not its structural or thermal stability in a hedgerow system (An et al., 2021).	Canada	6 sites	Study on quality and structural and thermal stability of SOC in hedgerows. They found overall higher quality soil C under forest land-use, but lower structural and thermal stability as compared to cropland.	Study on stability of SOC, points towards susceptibility of forest SOC to climate warming and other anthropogenic disturbances.
Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon — A case study in a	France	2 treatments, 100 and 93	18-year-old AF plot with walnut intercropped with durum wheat. SOC quantified for 2m soil	Calls for combination of AF and no-till or permanent plant cover.

Mediterranean context (Cardinael et al., 2015)		samples ("replicates")	depth and distribution of SOC in different soil particle sizes characterized. SOC accumulation rates between AF and agricultural control plot (only durum wheat) were 248+/-31 kg C/ha/yr for an equivalent soil mass of 4000Mg (to 26-29cm depth) and 350+/-31 kg C/ha/yr for an equivalent soil mass of 15700Mg (to 93-98cm depth). SOC stocks higher where no tillage was applied, no effect of tree distance on SOC was observed, most additional SOC was found in coarse organic fractions.	SOC storage in coarse fractions might not be stable enough for long-term.
Improvements in soil health and soil carbon sequestration by an agroforestry for food production system (Eddy and Yang, 2022)	USA	6 treatments,	Comparison between AF system, corn-soybean rotation (CSR) and secondary forest (SF). SOC stock increase from CSR (62.7 Mg C /ha) to AF (72.1 Mg C/ha), but not to secondary forest (80.8 Mg C/ha). Naturally, similar pH between CSR and AF, but SF was higher. Overall soil health improvement from land conversion of CSR to AF observed.	Moderators well described. Measured to 1m depth. CSR nutrient deficiency close to where it would impact yields, hence good benefits from conversion and diversification through AF.
Soil carbon sequestration in agroforestry systems: a meta-analysis (De Stefano and Jacobson, 2017)	Global	53 studies	Investigation of SOC changes up until 1m depth after land conversion to AF. SOC decrease from 26-24% from forest to AF. SOC increase of 24, 40 and 34% at 0-15cm, 0-30cm and 0-100cm respectively. SOC stock increase from pasture/grassland to AF by 9-10%. Switching from uncultivated/other land-use to AF increased SOC by 25% in the first 30cm soil but showed overall decrease by 23% from 0-60cm.	Main increase when converting from cropland to AF systems. Study questions sufficient use of explanatory variables in included studies. Result for uncultivated/other land-use to AF questionable.
Soil carbon stock in olive groves agroforestry systems under different management and soil characteristics (Bateni et al., 2019)	Italy	4 study sites	Results show Umbrian olive farms are characterized by high level of C storage. Most interesting way to further increase SOC stocks in olive plantations appears to be the use of pomace as soil amendment, which could also present a partial solution for oil production waste management. Silvopasture systems showed lower SOC stocks than the other farms. In all olive farms highest SOC content in upper 0-30cm soil. Particularly high in forested area. High variability of SOC between relatively similar (in microclimate) sites, especially in deeper soil layers.	Significant relation of pH and soil C of whole soil profile (0-60cm). Importance of measuring to deeper soil layers. Silvopasture values questionable.
Soil Organic Carbon and Nutrients Affected by Tree Species and Poultry Litter in a 17-Year Agroforestry Site (Amorim et al., 2022)	USA	1 study site, 2 treatments,	Evaluation of different fertilization and tree species. 17 years impact of poultry fertilization showed increased SOC concentrations under pecan trees and positive correlations between SOC, Ca and N at 0-15cm depth. Recommendation of tree species and fertilization practices that improve SOM levels in soil to reap benefits of overall soil health production.	Interesting showcase of how different species influence the changes of SOC in AF soils. Mostly explained by different litter and nutrient input. Poultry litter achieved more success in increasing biomass production of pecan trees than inorganic fertilizer. Shows how important research on SOC dynamics under agroforestry systems is.
Soil organic carbon sequestration in agroforestry systems. A review (Lorenz and Lal, 2014)	Global	Review of 114 articles	Estimated C sequestration potential of 2.2 Pg globally, above, and below ground in the next 50 years. SOC storage in AF systems may amount up to 300 Mg C/ha to 1m depth. In order to mitigate climate change through CO2, C-sequestration in AF systems must successfully store carbon for thousands of years. Yet, long-term storage is finite, since its dependence on binding materials available in the soil. Soil disturbance must be kept at a minimum.	General study with good overview and recommendations to increase C-seq. in AF systems.

Soil organic carbon sequestration in temperate agroforestry systems – A meta-analysis (Mayer et al., 2022)	Global, temperate climate	20 studies	Total of 61 observations (between 20 studies), consistent of 25 alley cropping systems, 26 hedgerows and 10 silvopastoral systems. Results showed substantial C-seq. potential in AF systems in temperate climates. Hedgerows revealed highes SOC sequestration rates in top- and subsoil (0.32 ± 0.26 and 0.28 ± 0.15 t ha-1 yr-1), followed by alley cropping systems (0.26 ± 1.15 and 0.23 ± 0.25 t ha-1 yr-1) and silvopastoral systems showing a slight mean SOC loss (0.17 ± 0.50 and 0.03 ± 0.26 t ha-1 yr-1). Broadleaf trees seem to sequester more than coniferous.	Good use of moderators and in- and exclusion criteria. Strong arguments for agroforestry.

4.7. Detection methods for long-term carbon storage

Table 8: Literature selection for detection methods for long-term carbon storage

Study	Study Location	Study Size	Results	Rating/Notes
Soil carbon market-based instrument pilot – the sequestration of soil organic carbon for the purpose of obtaining carbon credits (Badgery et al., 2021)	Australia	10 farms	10 farms contracted to do one of either 4 measures: 1. reduced tillage cropping 2. reduced tillage cropping with organic amendments (OA) 3. conversion from cropland to permanent pasture 4. conversion from cropland to permanent pasture with organic amendments Conversion from cropland under OA achieved highest C-seq. Each location was sampled with at least 10 sampling points and subsequently analysed with LECO elemental analyser (+ bulk density calculated). Carbon stocks were assessed in 2012 and 2017, based on equal mass. Prior site inspection to sampling to determine suitability. Stratification of farms into areas with relatively uniform soil type, land management history and geology maps. 8 soil cores taken, plant material and litter removed. Sampling sites not disclosed to farmer, to avoid bias.	2 samplings in 5 years as test. Not included from Australian Measurement Method: Discount for uncertainty, accounting for changes in other GHG emissions and permanence requirements. Study questions financial benefit of changed management, even with high C-seq. rates. Not per se a long-term detection method, but gives insight into sampling, its challenges, and its limitations.
Spatial and vertical variation of soil carbon at two grassland sites — Implications for measuring soil carbon stocks (Don et al., 2007)	Germany	2 sampling sites, with 18 and 25 repetitions	Comparison of two extensively managed grasslands, one with high clay content, the other with low. Measuring of bulk density and C and N concentrations in 5cm intervals (0-10cm) and 10cm intervals (10-60cm). SOC stocks were almost double at the clay rich site (86t C ha− 1 in 0–60cm depth), compared to the sandy site (48t C ha−1).	SOC stock was defined as a function of SOC concentration and bulk density of fine soil. Negative correlation of bulk density to SOC concentration was found. Very strong argument that SOC inventories cannot be made using only one of these variables. Very elaborate sampling practice, but interesting methodology.
Measuring soil organic carbon: which technique and where to from here? (John et al., 2015)	Global	Review	Overview of methods to measure to measure organic carbon contents, form historic colour and gravimetric analysis, dry and wet oxidations, to modern, spectroscopic, and even remote and mobile techniques. Techniques named as candidates for in-situ/on-the-go measurements: 1. NIR reflectance 2. Laser-induced breakdown spectroscopy (LIBS) 3. Inelastic neutron scattering (INS) 4. Airborne remote sensing Dry combustion for non-calcareous soils, and Heanes method for calcareous soils remain best methods for in-laboratory sample analysis.	Definition of which organic carbon is being measured by analytical method crucial for selection of appropriate methodology. Great review and overview of detection methods. Includes a great table of comparison of measurement techniques. RothC-Model needs to be described (in basics?).

			In-field techniques still need approaches that improve precision and accuracy to be used confidently.	
A space–time observation system for soil organic carbon (Karunaratne et al., 2015)	Australia	1 study site	This paper presents a framework for a space-time observation model for SOC, to embed into the RothC model. Namely, satellite derived biomass input data could improve the accuracy of SOC simulations by 16%.	Interesting approach to including modern technology into existing methodology. Studies like this are definitively needed to advance fusion of old and new carbon detection methods into what can ultimately provide accurate data under high feasibility.
Predicting soil organic carbon percentage from loss-on-ignition using Bayesian Model Averaging (Leon and Gonzales, 2009)	Scotland	3 study sites,	This study explored the influence parent material, soil type, drainage status, LOI, pH and clay content has on organic C%, when using LOI method to predict OC%. They conclude that parent material, clay content and soil horizon make important additions to predict organic C%.	Argument for inclusion of more data into LOI SOC measurement. Definitively valid, although questions of feasibility remain.
An advanced soil organic carbon content prediction model via fused temporal-spatial-spectral (TSS) information based on machine learning and deep learning algorithms (Meng et al., 2022).	China	2 study sites, 796 and 111 soil samples	Study on the role of different data sources when predicting SOC content, using two study sites for data comparison. Results show best prediction model consists of temporal-spatial-spectral (TSS) data as information input and a convolutional neural network as algorithm. Lowest mean square error was 2.49 g kg^{-1}	Study argues for a novel approach to predict soil properties using remote sensing and deep learning algorithms. Laying down a base for future research on "data fusion + deep learning", which might become very relevant for advances in remote sensing. The TSS could reduce soil parameter impact on prediction accuracy, for example soil moisture.
Towards cost-effective estimation of soil carbon stocks at the field scale (Singh et al., 2012)	Australia	100 sites	Accuracy of sampling SOC depends on the variability of soil carbon throughout the field. To find out, which simple and stratified sample design can achieve a standard error below 2MgC/ha, they created a carbon-variogram of 100 sampling sites, to estimate said variability. Cost of implementation of sample designs was calculated. They found a cost of $2500 (AUD) for soil sampling (0-30cm depth) with a target accuracy of <2MgC ha.	Very high cost at relatively low accuracy. Shows challenges detection methods for use in certification schemes still must overcome.
Comparison of the particulate organic carbon and permanganate oxidation methods for estimating labile soil organic carbon (Skejmstad et al., 2006)	Australia	44 samples	Analysis of labile OC in 44 soils under native vegetation using particulate organic carbon (POC) method and the 333 mM KmnO4 (MnoxC) method. POC method was found to be more sensitive by a factor of 2 to rapid loss of OC. Presence of charcoal was an issue for both techniques.	Laboratory measurements, unclear if suitable for long term detection.

4.8. Potential differences in SOC between organic and conventional farming

This last chapter includes literature that was collected in order to identify potential differences in SOC stocks and impacts of measures between organic and conventional farming.

Table 9: Literature selection for potential differences in SOC between organic and conventional farming

Study	Study Location	Study Size	Results	Rating/Notes
Impacts of the components of conservation agriculture on soil organic carbon and total nitrogen storage: A global meta-analysis (Bohoussou et al., 2022).	Global	97 (papers) 752 (comparisons)	21.39 higher SOC stocks in conservation agriculture (CA), defined as combination of 3 practices: 1) minimal soil disturbance, 2) cover crops and 3) residue return. Manure and mixed fertilizer increased SOC stocks by 20.67% and 41.67% respectively. Highest impact of CA in first 30cm of soil.	Not certified organic agriculture, but similar tillage practices. Pesticide use must be accounted for.
Effects of Organic Agriculture in Structure and Organic Carbon Adsorption at Colloidal Scale in Marginal Olive Groves, Characterized by the Extended DLVO Model (Calero et al., 2022).	Spain	3 treatments, 5 replicates	Comparison of conventional olive grove with no plant cover (CAS) to organic olive grove under 10 years spontaneous plant cover (OAS) and natural soil under small forest batch (FS) as control.	Strong argument for organic agriculture and plant cover under olive groves.

			Highest carbon content in FS (12.03%), then OAS (1.44%) and CAS (0.88%).	
Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach (Foereid and Høgh-Jensen, 2004).	Denmark	2 study sites, 4 treatments	2 long-term trials, one a comparison of manure/slurry application to mineral fertilizer and the other a comparison of different crop rotations, representing the differences between organic and conventional agriculture. The model found an increase of SOC in the first 50 years of about 10-40g C/m2/y, with use of grass-clover mixtures as cover crops between the rotation as most important factor.	Great study on the differences between organic and conventional agriculture. Strong argument for cover crops.
Soil organic carbon and microbial biomass after six years of reduced tillage under organic farming (Gadermaier, 2009).	Switzerland	8 treatments, 4 replicates	Results show significant impact of tillage on SOC and MB and only little impact from different fertilization (manure/slurry).	Important argument for tillage, while fertilization had a minor effect.

5. Synthesis and Discussion

This chapter contains the systematic analysis and discussion of the previously introduced literature. Each sub-chapter contains an individual table, where all included measures falling into the sub-chapters category are listed. The table contains both the key moderators, influencing the impact of said measure, as well as potentially important, correlating practices. Finally, a rating is given to the impact on SOC-storage, in form of -- (negative impact), - (no impact), + (moderate, positive impact) and ++ (positive impact).

5.1. Extensification

Extensification includes a variety of measures, each with their own specific impacts on SOC (as listed in table 2).

Kramberger et al. (2015) researched the impact of different cutting frequencies on SOC in grassland under the same fertilization. Their results showed that cutting frequencies do present a tool to build SOC stocks, but also the importance of considering additional, environmental parameters, such as the N-budget, when fertilizing. Since under lower cuts, not all N was taken up by plants, it could therefore be lost from the systems and cause problems otherwhere. Regardless, when considering cutting frequency as a tool to sequester carbon into a system, to reduce emissions, application of fertilizer must be seen as problematic, as fertilizer production comes with its own environmental cost.

Gossling et al. (2017) identify perennial grass cover as one of the driving factors of SOC-increase in from cropland to grassland converted soils in England. As a key moderator, they name land-use (O), as the previous carbon input through crop residues makes an important contribution to the final carbon balance. In Germany, Breuer et al. (2006) found contradicting results. They identified the parent material (mP), slope (mR) and climate (mC) of a soil as significant moderators. In their study, they compared two similar sites and their chronosequence, in which they analysed the effects of land-use change (crop- to grassland) on C-storage over a 60-year time-period. They sampled at 10-20cm depth, which might be considered low for a 60-year comparison.

In their global review consisting of 83 studies, Abdalla et al. (2018), researched the impact of grazing intensity on SOC stocks and found interesting results. While in temperate climates, low to medium grazing intensities showed best SOC values, tropical climates showed better results under higher grazing intensity, pointing to a strong correlation between grazing intensity and climate (mC). Another interesting result was the difference found in grassland response to grazing intensity, depending on weather the dominant grass species were C3 or C4 types.

Considering our changing climate and the expected rising temperatures in temperate climates, which could lead to increasing C4 plant types, this information might hold great relevance in the future.

In his recent review, Poeplau (2021) covers three different measures, which can be seen in an extensification context. In contrast to Kramberger et al. (2015), Poeplau found higher cutting frequencies to positively impact SOC stocks, although under certain conditions, which might not be applicable to agriculture (fertilization, clippings remain on site). The study shows how fertilization, via increased NPP, can increase SOC, but highlights the complications when it comes to applying this for actual GHG mitigation. Lastly, he makes an argument for perennial cover crops, which can be seen as a supportive argument for chapters 5.2. and 5.6.

In an interesting Danish experiment done by Bluwstein et al., in 2015, the authors tested the GHG emissions of an organic farm under extensification. With a reduction of livestock density and an increase of cropland, they achieved the same output as compared to conventional agriculture, under lower GHG emissions. The limitations of the study, namely the lack of soil parameters and the calculation only until farm-gate, have to be considered.

A global analysis (Gray et al., 2009) of the relationships between environmental factors and SOC based on 4382 soil profiles revealed only a weak correlation between parent material classes and SOC (contradictive to Gossling et al., 2017).

McSherry and Ritchie (2013) argue that extensification via reduction of grazing intensity is highly dependent on soil (mS), climate (mC), land-use and vegetation cover (mO). Reducing grazing might be counterproductive on C4 grasslands but may, in fact, be necessary to avoid chronic SOC loss in C3 grasslands. This is in concordance with Abdalla et al., 2018 study.

Similar to Kramberger et al., Nüsse et al. (2018) researched the effects of harvest frequency and N-fertilization on grassland SOC stocks. They found significantly higher SOC and SMBC in the first 10cm under 5-cuts with fertilization than compared to the other treatments. These results are explained by the stimulated root and above-ground biomass production. Yet, results also showed that SOC stocks under 3-cuts were higher when grassland was not fertilized. When considering cutting frequency as measure to increase SOC with the goal of emission reduction, this must be considered.

Another Poeplau et al. study, done in 2016, researched the cutting frequency effects on SOC in urban lawns, which showed significantly higher SOC stocks under multiple (8) cuts per season, as compared to meadow-like lawns with only 1 cut. And while this research, much like its 2021 successor, points well towards the importance of further parameters such as the C:N ratio, when estimating the effect of cutting frequency on SOC stocks, it cannot be compared to agricultural grassland management, where 8 cuts, with no biomass extraction are hard to imagine.

In last study in this first evaluation chapter, author Boellstorff (2008) introduces a five-year pasture rotation into the crop rotation, as a measure to increase SOC stocks and aid with soil restoration. In a novel approach using a model called SOCRATES he estimates the SOC changes until the first 10cm, which are stated as main region of impact of crop rotation, soil properties and climate.

Considering the literature summarized above, the 3 main extensification measures are rated on their effectiveness in building SOC stocks and the most important moderators which must be taken into account when estimating the expected effects, as well as correlating practices influencing the effect of said measures, are named (table 10).

Table 10: Rating of extensification measures impact on soil organic carbon (SOC)

Measure	Moderators	Correlating practices	Impact on SOC
Conversion of crop- to grassland	mS, mC, mO,	Fertilization, species selection	++
Cutting frequency	mO	Fertilization	+
Grazing intensity	mS, mC, mO	Species composition of grassland	++

Conversion of crop- to grassland: There is evidence of grassland and permanent pastures in temperate climates having higher levels of SOC than cropland (Wenzel et al., 2022). Yet, the conversion of crop- to grassland is not an easy measure to feasibly execute. Uncertainties and risks are high and farmers who cannot afford to lose highly productive parts of their farming system, especially considering the long-term scale of grassland SOC build up, might be very hesitant to adapt this measure. Those who do convert, must precisely consider their soils current condition (mS and mO) and how to successfully transfer from possibly fertilized, high-output arable land, to extensive pastures. Further, climatic conditions play a crucial role in determining the conversion strategy, adaption to changing annual temperatures and precipitation might be done through species selection or fertilization schemes.

Cutting frequency: Changing the frequency of biomass removal, or re-entry of grass- or pastureland presents a potentially effective way to increase SOC stocks. Especially the current number of cuts and the fertilization decide the outcome. As described in the literature above, reduction or increase of cutting frequency might have a positive effect on SOC stocks.

Grazing intensity: McSherry and Ritchie (2013) highlighted the impact of climatic parameters on grazing intensity as a tool to increase SOC stocks. Under the right conditions, decreasing the livestock density might therefore be the right way to go, especially in temperate, C3 dominated grasslands. The accompanying reduction of animal emissions (CH_4^+, N_2O) can be seen as additional benefit for climate change mitigation.

An important addition to the topic of extensification is the reduction of fossil fuel and non-renewable energy (NRE) input: The use of NRE is a potentially underrated source of emissions, although it presents an effective lever to lower a farms CO_2-output (SOURCE). With modern technologies such as solar power or biogas finding its way into the European agriculture, reducing fossil fuel usage and/or switching over to renewable sources of energy might not increase SOC, but presents feasible possibility to reduce the ecological footprint from another angle.

5.2. Cover- and intercropping

Compared to the rather contradictive data for extensification effects on SOC, cover and intercrops deliver almost unison evidence of their effectivity in sequestering and building up carbon in agricultural soils (table 3).

Cover cropping as such spans a large range of individual techniques but will with a high probability increase the SOC stocks of agricultural soil in the long term.

In their meta-analysis Poeplau and Don (2014) found significantly higher SOC stocks under cover crops than under uncovered cropland and identified the use of cover crops as green manure as an important management tool to increase SOM and therefor SOC.

In their recent study (2022) Zhang et al., formulated another strong argument for the use of cover crops. When comparing different plant species (legumes, grass, brassica), they found that a mixture outperforms the individual plant by itself. Especially when it comes to long-term SOC persistence, the mixture of cover crops could stabilize SOC better. These results underline the importance of biodiversity, especially in the often-overlooked soil microbiome.

In an older study by Steenwerth and Belina (2008) on rye and triticale cover crops in a vineyard cultivation, temperature, precipitation, and water content (mC) was found to be the most important parameter influencing SOC-parameters.

Reimer et al., 2019, point towards the problematic of weed pressure under non-inversion tillage, but find the use of subsidiary crops (cover- and intercrops) to significantly reduce weed pressure during fallow periods.

In Cong et al.'s 2014 study, the authors found 3-5% higher SOC content in intercropping systems than in sole crop systems. They combined maize, faba beans and wheat in a 2-year rotation and found higher total root biomass and soil organic nitrogen. Further, crop diversification such as the intercropping done in this study will likely yield additional benefits, such as a reduction of pest pressure (Poveda et al., 2008) and a lower erosion potential through the increased root biomass and an overall higher soil fertility.

While the recent review of McClelland et al. (2021) is not a direct field study of a cover- or intercropping treatment, it produces interesting results on which parameters to consider when applying cover crops to increase SOC stocks. They found the growing window (planting and termination), annual cover crop biomass production and soil clay content as the most important factors influencing SOC response, with permanent plant cover and autumn-planted and terminated cover crops achieving up to 30% higher SOC stocks relative to other cover crop growing windows. This study underlines the importance of cover crop management, but also supports the argument of permanent plant cover to increase SOC stocks.

Novara et al. (2018) take a different approach and argue that the sloping gradient, through its effect on soil (and therefore SOC) erosion, has a more significant impact on SOC stocks than the choice and management of cover crops themselves. They describe the C-input through cover-crops as overestimated.

In a very large review (over 2000 included studies) Seitz et al., 2022, analyse the total potential of cover crops in German croplands. They calculate the possibility of tripling the cover crop areas to a total of 30% which could lead to 12% increase in C-input. This naturally must be seen as highly hypothetical, but the study as such raises a very important point. Even under the realisation of the full cover crop potential in Germany, the croplands would still be a carbon source. This is a clear indicator at the complexity of climate change mitigation and how agriculture cannot be seen as the sole actor to somehow sequester and mitigate all emissions back into the soil. Seitz et al., also point out the importance of subsidies and farmer-know how, both tools needed to support and aid farmers towards a more sustainable agriculture.

The last study of Blanco-Canqui (2022) is another critical review on cover crops. Again, growing window and general cover crop management was found as most important factors influencing SOC accumulation through cover crops.

Summarized, even though cover- and intercrops are almost too diverse to be rated as one measure, the evidence from literature clearly suggests that their application is always favourable for building SOC stocks, especially if applied on previously uncovered soils (table 11). The additional benefits of cover crops are high, increased biodiversity both above and below ground provide ecosystem services valuable to land and farmer, with the possibility of positive feedback loops increasing the effect in the future. Naturally, planning and managing cover- and intercropping systems is of high priority.

Table 11: Rating of cover- and intercropping measures impact on soil organic carbon (SOC)

Measure	Moderators	Correlating practices	Impact on SOC
Cover cropping	mS, mO,	Species selection, growing window	++
Intercropping	mS, mO,	Species selection, growing window	++

Cover crops: Cover crops present an especially effective way to increase SOC stocks, as they both increase OC input into the systems and at the same time can greatly reduce carbon losses via decreasing SOM losses under bare fallows, which have been identified as cause for greatest SOC losses by Tiefenbacher et al. (2021). Choosing the right species and growing window is key in achieving maximum carbon-sequestration and the outcome highly dependent on previous land-use (mO) and soil parameters (mS), such as soil type and texture.

Intercropping: Similar to cover crops, intercrops present an efficient way to improve soil health, reduce bare soil in the farming system and sequester additional carbon. To add to the factors listed above, intercrop-seeding (mO) needs to be carefully planned to avoid unwanted interaction with main crops.

5.3. Erosion

Erosion is a serious driver of land degradation and thereby erosion control an important measure that is always recommended. The following chapter discusses the various measures listed in table 4 and how they halt soil carbon loss and additional information on how erosion impacts SOC stocks.

Nerger et al. (2019) created a model to measure soil carbon loss by wind erosion in northern Germany. They combined long-term monitoring data with a wind-erosion model and were able to link them to the measured SOC losses in sandy soils of the area. The measured soil loss corresponded to the measurements of the two study sites. And while this is not a direct measure for erosion control it does highlight the impact of wind erosion on SOC loss and presents a potential monitoring tool to keep track of it.

The Wells et al. (2019) study compared minimum tillage cropland to native pasture in regard to their SOC stocks and erosion potential. Results clearly showed that even under conservative agricultural management, the pasture had higher SOC stocks and a significantly lower erosion potential. It must be noted that geographically the study was done in Australia, which might be cause for different results than if it was done in Europe. Regardless, the study does support the argument of long-term benefits of cropland to grassland conversion or the inclusion of perennial pastures into the rotation.

Moving back into Europe, a study in Moldova researched how to rebuild SOC stocks in degraded steppe soils (Wiesmeier et al., 2019). The study compared SOC build-up under windbreaks, cropland with manure application and cropland under cover crops (highest sequestration rates) and found positive results for all measures. The study makes a really important argument for the combination of measures for best results.

Zuazu and Pleguezuelo (2008) did a review of the effect of plant cover on soil erosion and runoff. Their results present another important argument for permanent plant cover, as they found that its effect on erosion might be greatly underestimated.

While Naipal et al. (2018) did not research a concrete measure, they developed a model to calculate global SOC removal through erosion. They found that up to 85% of total soil erosion since 1850 occurred in agricultural lands and that soil erosion very likely presents an equal threat to global SOC stocks than climate and land-use change.

Another Australian study, done by Hancock et al. in 2019 provides further, clear evidence of erosion impact on SOC erosion and deposition. Results show how SOC is translocated through heavy rain events and presents a measurement method with a tracker element.

Hombegowda et al. (2019) researched the effects of hedgerow intercropping on soil runoff and carbon sequestration and found very positive results. Naturally, the plant choices and climatic parameters will differ substantially to European conditions, as the study was conducted in India. Regardless, the authors provide important evidence of the potential of hedge row intercropping to reduce soil erosion and build up SOC stocks.

In a very recent article from China, authors Pan et al. (2022) researched soil erodibility under different agroforestry systems. Since geographical differences, plant choices might not translate to European context, yet the results show clear evidence of soil erodibility resistance improvement under agroforestry systems, further supporting the argument for permanent plant cover as a measure against soil erosion.

Another recent, but European study by Baartman et al. (2022), focused on the effects of soil improving cropping systems (SICS) measures on soil erosion and SOC-stocks. They presented 4 scenarios with different levels of SICS applications, ranging from none to all measures. The measures included cover crops, mulching, soil compaction alleviation and minimum tillage. Results showed an increase in soil erosion across Europe at no SICS-application and a strong decrease of soil erosion under the highest SICS application, corresponding strongly with Wiesmeier et al.’s 2018 Moldova study and the argument for a combination of measures.

In 2020 Kahleel et al. published an article on the effects of windbreaks on SOC and further soil properties. They quantified the SOC under windbreaks to a depth of 125cm and found 16% higher stocks under the windbreaks than under adjacent fields. What sticks out is that 7% more SOC was stored at a depth from 30cm to 125cm. Therefore, aside from showing the C-sequestration potential of windbreaks, this Kahleel et al. highlight the incredible spatial versatility and variability of SOC.

In a global review, Kirkels et al. (2014) explored the fate of carbon upon erosion. And while not a measure to include into the evaluation, the study does provide important insight into the discussion around agriculture, erosion, and SOC.

In Spain, Sastre et al. (2018) studied the effect of protecting a sloping olive plantation with cover crops on SOC. The researched a variety of soil parameters such as root density, organic carbon, organic nitrogen, aggregate stability, porosity, infiltration, water storage and soil penetration resistance and concluded that cover crops need to be planted for a minimum duration of 3 years to improve said parameters. This can be seen as another clear argument for the use of perennial cover crops or permanent planting.

In their 2016 article Lacoste et al. present an experiment of a 90-year simulation of SOC-dynamics under a temperate hedgerow landscape. Erosion was relatively low due to protective hedgerow network but results also linked the hedgerows and tillage as an important factor influencing the effects of soil redistribution on SOC stocks.

Building the increasingly evident benefits of permanent plant cover event further, Marques et al. (2020) researched the effects of permanent plant cover on water dynamics in a sloped vineyard in Spain. The results showed that cover crops could reduce runoff, improving infiltration and therefore making up for potential water composition. Like Sastre et al. (2018), the authors highlight the importance of a longer duration of cover corps, for them to build up enough root mass to achieve their beneficial effects.

Two more studies underlining the importance of soil erosion when trying to understand SOC dynamics, especially at a global level, are included by Zhang et al., (2019) and de Nijs and Cammeraat (2020).

When summarizing the included literature, it becomes clear that erosion presents an increasing threat to our soils and that it has evident effects on SOC-distribution and dynamics. The evaluated measures all provide important tools to not only reduce soil erosion but sequester additional carbon into the farming system and increase biodiversity (table 12).

Table 12: Rating of erosion control impact on soil organic carbon (SOC)

Measure	**Moderators**	**Correlating practices**	**Impact on SOC**
Windbreaks	mO, mR	Species selection	+
Permanent planting	mC, mO	Species selection, Fertilization, Tillage	++
Hedges	mO	Species selection	+

Windbreaks: Erosion control efficiency (and thereby SOC loss prevention) through windbreaks naturally depends strongly on the disposition of the field (mR) and the vegetation cover (mO). Through the right species selection windbreaks can become a beneficial ecosystem for the farm, creating habitat for insects, birds and small mammals and potentially even produce additional resources such as timber, fruit or biomass for composting.

Permanent planting: Perennial plant cover appears to be one of the main recommendations made for reducing erosion and has shown to efficiently increase SOC stocks through both increase of OC input and reduction of CO_2-efflux.

Hedges: While the benefits of hedges are very similar to windbreaks, hedges must not necessarily be for decreasing wind speed. Regardless, they provide a great tool to stop soil erosion and runoff and increase the carbon sequestered into the farming system.

Cross seeding: The literature search on effects of erosion control through cross seeding on SOC showed insufficient results to include a complete evaluation of the measure into the study. Although cross seeding does not seem a very prominent technique, it seems to be a potentially easily adaptable tool, which should warrant further research on the topic.

5.4. Tillage

Tillage is much discussed and highly complex topic, which is reflected by the literature included in this evaluation (table 5). The current scientific consensus leans towards no-till as most effective when it comes to building SOC stocks, but the practice of no-till comes with its own set of issues that need to be addressed in the scientific debate.

Beginning with the 2018 study of Ramnarine et al. in Canada, where they researched the effect of no-till and conventional tillage on non-hydrolysable fractions of SOC. They found significantly higher SOC stocks under no-till in the first 10cm, but no significant differences at 30cm depth in the short term. These results must be interpreted carefully, as no-till can influence other parameters, such as soil runoff and soil loss, and therefore indirectly SOC, which was content of Chowaniak et al.'s 2020 research on the effect of tillage on erosion and SOC loss. While the authors describe an initially lower runoff under conventional tillage (4.3%), soil loss was substantially lower under no-till (66.8%), with an increase over time, as plant cover developed.

Both these articles serve as fitting examples of how interpretation must be done carefully in order to avoid misconception of the results. Especially with tillage, a lot of additional, environmental parameters make it impossible to excerpt a singular effect.

Zhang et al. (2019) evaluated tillage effects with residue return on degraded soils. In their comparison of different tillage techniques, they found overall increase of SOC stocks compared to no soil management, but like Ramnarine et al. (2018), the differences over 30cm depth between the tillage forms were minimal, although no-till and ridge-tillage showed higher SOC in the first 20cm than mouldboard plow. Since this study was done under tropical monsoon climate, results might not be accurate for European soils.

Another recent Chinese study by Shi et al. (2022) found no-tillage with additional straw-return to yield highest SOC increase in comparison with rotary tillage with and without straw return.

Badagliacca et al. (2018) raise awareness to an unwanted side effect of a long-term no-till experiment, where they found significantly higher N_2O emissions compared to conventional tillage.

Often, no-till goes hand in hand with herbicide application, which likely has (still) unknown effects on the microorganisms living in the soil. A very interesting review by Li et al. (2021) highlights the importance of the soils microbiome when it comes to increasing SOC stocks. Li et al.'s study links the increases of SOC under no-till to microbial biomass carbon and particulate organic carbon. They define precipitation and temperature (mC) as important parameters when increasing SOC through no-till and recommend a minimum duration of 6 years for it to take effect.

In a European study, Krauss et al. (2022) compared reduced to conventional tillage in organic farming. Reduced tillage showed a significant increase of SOC in the first 10cm, showed a depletion of SOC stocks in the intermediate layer (10-50cm) and an increase in 70-100cm depth, again highlighting the importance of looking at the entire soil profile. They found a reduction of biomass production of 8% under reduced tillage, although this was outbalanced by weed biomass increase.

Naderi et al. (2021) tested the short-term response of SOC (and crop yield) to different tillage and organic amendment regimes. They found highest SOC under no-tillage with manure application, with no effects on yield. Contrary to Chowaniak et al. (2020) they found reduced tillage to reduce runoff. It is worth noting that in their comparison for SOC, no bulk density was considered.

Another recent study by Li et al., done in 2022, the authors build on their previous study and research effects of straw amendment on the chemical composition of SOC and how it relates to the microbial community structure. The results show the benefits of adding straw to tillage practices in order to strengthen the microbial community and support the build-up of SOC.

In regard to SOC build up, no-till seems to produce best results, although the outcome highly depends on environmental factors that farmers need to consider when adapting this practice. The following table (13) rates the 3 tillage methods and lists the relevant moderators and correlating practices:

Table 13: Rating of tillage impact on soil organic carbon (SOC)

Measure	Moderators	Correlating practices	Impact on SOC
Conventional tillage	mC	Straw amendment	--
Reduced tillage	mC	Weed management, straw amendment	+
No-till	mC, mO, mR	Weed management	++

Conventional tillage: There is increasing evidence of conventionally tilled soil having lower SOC stocks than reduced tillage and no-tillage soils, especially when measuring below the plough sole. With straw amendments, disturbance of the microbiome can be mitigated a bit and climate (mC) has been identified as key moderator.

Reduced tillage: There are a number of studies showing conservation tillage succeeds in increasing SOC stocks through its reduced tillage intensity. Weed management plays an important role, as the lack of mechanical weed control often leads to an increase in pesticide application. As conventional tillage, climatic factors are the key moderator determining its success.

No-till: The increased biomass through lack of tillage leads to provable increases in SOC stocks and under good management can produce additional benefit of reducing the soils erosion potential, although increased run-off (mR) must be reckoned with in the short term (Chowaniak et al. 2020).

5.5. Fertilization and soil meliorations

Fertilization is an interesting topic, as it covers a lot of different approaches, from the use of synthetic NPK fertilizer, to manure application and biochar amendments. The following chapter describes recent scientific studies of these approaches in a soil organic carbon context (table 6).

The effects of different fertilizer treatments on carbon sequestration under wheat crops was tested by authors Begum et al. in 2017. They compared mineral N fertilizer to farmyard manure, both with on-site trials and using a model to calculate future SOC sequestration. Results between model and field measurements differed, as former pointed towards manure only achieving best results, while the latter presented best results when combining the two.

An argument against the use of mineral fertilizer was brought by Correa et al., (2019), who found only little changes in TOC after application, although it must be mentioned that the study was conducted in highly fertile, tropical soils of Brazil, which might mean an alternative outcome for European soils. The increase observed in SOC could be linked to no-till practice.

In a meta-analysis by Eze et al. (2018), searchers studied effects of three different practices on global grassland SOC stocks. They found that grazing intensity was mainly at fault for SOC decrease, while fertilization (N+P) and liming showed positive effects. These positive effects were greatest in the tropics, but only minimal in temperate grasslands, making them a potential carbon sink. While this study definitely underlines grazing intensity as an important management tool for influencing grassland SOC stocks in temperate climates, it also showcases how synthetic fertilizers might not be the answer to balance emissions.

Karhu et al. (2012) did a study on the ability of a certain model to predict changes in SOC stocks, which in itself might present an interesting opportunity for future. Their results were focused on the model’s accuracy, but interpreted in a “fertilizer context”, measurements show strongest SOC increase under straw and peat, both paired with N, or farmyard and green manure by itself. Additionally, they describe climate (mC) as most influencing parameter for fertilizer impact on SOC.

The reoccurring question of why (and how) mineral fertilization increases SOC in temperate grasslands was taken as a research topic by Poeplau et al. in 2018. This interesting experiment consisted of seven long-trials, where different forms of mineral fertilization were compared to unfertilized plots. All fertilizers showed significantly positive effects on SOC stocks. This could neither be explained by increased root C input, nor decreased mineralization, but a potential increase in microbial C use efficiency might be an answer. The cost of 1kg of sequestered SOC was found to be 1.15 kg of N fertilizer.

According to the 2016 lifecycle assessment (LCA) of mineral fertilizer production by Brentrup et al., 1 kg of N fertilizer ranges from 2 to over 10 kg of CO_2 equivalent, depending on where it is made. This LCA does not include the application of the fertilizer, but assuming the 1.15kg N fertilizer cost that Poeplau et al. (2018) found for 1 kg of C, the problem of using mineral fertilizer as an emission mitigation measure becomes obvious.

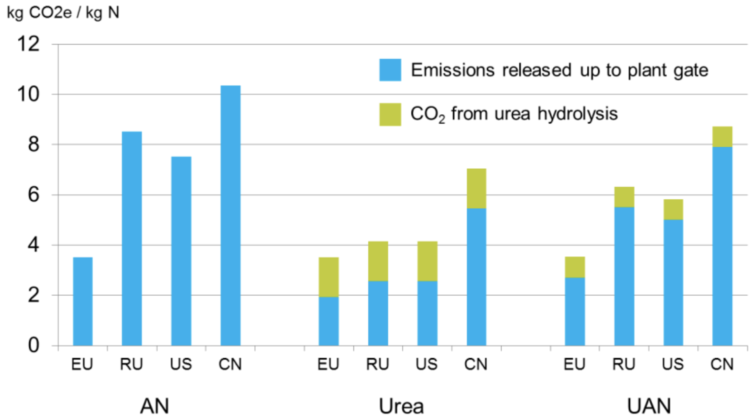

Figure 8: Lifecycle assessment of mineral fertilizer production. Source: Brentrup et al., 2016

In a recent study by Qiu et al. (2022), authors compared long-term application effects of chemical and organic fertilizers on SOC stocks. They found clear evidence of organic fertilizer improving soil aggregation, which in turn helped to bind additional organic carbon.

A Brazilian study by Tenelli et al. 2021 measured the effects of nitrogen fertilization and cover crops on SOC stocks and sugarcane yield. And while the study makes a good argument for the use of cover crops to reduce necessary mineral fertilizer, it must be interpreted carefully, as it only measured SOC twice (before and after), which leaves room for high variability of results. Further, the tropical, Brazilian climate differs strongly European temperate climate, with potentially significant effects on SOC dynamics.

Vandermoere et al. (2021) researched soil phosphorus mining in agriculture. While the issue of P eutrophication might be rather specific to the north-western regions of Flanders and the Netherlands, the study does highlight the issue, which might become a more global problem if mineral fertilization sees further growth.

Additional arguments for a carefully planned fertilization management are made by a study on long term effects of N-fertilization on SOC stocks by Zhon et al. (2015). Most prominently, they found that after 9 years of excess N fertilization, the soil became a C source, while the right amount of fertilization achieved C fixation.

Fertilization effect on SOC stocks is a complex topic, as fertilizers primary function in a farming system is not necessarily permanent carbon sequestration, but the increase of biomass production for later harvest. What becomes clear, is that argument such as increased SOC stocks through N-fertilization must be taken with care, especially when seen through a climate change mitigation lens. The microbiome plays an important role in SOC dynamics in agricultural soil and must be considered when planning a fertilizer regime.

The next section focuses mostly on biochar, which has seen a rising interest over the past decade due to its promising results in sequestering carbon into soils.

Criscuoli et al. (2019) make an important statement to consider (changing) climate (mC) when applying biochar. They measured the temperature effect on GHG emissions under biochar amended soils and found a negative impact on soil uptake of CH_4.

In a later second study, the authors studied the effects of woodchip biochar on SOC stocks in a two-year field experiment, under different quantities and with or without compost. They found significant increase of SOC under 50t/ha biochar amendments, with no decrease in SOM-C decomposition (Criscuoli et al., 2021).

Authors Dubey et al. (2020) studied different agronomic practices to increase soil quality. The compared effects of vermicompost and biochar and found that while vermicompost showed higher effects on soil quality, biochar showed higher potential for climate change mitigation, as it reduced CO_2 efflux from the soil (which vermicompost seemed to increase).

A global review by Han et al. (2022) showed biochar increased SOC by 45.8% on average (with large regional variations). They identified application rates (mO), initial SOC (mS) and edaphic (mS) and climatic factors (mC) as most important parameters when calculating the SOC response to biochar amendment.

Horák and Šimanský (2016) researched the SOC effect of biochar in combination with N-fertilizer. The rather short study showed higher SOC contents at biochar amended plots, compared to control, but results must be taken with care, as samples were only taken until 10cm depth and only taken twice.

While the experiment of Palvainen et al. in 2020 was done in a forest, it does deliver interesting evidence of biomass increase under biochar amendment, especially under nutrient poor soils.

Another study on temperature effect on SOC dynamics under biochar application was done by Rittl et al. in 2018 in Brazil. The temperatures of up to 40°C might not apply to Europe, but results did agree with Dubey et al. (2020) and showed a reduction in CO_2 emissions from biochar treated soils, with higher temperature sensitivity of the GHG than untreated soils. The authors reiterate the need for regionally specific biochar application schemes to achieve best results.

Further work on emissions and biochar, but this time in forests, was done by Sarauer et al. (2018). The authors studied GHG emissions in forests in the western USA and found and increase in soil C content by 41% compared to control. In contrast to results of Criscuoli et al. (2019), CH_4 fluxes did not show any impact by biochar, which might be explained by the differences in experimental set-up (forest to pot-experiment).

Shasheen and Bukhari (2019) show other benefits of biochar in a 7-treatment experiment with different forms of biochar and biochar with fertilizer combinations. The found biochar to significantly improve soil structure.

Presenting results form a ten-year field experiment in China, Shi et al. (2020) show the importance of the priming effect (mineralisation of SOC) of biochar and how inorganic carbon can contribute to carbon sequestration after biochar application.

Another recent Chinese experiment by Yang et al. (2022) tested the previously mentioned priming effect on two soils with different clay contents. Their results showed that aged biochar caused a negative priming effect, meaning a decrease in C mineralisation. Additionally, pyrolysis temperature of biochar seemed to correspond c-sequestration potential. Both studies Yang et al. (2022) and Shi et al. (2020) illustrate the importance of understanding the priming effect and biochar effects on SOC dynamics.

Table 14: Rating of fertilization and soil melioration impact on soil organic carbon (SOC)

Measure	**Moderators**	**Correlating practices**	**Impact on SOC**
Mineral fertilizers	mO,	Organic amendments	+
Organic fertilizers	mO,	Fertilization	+
Mixed fertilizers	mO,	Fertilization	++
Biochar	mS, mC, mO,	Fertilization, organic amendments	++

Mineral fertilizer: The effect of mineral fertilizer on SOC stocks is obviously very dependent on land-use type and vegetation. Nitrogen and the C:N ratio (mO) definitely presents an important factor that must be considered in every farm management, but it seems as if the cost of mineral fertilizer outweighs the benefit when it comes to GHG mitigation. Through additional organic amendments, positive effects on soil parameters can be enhanced.

Organic fertilizer: A definite must when it comes to soil health and SOC improvement. Most organic fertilizers (manure, slurry, compost, etc.) provide an important source for organic carbon to re-enter the system, favouring the microbial community development and diversity.

Mixed fertilizers: A number of studies listed above found promising results in the combination of mineral and organic fertilizers. Again, emission cost of mineral fertilizers must be considered when using fertilization to sequester CH_2-emissions (mO).

Biochar: There seems to be unison agreement that biochar presents an effective tool for carbon sequestration and long-term storage. The impact of certain parameters (mS, mC) is not yet fully understood and must be further researched. Regardless, biochar, when available can achieve efficient SOC increase, especially in combination with further organic amendments.

5.6. Agroforestry

While agroforestry is not a new practice, the interest in it, due to the promising carbon sequestration potential is relatively recent. Throughout the literature, mainly positive results are found, with interesting insights that were found in the last decade (table 7).

In the first, recent study by Gross et al. (2022), the authors tested effects of agroforestry systems (AFS) on N_2O emissions and SOC stocks. In a three-year experiment, AFS such as hedgerows, shelterbelts, woodland, and grassland (with perennial plant cover) were tested. Results showed 89% lower N_2O emissions under perennial plant cover, double the SOC under woodland than other land-use types and up to three times as much carbon under hedgerows than under cropland. While these results come relatively expected, it provides valuable prove in a debate for adaption of AFS. The study makes another point about the importance of microbial life under AFS and their influence in SOC sequestration and retention (mO).

Shi et al. (2008) conducted a meta-analysis on global AFS, their current SOC stocks and their future potential. Including 76 studies, the authors paired 427 SOC stocks into different AFS and found an average of 19% higher SOC in AFS until 1m depth, compared to cropland. The study leaned its focus more towards tropic and subtropic climate, showing highest C stocks to be found in tropical homegardens. These results might not be accurate for a European context, but the conclusion on the high potential of AF to store carbon remains valid.

In a Canadian study by An et al. (2021), authors researched quality and structural and thermal stability of SOC stocks under hedgerows. They found higher quality carbon, but lower structural and thermal stability as compared to cropland. These results point towards susceptibility of forests to climate warming. The authors make a valid point in recommending to consider these results when planning for long-term C storage in AFS. Regardless, factors such as tree species, previous land-use and current management practices (such as OM application) could alternate the outcome.

Cardinael et al. (2015) studied the impact of alley cropping on soil carbon dynamics. Their experiment consisted of an 18-year-old AFS, where a depth of 2m was measured. They found significantly higher SOC accumulation rates and SOC stocks under the AFS intercropping system, with higher stocks where no tillage was applied. They observed no discernible effect of tree distance on SOC throughout the experimental plots. Further, the study showed that most additional SOC was stored in coarse organic fractions of the soil, which might not be stable enough for long-term storage. These findings support the argument made by An et al. (2021).

In another recent article written by Eddy and Yang in 2022, a comparison between an AFS, a corn-soybean rotation and secondary forest showed higher carbon stocks in AFS as compared to the cropland, with highest SOC in secondary forest. The authors found the cropland to be nutrient deficient to a point where it might impact yields, therefore underlining the potential benefits a conversion to AFS could bring (increase OM input, diversification, water retention, etc.).

In a global meta-analysis from De Stefano and Jacobson (2017), the authors researched exactly this, studying the effects of conversion from different land-use types to AFS on SOC stocks. They examined the soil profile until 1m and found decreases in SOC when converting from forest to AFS but increases when converting from cropland to AFS. Even from pasture conversion to AFS, authors found an average increase of SOC by 9-10%. Another interesting result was an increase of SOC when converting from uncultivated land-use to AFS in the first 30cm, but a decrease when looking at a greater depth (0-60cm). This is likely heavily influenced by the previous land-use, but it supports the important argument for deeper sampling depths, for a better understanding of SOC stocks and their dynamics.

Bateni et al. (2019) studied SOC in olive grove AFS under different management practice in Italy. Their results showed the most promising way to further increase SOC in these olive groves was the use of pomace as organic amendment, which would present a potential solution for oil production waste management. Interestingly, silvopasture systems showed lower SOC stocks than other farming systems, but no explanation is found. Potential causes might be different tree species or different previous land-use types. The authors did find a strong relation of pH and SOC for the whole profile until 60cm depth. This is explained by the pH effect on microbial activity (mO).

Amorim et al. (2022) tested how tree species and application of poultry litter affected SOC in a 17-year-old AFS. They found clear differences in the effect of the fertilizer on the two researched tree species, which most likely is due to the differences in litter and nutrient input. The results demonstrate the importance of understanding the complex dynamics of SOC under AFS to find management strategies that maximise the production and C-sequestration potential.

To build on the previous statement, the review by Lorenz and Lal (2014) revealed an estimated C sequestration potential of 2.2. Pg globally, above and belowground for the next 50 years. Such results must always be interpreted with caution and the authors themselves include concerns about the long-term storage function of AFS (An et al., 2021; Cardinael et al., 2015) and advice for soil disturbances to be kept at a minimum.

Mayers et al. (2022) did a meta-analysis on SOC sequestration in temperate AFS, consisting of alley cropping, hedgerows and silvopastoral systems. Much like Lorenz and Lal (2014) they found substantial C-sequestration potential in AFS in temperate climates, with hedgerows revealing the highest, followed by alley cropping systems. But like Bateni et al. (2019), silvopastures actually showed a slight mean SOC loss. As previously assumed, cause for this is likely due to the hedgerows comparing with cropland as previous land-use type, while the silvopastures compares with grassland.

Agroforestry shows promising results throughout the current literature, with leading practices being hedgerows and alley cropping (table 15). There seems to be a lack of understanding on silvopasture effects on SOC dynamics and causes for lower results than other AF-practices. Especially carbon stabilization and retention will play an important role when it comes to ensure successful long-term carbon storage in AFS, which will be necessary to ensure successful realization of its potential.

Table 15: Rating of agroforestry impact on soil organic carbon (SOC)

Measure	Moderators	Correlating practices	Impact on SOC
Alley cropping	mO, mR	Fertilization, Species selection, Tillage	++
Silvopasture	mS, mC, mO	Species selection	-

Alley cropping: There is a lot of research showing the positive effects of alley cropping on a variety of ecological parameters, SOC inclusive. Naturally, the species selection and fertilization and tillage scheme must be planned according to fit the climatic and soil conditions. When it comes to success chances in increasing SOC stocks, especially the previous land-use and the relief have been identified as key moderators.

Silvopasture: Surprisingly, as of yet there is no strong evidence for silvopasture to increase SOC stocks in agricultural soils. This might be due to different previous land-use types. Generally, silvopasture systems should still be seen as an improvement to conventional pastureland with high grazing density.

Forest farming and riparian buffer stripes: Two of the four measures described in 1.2.2.6. did not produce enough literature to be included in the evaluation. While forest farming appears rather marginal, with no significant, larger-scale application in European agriculture, riparian buffer stripes are an increasingly common sight throughout the landscape. Similar to hedges, they fulfil various ecosystem service beneficial for farmer and environment, especially when it comes to retention of nutrients and agrochemicals. There is no doubt that there is also potential for carbon sequestration in these buffer stripes, making further research a necessity. Forest farming on the other hand offers as many benefits as it faces challenges when it comes to the debate of modern agriculture. But with increasing interest in agroforestry, it might see further interest in solving these challenges and reaping the benefits of a closed canopy farming system.

5.7. Detection methods for long term carbon storage

Unfortunately, up to date, there is no uniform methodology when it comes to detecting and measuring carbon, impeding comparison on larger, international scales. Regardless, measuring carbon, be it in the air or soil, must stay a focus. Especially detection of long-term carbon storage, which is crucial when it comes to using carbon sequestration as a tool against GHG-driven climate warming, is in dire need of attention, if emission trading continues to grow as it did.

An Australian study by Badgery et al. (2021) took this issue at hand and explored different agricultural measures and how they would translate into a carbon credit system. The authors sampled according to the Australian Measurement Methods and found highest C-sequestration under conversion of cropland to pasture under organic amendments. While these results do not surprise, the experiment gives important insight into how carbon develops from being a GHG to a credit that can be sold on a market. The sampling was done twice in five years, leaving much room for error and the authors state that over long-term sampling, sequestration rates will likely be a lot lower than anticipated. Further, they question financial viability for the farmer, even when achieving high c-sequestration rates. This, paired with high uncertainty and a lack of discount for other GHG, illustrates the challenges carbon credit systems currently face.

In an older, more theoretical paper, authors Don et al. (2007) argue for precise sampling methods, using both bulk density and SOC-concentration. The study adds important evidence to the debate, as unfortunately, until today, mistakes concerning bulk density when calculating SOC-stocks are made. A lot of effort went into trying to formulate SOC as a sole function of soil parameters such as clay content for example, but Don et al. show the difficulties of using only one parameter and the high chance of error.

John et al. (2015) conducted a global review on sampling techniques, providing an excellent list of up-to-date measurement methods. Aside from a great overview of detection methods, current advances in sampling, as well as their challenges and issues are listed.

Another Australian study by Karunaratne et al. (2015) presents an innovative approach to include modern technology into existing methodologies, laying out a framework for a space-time observation model for SOC. Research such as this, is crucial for the advance of sampling technology. The authors predict a possible improvement of SOC sampling accuracy by 16%.

Leon and Gonzales (2009) studied the influence of different soil parameters (mS) on sampling outcome when using the LOI method to predict SOC-content. They find clay content and soil horizon to have important impact on the outcome and in contrast Araujo et al. (2017) and Gray et al. (2009), parent material as well. And while the impact of parent material on SOC-content is still up for debate, Leon and Gonzales do raise an important argument for inclusion of additional data in LOI carbon measurements, although, the question of how these measurements will translate into feasible practice, remains.

The recent research of Meng et al. (2022) is rather technical, as it lays down interesting hypotheses for remote sensing carbon contents. Through the fusion of temporal-spatial-spectral data with a deep learning algorithm, accuracy of the SOC prediction process could be improved. This might still be far from finding its way into common field-studies, but it does point into an interesting direction.

Singh et al. (2012) researched through which sampling design the high spatial variability of SOC can be counterbalanced to a standard error below 2Mg C/ha to 30cm depth. What makes this study especially interesting is that the authors then, after finding a fitting sampling design, proceeded to calculate the cost of implementation. They concluded on a cost of $2500 AUD to estimate carbon stocks for one hectare, with a standard error below 2t/ha, at a depth of 0-30cm. Regardless of differences between Australia and Europe, this paints a clear image of the current challenges in SOC sampling.

In 2006 authors Skejmstad et al. compared two different carbon-measuring methods, namely the particulate organic carbon (POC) method and the 333 mM KmnO4 method. The found the POC method to be more sensitive to rapid carbon loss under management or land-use change (mO), but both methods showed difficulties when charcoal was present in the soil.

5.8. Potential differences in SOC between organic and conventional farming

Four practices have been selected to represent the most important differences between the two approaches to agriculture. These practices have been covered in the previous evaluations. Additional literature (listed in table 9) was collected via the same selection process (see chapter 3).

i. Crop rotation: while both approaches use crop rotations, in practice they often heavily differ. While conventional agriculture can rely on chemical fertilization to ensure sufficient nutrient supply, organic agriculture often depends on the introduction of inter- and cover crops such as legumes and grass-clover mixtures to the rotation (Zhang et al., 2022). The expected impact on SOM and therefor SOC is high.

ii. Synthetic fertilization: In organic agriculture, use of synthetic fertilizer is forbidden. The resulting difference in plant nutrient management between organic and conventional agriculture naturally express themselves in plant- and root growth, microbial activity, and overall biomass production, thus, resulting in differences in SOC build up and retention (Eze et al., 2014; Zhon et al., 2015).

iii. Pest management: Pest management strongly differs between the two approaches. While pesticides, fungicides and herbicides are being used in conventional agriculture, organic agriculture relies mostly on mechanic pest control, with a few exceptions. Since there is broad evidence of the impact of tillage on SOC (Dupla et al., 2022), the approach to pest management presents an interesting point for discussion.

iv. Livestock management: Differences in livestock management between the two forms of land management can have a significant impact on SOC stocks, especially grazing density and manure and slurry application (McSherry and Ritchie, 2013).

Reduction of chemical input presents a common challenge for farmers converting from conventional to organic agriculture. Since the soils are often low in SOM, they often depend on external input, which causes lower yields when transitioning to a more extensively managed farming system. Through well thought-out, permanent increase of OM, through increased manure or compost application and integration of perennial grasses or trees into the system for example, can soils then be regenerated to return to a fertile state.

6. Conclusion

A broad range of measures included in this study have been selected to represent the current status quo of practice and research. As such, the following can be concluded for each of the 8 discussion points.

1) Extensification: The different extensification methods provide tools with mixed influence on the SOC content of agricultural land. Practices such as grazing intensity, cutting frequency and conversion of cropland to grassland only yield significant increases under very specific conditions and at partially very high risks, which must both be precisely determined beforehand. Considering the status-quo of the current sampling and laboratory costs, this might not be feasible enough for farmers operating an agricultural business.

2) Cover- and intercropping: There is almost unison evidence of the effectivity of cover- and intercrops for building SOC stocks. Inclusion of cover crops into the rotation might almost be considered a must when striving for sustainable agriculture. Aside their high potential for increasing SOC, cover- and intercrops bring a variety of beneficial ecosystem services.

3) Erosion control: Erosion appears to be an almost underestimated threat to our soils and therefore SOC stocks. Measures to combat soil erosion can always be recommended, but taking a closer look revealed that they can have strong additional benefits, such as the effective build-up of OC. Permanent plant cover is one of the most named practices to both reduce erosion and increase SOC stocks. Introducing windbreaks and hedgerows into a farming system provides another win-win strategy, with high benefits, especially in the long run.

4) Tillage: Soil management is one of the most important management factors of farming, which shows in the ongoing debate between conventional, reduced and no tillage. An increasing number of papers shows that no-till can have a positive effect on building SOC stocks, but there are still plenty of opposing opinions. A lot of additional parameters (such as climate, weed management, relief, etc.) must be considered when deciding on tillage technique. Other factors, such as long-term effects on the soil's microbiome might yet be underestimated.

5) Fertilization and soil melioration: The use of mineral fertilizer to drive carbon sequestration by plant growth is under debate. While its application certainly has its benefits, its costs elsewhere must be considered. The use of organic fertilizers and amendments (manure, compost, etc.), especially from the farm itself, are always recommended. Circling lost OC back into the system presents an important part of sustainable farming.

   Biochar: The recent increase in the organic amendment caused a rise of research around this group of materials, with the majority producing positive results. While not all questions are answered yet, it seems as if biochar provides an important addition to organic amendments that can be used to increase a soils carbon and thereby its health and fertility.

6) Agroforestry: Agroforestry presented as seemingly innovative farming system, is nothing further than that, as it is simply the approach to close the gap between the ultimate succession of an ecosystem, the forest, and anthropogenically created

cropland. The scientific consensus is that forests hold highest carbon stocks, hence making the approximation of our agricultural systems to it a clear recommendation. Besides that, there is a variety of additional benefits derived from adapting agroforestry systems, many of which will likely play a crucial role in the adaptation of agriculture to the changing climate.

7) Detection methods for long-term carbon storage: The detection of carbon is an interesting topic and highly relevant, as technologies such as remote sensing and algorithms advance. The proven methods like LOI combined with equal soil mass method remain important and high feasibility is key. However, great care when interpreting results of field tests and experiments is advised, as uncertainties arise predominantly from sampling.

8) Potential differences in SOC between organic and conventional farming: A comparison between the two approaches to farming is difficult, as it would have to include a large number of parameters to be accurate. Yet, it must be pointed out that organic agriculture is based on maintaining fertile soils with high OM content. A lot of their management practices indirectly aim at increasing SOC, such as the use of compost and manure or well-thought-out crop rotations with cover- and intercrops.

There is an abundance of research on soil organic carbon and how humans can influence and manage it to their advantage. And while many questions remain, the importance of further understanding carbon dynamics in agricultural soils is clear. Especially when it comes to the fusion of agriculture and the carbon market, where accurate and highly qualitative data is needed to ensure that the right efforts are being rewarded.

6.1. Future research questions

To conclude, some of the most interesting, unanswered questions and impulses that resulted from this study will be listed to create a base for future research.

1) Extensification of cropland: While often being named as an efficient measure to build up SOC stocks, the reality of converting arable, intensively managed cropland into extensive grass- or pastureland is rather difficult. Future research must consider practical aspects such as the feasibility for the farmer in the short and mid-term (0-10 years), additional arguments - including economic feasibility - for such transitions must be found and strengthened.

2) Cover- and intercropping: The positive effects of cover- and intercrops appear to be scientific and even agricultural consensus. Future research questions could be formulated around the topic of plant-to-plant and plant-to-soil interactions. The doors to understanding allelopathy have only just been opened.

3) Erosion control: Unfortunately, there appears to be a severe underestimation (especially in political context) of the threat that erosion presents. Future research could focus on underlining the true cost of soil degradation and loss, which by far outweighs the cost of adapting additional erosion control measures, such as hedges. This might help formulate driving arguments for the political debate.

4) Tillage: It appears a relatively underestimated aspect in the conventional or no-till debate is the MO response to different tillage methods. Often tillage effects are discussed in a short-term context, while development of a balanced microbiome might take years (especially if recovering form agrochemical usage).

5) Fertilization and soil melioration: Research on biochar often voices concerns on the production and availability of the charcoal. Future studies on how to integrate biochar production into regional energy networks are needed.

6) Agroforestry: Another topic with sheer endless potential for future research. The agroforestry method silvopasture – the combination of forestry systems with livestock management – appears in dire need of further research, through which the method can be optimized in its environmental impact. Livestock management is a hot topic in the climate change debate, the need for adapted, future-proof management methods is high.

7) Detection methods for long-term carbon storage: The potential in future research on soil carbon in this category is definitively very high. From the development of easy-to-use in field tests, that are affordable and can be used as a measuring tool for the farmer to track his soils carbon status, to innovative remote-sensing technology and extremely precise laboratory measurement-methods, there is an abundance of research questions waiting to be answered.

8) Potential differences in SOC between organic and conventional farming: Like tillage, the overall soil health and microbiome seems too often be overlooked. Especially in the long-term, organic agriculture could produce superior results, even in questions of productivity, when including the reduced needs for external input, such as fertilizers and pesticides. Since the comparison of the two agricultural management forms is complex, difficult and highly political, objective and precise further research will be of great value.

The need for further research around soil organic carbon becomes obvious after reading only a few papers. After concluding this study, it is almost impossible to only name a few topics for future research questions, as the list could easily go on. There is an incredibly dense network of directly and indirectly intertwined interactions between the different ways humans interact with soil and therefor carbon. To entangle this network often only produces more pathways, leading to different outcomes, not yet understood. But however we research and interpret, it has become undeniably clear that the underlying goal of all these measures described in the study above can and should ultimately be seen in a context of maintaining and increasing the soil organic carbon pool, not only because it mitigates greenhouse gas effects on the changing climate, but because it essentially provides the foundation for human life: fertile and healthy soils.

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