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Benefits and drawbacks of selected carbon farming actions

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D.1.3 Benefits and drawbacks of selected carbon farming actions



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PARTNER IN CHARGE (AUTHORS)	CREA: Roberta Farina, Silvia Vanino, Mariangela Diacono, Valentina Baratella, Ulderico Neri, Alessandro Persiani (CREA), Orson Acosta, Laura Rubio, Irene Parisi (Azolla), Daniel Monteleone, Gerry Lawson (EURAF), Carlos Alberto Torres Guerrero
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Executive summary

Objectives

Carbon farming refers to a set of agricultural practices designed to enhance the sequestration of carbon dioxide (CO₂) in the soil, plants and biomass. The primary objective is to increase the storage of carbon while simultaneously reducing greenhouse gas emissions, thereby contributing to climate change mitigation.

Benefits of Carbon Farming Actions

Carbon farming encompasses a variety of practices aimed at sequestering carbon and reducing greenhouse gas emissions in agricultural systems. The benefits of these practices include:

- **Improved Soil Health** Carbon-rich soils enhance soil structure and fertility, leading to higher crop yields and reduced erosion risks. Healthier soils retain water better, which can increase irrigation efficiency and lower costs associated with water use. Moreover, the reduced or no use of pesticides improves the quality of the food.
- **Biodiversity Support.** Practices such as agroforestry and cover cropping promote beneficial microorganisms and create habitats for wildlife, thereby supporting biodiversity [2][5].
- **Revenue Generation** Farmers can earn additional income by selling carbon credits generated from their carbon sequestration efforts. This provides a new revenue stream that can help diversify income sources beyond traditional agricultural markets [3][4].
- **Reduced Input Costs.** Enhanced soil health can decrease reliance on chemical fertilizers and irrigation, resulting in significant long-term cost savings for farmers [2][3].
- **Climate Resilience.** By improving soil quality and water retention, carbon farming practices can enhance farm resilience to climate-related challenges such as droughts and floods [1][2].

Drawbacks of Carbon Farming Actions

Despite the potential benefits, carbon farming also presents several challenges and drawbacks:

- **Farmers knowledge and skill to be improved:** farmers have to learn new way of cultivate and to create these skills is not easy and is an important drawback.
- **Initial Investment Costs.** Transitioning to carbon-smart practices often requires upfront investments in new equipment and training. This financial burden can be particularly challenging for smallholders.
- **Non-Permanence of Sequestration.** The carbon stored in soils can be released back into the atmosphere if farming practices change or if the measures are not continuously maintained. This impermanence raises concerns about the long-term effectiveness of carbon farming.
- **Measurement Challenges.** Accurate monitoring, reporting, and verification (MRV) of carbon sequestration is complex and costly. This poses a significant barrier for both farmers and funding organizations looking to support these initiatives.



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- **Land use conflict.** Some carbon farming techniques, such as agroforestry or cover cropping, require dedicating land that could otherwise be used for conventional crops, potentially diminishing short-term yields.
- **Fairness Issues.** The potential for increased income from carbon credits may disproportionately benefit farmers with degraded soils that have more capacity for carbon sequestration. Conversely, those who have already implemented sustainable practices may see less financial reward despite their contributions to carbon storage.

In summary, while carbon farming offers significant environmental benefits and economic opportunities for farmers, it also involves substantial challenges that must be addressed to ensure its effectiveness and sustainability.



Section 1: General concepts and definitions

1. Introduction

The Mediterranean climate includes all Countries which overlook the Mediterranean basin and other regions of the planet such as Southern Australia, South Africa (Cape province), Southern California, northwestern of Mexico, and parts of Chile.

The Mediterranean region is one of the most climate-sensitive areas in the world, experiencing significant and diverse impacts from climate change. Its unique geography, characterized by a mix of coastal areas, islands, and mountainous terrain, makes it particularly vulnerable to environmental and socio-economic disruptions.

Mediterranean regions, many of which exhibit semiarid characteristics (i.e. a ratio of average annual precipitation (P) to potential evapotranspiration (PET) of less than 0.65 and an annual precipitation of less than 600 mm) are particularly vulnerable to soil degradation and desertification due to their climatic conditions, including long dry summers and variable rainfall. These factors, threaten agricultural productivity, leading to lower crop yields, soil degradation, and water scarcity, which are particularly critical in an already water-stressed region. Additionally, climate change fosters the spread of pests and diseases, further endangering food security and farmers' livelihoods. Small-scale farmers, who form the backbone of Mediterranean agriculture, are especially vulnerable due to limited access to financial and technological resources for adaptation. Combined with unsustainable agricultural practices, have led to significant losses in soil organic carbon (SOC) and overall soil health. In this context, regenerative agriculture (RA) and agroforestry, which encompass various carbon farming practices, are emerging as effective solutions to address these issues.

The Regenerative Agriculture paradigm is gaining increasing attention from land managers and policymakers for its potential to simultaneously mitigate climate change and restore degraded soils by sequestering soil organic carbon through improved management practices (Moyer., 2020; Newton et al., 2020; Giller et al., 2021).

Nowadays, no scientific nor legal definition of regenerative agriculture (RA) exists. However, there is a consensus on the main characteristics and features.

Particularly, in Carbon Farming Med project, we defined the regenerative agriculture “... as an adaptive farming approach applying practically proven and science-based practices, focused on soil and crop health aimed at yield resilience and a positive impact on carbon, water, and biodiversity.”



A pivotal concept is that soil conservation is the entry point to regenerate and contribute to multiple ecosystem services (Schreefel et al., 2020), including Carbon farming. Hence RA is aimed at restoring and improving the health of ecosystems, particularly soil, while simultaneously enhancing crop productivity, biodiversity, and resilience to climate change. It emphasizes principles that work in harmony with nature to create sustainable and regenerative systems (Newton et al., 2020).

RA is based on practices such as crop diversification, cover cropping, reduced tillage, and organic amendments, which enhance soil structure, increase SOC, and improve water retention. Agroforestry, that can be considered as a regenerative agriculture practice, integrates trees and shrubs with crops and/or livestock systems, offering additional benefits such as product diversification, shade, windbreaks, biodiversity conservation, and enhanced carbon sequestration.

Carbon farming, which focuses on maximizing carbon sequestration and minimizing greenhouse gas emissions in agricultural systems, offers an additional framework that aligns environmental needs with economic incentives through carbon credit markets.

These approaches are particularly relevant in Mediterranean regions, where degraded soils, water scarcity, and rising temperatures pose significant threats to agricultural sustainability and ecosystem resilience.

Moreover, given the vulnerability of Mediterranean soils to climate change, land-use changes, and desertification, the adoption of carbon farming practices through regenerative agriculture and agroforestry could transform the region into a significant carbon sink, offering ecological and economic benefits through contributions to carbon credit markets.

The objective of this report is to focus on the Mediterranean regions and its agriculture to explore which practices of carbon farming can be realistically implemented by regenerative agriculture and agroforestry management to understand the benefits and thresholds of tailored carbon farming practices on the potential of storing carbon in soils and plant.

2. Why a focus on Mediterranean regions

The Mediterranean climate is characterised by winter rain and summer drought which has given rise to a distinctive type of agriculture.

The climatic peculiar features for Mediterranean regions are (Fig. 1):



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-Hot, dry summers and mild, wet winters, leading to a strong seasonal water deficit during the growing season. Farmers rely heavily on drought-resistant crops and water management strategies, when it comes to summer crops.

-Rainfall is often erratic, with a high likelihood of both droughts and intense rainfall events, which can lead to soil erosion. This variability necessitates practices that improve water retention and reduce runoff. The variability of rainfall pattern has been recently exacerbated by climate change (Luppichini et al., 2022, Todaro et al., 2022)

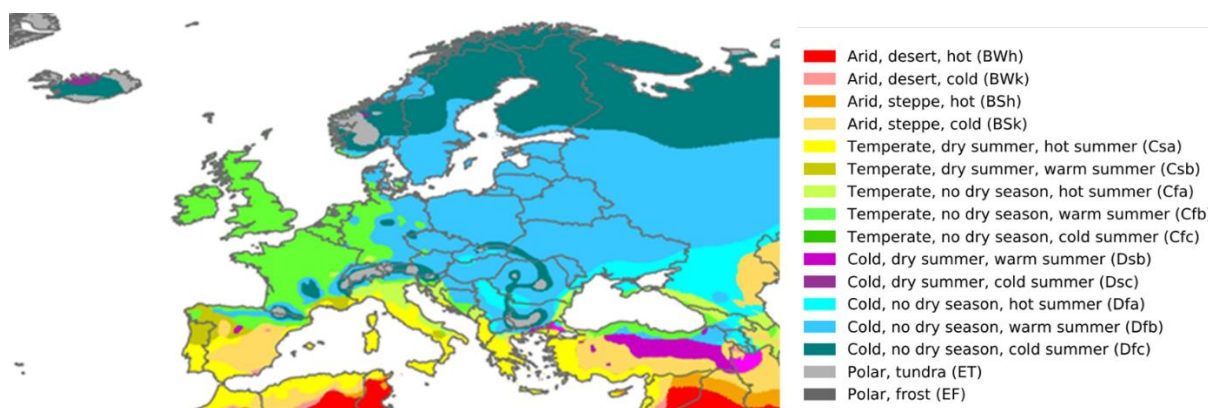


Fig. 1 Köppen-Geiger climate map and legend.

(Source Wikipedia)

A diverse range of crops is cultivated, reflecting the richness of the agricultural landscape. In rainfed areas, winter cereals such as wheat, oats, and barley dominate, shaping the region's traditional farming practices.



Fig. 2 A traditional Mediterranean landscape (Tuscany, Italy)

Photo from Roberta Farina's personal agriculture collection.



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Additionally, citrus fruits, vines, olives, almonds, and figs are distinctive and enduring features of these landscapes, contributing to their cultural and ecological significance (Fig. 2).

In irrigated areas, the focus shifts to intensive agricultural practices. These include the cultivation of summer annual crops and a wide variety of vegetables, which play a vital role in local and regional food systems. Orchards, vines and olives, often irrigated for part or the entire vegetative cycle, further enhance the agricultural diversity and productivity, making irrigated lands an essential component of the agricultural mosaic.

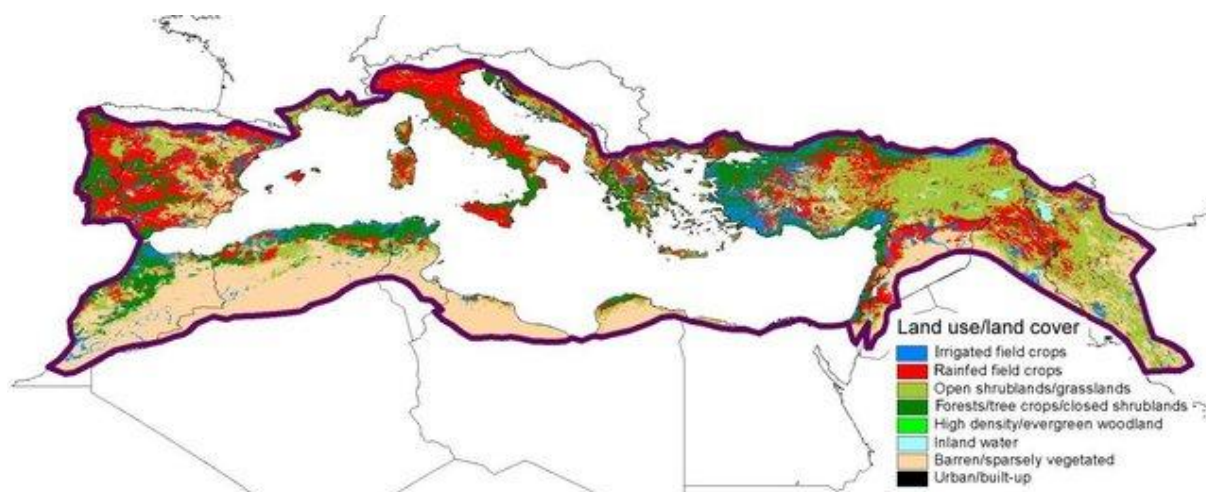


Fig. 3 Land use and land cover in the Mediterranean Basin

From Ryan et al., 2006.

Even agricultural practices in the Mediterranean reflect the soil-climate features of these region. Such practices can be summarised in:

-Drought-Resistant Crops

Traditional crops include olives, grapes, figs, almonds, and cereals like wheat and barley. These crops are well-suited to the region's dry conditions and thrive with minimal water input.

-Mixed Farming Systems

The integration of crops, livestock, and agroforestry is common, creating diversified systems that maximize resource use and minimize risk. Livestock grazing in olive groves or vineyards is a typical example.

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-Terracing

To combat soil erosion on the steep slope's characteristic of the Mediterranean landscape, farmers have traditionally built terraces. These structures reduce runoff, conserve soil, and improve water infiltration.

-Dryland Farming

-In areas with limited irrigation, dryland farming techniques such as fallowing, crop rotation, and the use of drought-resistant cultivars are prevalent.

-Water Management

Given the scarcity of water, irrigation systems like drip irrigation are widely used to optimize water use efficiency. Rainwater harvesting and the use of reservoirs are also traditional practices.

-Polyculture

Growing multiple crops together, such as olive trees with legumes or cereals, is a common practice that enhances biodiversity, improves soil health and reduces pest pressures.

-Agroforestry

Silvopastoral systems with widely spaced trees like holm oak and cork oak in pastureland are common in the Mediterranean. Silvoarable systems involve rows of timber or multi-purpose trees with alleys of annual crops between them and Permanent crop agroforestry involves orchards and fruit trees like olives and carobs are interspersed with crops or grazing lands. They combine ecological and economic benefits, and improve carbon sequestration, soil stability and microclimatic conditions.

-Low-Input Farming

The region has a strong tradition of organic and low input farming practices, relying on compost, green manures, and reduced chemical usage to maintain soil fertility and health.

-Cultural and Historical Influence

The Mediterranean region has a rich agricultural heritage shaped by millennia of farming. Traditional practices, such as communal grazing and knowledge of local crop varieties, have been passed down through generations, creating a strong link between cultural identity and agricultural systems.



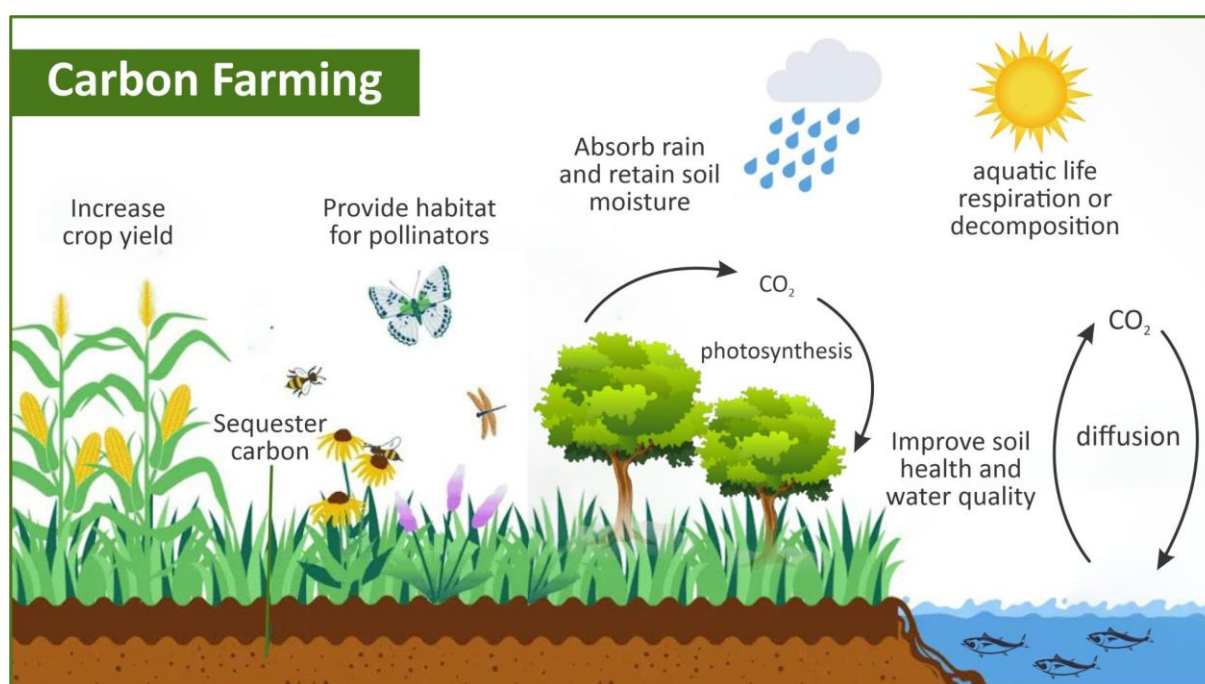
3. Carbon farming actions in regenerative agriculture for Mediterranean climates

RA represents a paradigm shift in modern farming, focusing on ecological restoration while maintaining or improving agricultural productivity. Central to its framework is the concept of enhancing soil health, an approach that not only ensures sustainable food production but also contributes significantly to carbon sequestration, a critical component in mitigating climate change.

RA, unlikely other practices proposed to reduce the overall impact of agriculture, refer to a suite of practices that should be pursued together to ensure good results with a holistic view.

The key element of regenerative practices is the soil organic carbon (SOC) enrichment. By implementing strategies such as reduced tillage, cover cropping, and diverse crop rotations, farmers can increase the organic matter in soils. This process enhances the soil's physical structure, water retention capacity, and microbial activity, creating a self-reinforcing system that boosts soil fertility and resilience. These same practices reduce the rate at which carbon stored in soil is lost to the atmosphere through erosion or oxidation, effectively transforming agricultural soils into a long-term carbon sink.

Carbon farming takes a targeted approach to transform agricultural systems to carbon capture and storage systems.



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Fig. 4 A schematic representation of Carbon Farming.

Source: <https://plutusias.com/carbon-farming/>

Practices in carbon farming are designed to optimize the balance of carbon fluxes, ensuring that more carbon is drawn from the atmosphere via photosynthesis than is released back into it (C removals). This is achieved through mechanisms such as:

- Agroforestry and Silvo-pasture. Integrating trees with crops and grazing systems increases carbon storage above and below ground. Trees act as long-term carbon reservoirs, while their root systems enhance soil carbon deposition.
- Perennial Cropping Systems. Deep-rooted perennial plants not only stabilize soils but also contribute to carbon storage in subsurface layers, where it is less susceptible to release.
- Biochar. Adding biochar—a stable, carbon-rich product derived from biomass—directly to soils provides an immediate boost to soil carbon content and improves soil health properties over time.
- Use of organic fertilisers and amendments: they increase the carbon content of the soil and improves soil health properties over time as the biochar.
- Managed Grazing. Strategic rotational grazing supports grass regrowth, allowing for higher rates of photosynthesis and carbon capture in grassland ecosystems.
- Minimizing External Inputs. Reducing the reliance on synthetic fertilizers, pesticides, and herbicides helps to maintain natural ecosystem processes and reduce environmental harm.
- Optimising water flux. Strategies like mulching, cover crops, and maintaining permanent vegetation enhance water retention, reduce erosion, and improve watershed health

The benefits of these practices extend beyond carbon storage. By improving soil organic matter, they increase agricultural resilience to climate extremes such as droughts and floods. Enhanced soil biology fosters nutrient cycling, reducing the dependence on synthetic fertilizers and decreasing nitrous oxide emissions, a potent greenhouse gas.

Research suggests that widespread adoption of regenerative agriculture could sequester significant amounts of atmospheric CO₂ annually while simultaneously enhancing global food security. By aligning agricultural practices with natural processes, RA and carbon farming represent a scientifically grounded, systems-level approach to addressing some of the most pressing environmental challenges of our time.



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In the following sections of the document, a selection of the individual practices of carbon farming will be presented, focusing on their potential applications in the Mediterranean environment, their associated benefits, and their limitations, with a specific emphasis on their relevance to regenerative agriculture.

Each practice will be systematically organized into the following categories: Definition, Description, Application, Mediterranean Examples, Benefits, Drawbacks, and Carbon Farming Potential.

Furthermore, the carbon sequestration potential of each practice will be analysed and reported in detail.



Section 2: An overview of the effect of the single practices in the context of carbon farming

1. Cover Cropping

1.1. Definition

A cover crop is usually but not exclusively, a non-cash crop grown primarily to protect and improve the quality of soil between periods of regular crop production. Unlike traditional crops grown for harvest, cover crops are used to maintain and regenerate soil health, prevent erosion, enhance water retention, improve microbiological and macrofauna functions and suppress weeds.

1.2 Description

Integrating cover crops into cropping systems offers a wide range of benefits, specifically: (i) reducing the risk of nitrate leaching by acting as a catch crop, scavenging excess nitrogen from the soil through the fibrous root systems of grass species (Thorup-Kristensen et al., 2003); (ii) fixing atmospheric nitrogen when legume species are used (Tittarelli et al., 2018); enhancing soil mycorrhizal activity, which improves nutrient cycling and soil health (Kabir et al., 2000); (iv) increasing soil organic carbon (SOC) stocks and regulating soil temperature (Farina et al., 2018); (v) promoting pest control through natural biological interactions (Bale et al., 2008) and suppressing weeds (Ciaccia et al. 2016); and (vi) reducing soil erosion and runoff by stabilizing the soil surface (De Baets et al., 2011, Blanco-Canqui et al., 2008)

Cover crops, especially as living mulch, significantly improve field accessibility after heavy rainfall, which is crucial for farmers, as it allows for timely interventions, such as plant protection treatments.

Moreover, certain benefits are directly related to cover crop biomass production. For instance, leguminous species are particularly effective at fixing nitrogen in the soil, while grasses (gramineous species) produce substantial biomass, with persistent residues that decompose slowly. Their fine, fibrous root systems improve soil structure and contribute significant amounts of carbon to the root zone. Brassicas, on the other hand, offer advantages in weed and pest control through the release of allelochemicals into the soil and by alleviating soil compaction with their deep and distinctive root systems, which also increase water infiltration.

However, no single species can provide all the desired benefits simultaneously. As such, cover crop mixtures are often employed to leverage the diverse advantages of multiple species (Chapagain et al., 2020). This approach maximizes the ecological and agronomic benefits of cover crops, making them a versatile tool in sustainable agriculture.



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As for the termination strategy, cover crops are mainly incorporated into soil as green manure, but there are indications that terminate cover crops using a roller crimper improves weed control in some no-till grain production systems (Delate et al., 2012), but also for vegetable production (Montemurro et al., 2013). The persistence on soil of the flattened material modifies soil temperature and water content and can potentially affect soil organic matter mineralization (Farina et al., 2018).



Fig. 5 Examples of intercropping or cover crops.

Photo from Roberta Farina Diverfarming's project

1.3 Type of cover crops

a) Temporary Cover Crops

These are typically sown during the rainy season (fall to early spring) between two consecutive cash crops and are terminated in early spring to prevent competition for water with main crops. This method allows for the cover crop to regrow from seeds produced during the previous year, optimizing soil cover during critical periods (Kaspar and Singer., 2011). In Mediterranean rainfed cereal-based systems, often, the cover crops can be cultivated only replacing cash crops, unless practices such as inter-seeding are applied (see below) due to the scarcity of water during the summer fallow period.

b) Living mulch

Living mulch, is a cover crop intercropped with a cash crop and maintained as a living ground cover throughout the growth cycle, particularly used/tested in horticultural cropping systems (Montemurro et al., 2020) and orchards (Hammermeister A.M., 2016)

c) Permanent Cover Crops

Involves maintaining vegetation throughout the year, although it may be dormant during drought or cold periods. This can include perennial herbaceous plants or annuals that self-seed or rely on species naturally growing or regrowing (Blanco-Canqui & Lal, 2008). In Mediterranean climates the natural cover is mainly composed by annual plants.

d) Alternate Cover Crops

Mainly used in dryland vineyards, cover crops are established in every other lane, allowing for different management practices in adjacent lanes, often alternating between bare soil and cover crops over time. This practice is common in viticulture in Central Italy (Vanino et al., 2024).

1.4 Selection of cover crops species

When selecting cover crops, key factors to consider include biomass production, consistency of growth, soil nitrogen contribution, and water use. It is unlikely that a single cover crop will meet all desired functions. The 'ideal' species or mix depends on location and yearly conditions. To make informed decisions, other farmers' experience or on-farm strip trials are valuable resources.

General criteria for the selection of the cover crops include the following aspects:

- a. Main crop: avoiding cover crop species that might negatively interact with main crops (for allelopathy reasons) than can affect plant development or yields.
- b. Crop rotation design: it is important to insert the cover crop in the right position
- c. Growing cycle period
- d. Soil type
- e. Agronomic and technical potential of the farm
- f. Main agroecological functions to tackle maintenance/increase soil organic matter, N source for the following cash crop, biodiversity protection, weed control, biomass production, improvement of soil structure and erosion reduction, pest control.

Table A1 in Annex 1 provides a list of species, their place in rotation, main agroecological role and potential for carbon sequestration.

1.5 Seeding Methods

a) Timing

In Mediterranean regions, the optimal time for sowing cover crops is generally in the fall before the onset of winter rains (Soriano et al. 2023).



b) Seeding Techniques

Utilizing no-till or minimal tillage methods is encouraged to preserve soil moisture and structure. However, in presence of heavy soils (high clay and silt content) a tillage intervention, preferably without layers inversion, might be required. Rolling before sowing can facilitate better seed-soil contact, especially for small seeds (Citation).

c) Seed Rate

Adjusting seed rates is crucial for achieving strong crop emergence and effective competition against weeds. In a mixture with gramine and legumes, it is important to balance the C/N ratio of plant C inputs to soil ($C/N > 12$) to avoid excessive soil organic matter mineralisation if the objective is to increase soil C storage (citation).

1.6 Management Practices

a) Termination

Terminating cover crops by boot or early-pod stage allows to capture high root biomass. Roots are an important source for building soil carbon in the long term, Therefore, cover crops are typically terminated in early spring. In RA chemical control (desiccation), that is often used in conventional agriculture, is avoided given the negative impact on the environment and on soil biodiversity. But it remains the unsolved the challenge of combining no-till to no-chemical cover crops/weeds termination. One of the most interesting and feasible solution is the possibility to use a specialized equipment like the roller-crimper that terminates the crop leaving in place the aboveground plant residues as mulch on the soil surface (Fig.4). However, a high percentage of soil skeleton or exposed rock, poor soil cover, or excessive plant growth can make the roller crimper technique very difficult to apply. For some species and climates, the cover crop will die automatically when temperature start to increase/decrease and rainfall diminish. Farina et al. (2018) showed that using barley as cover crop in a horticulture system (melon was the cash crop), the roller crimper was less efficient than the green manure after 1 year in terms of carbon accumulation in soil,, but anyway at the end of the second year much of the organic C derived from barley was degraded, no matter the termination technique. Mazzoncini et al., (2011) reported an increase of carbon by 7% with no-legume cover crops and 11% with legume cover crops after 15 years.



Fig. 6 Roller crimper (on the left) and vegetation lodged after the passage of the equipment (on the right side).

Photo from Roberta Farina's personal agriculture collection.

b) Residue Management

Leaving cover crop residues on the surface until the next fall helps improve soil organic matter and moisture retention. This practice also improve erosion control during heavy rainfall events and reduces soil water evaporation.

c) Mixing cover crops

Farmers can seed pure (100%) legume cover crops if high amounts of N are needed in a short term as for vegetable crops, or pure grasses in case of low N requirement of the next crop and/or, in climatic conditions with high potential risk of nitrate leaching. Conversely, sowing a mixture of different proportions of legume and non-legume cover crops can determine intermediate scenarios, fine-tuning the N dynamic in the soil-plant system (Canali et al., 2015). Incorporating a mix of grasses, legumes, and crucifers can enhance biodiversity, improve soil conditions, and provide habitat for beneficial organisms (citation).

d) Grazing cover crops

In mixed farming cover crops can be grazed at some time of their development or at the end of the cycle. Grazing can provide a positive return.

Integrating livestock with cover crops benefits long-term soil health. Grazing animals' urine, manure, and saliva stimulate soil biology, mimicking natural ecosystems. Early results suggest

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grazing cover crops, especially with high biomass, may rapidly boost soil organic matter, though more research is needed (SARE, 2019)

1.7 Benefits and drawbacks of Cover Crops

Table 1 Summary of benefits and drawbacks of cover crops

Benefits	Drawbacks
Increased Organic Matter. They add biomass to the soil, boosting its organic content over time.	Cost of seeds. Purchasing seeds for cover crops can increase expenses, especially for small farms.
Improved Soil Structure. Cover crops enhance soil aeration and aggregation, reducing compaction and making it more suitable for plant growth.	Additional Labor. Planting and managing cover crops require time and labour, which can impact and stress farm resources.
Reduced Soil Erosion. Cover crops protect the soil surface from wind and water erosion by providing a vegetative cover.	Opportunity Costs. The land used for cover crops is not producing cash crops, which may affect short-term profitability
Disruption of Pest Cycles. Cover crops can break pest cycles by interrupting their host plant availability.	Pest and Disease Risks. Cover crops can serve as hosts for pests and diseases that might affect subsequent cash crops.
Natural Weed Control. Cover crops can outcompete weeds for resources and release allelopathic chemicals that inhibit weed germination.	Weed Management. Improper management may lead to certain cover crops acting as weeds or harbouring weed seeds.
Nutrient Cycling. Some cover crops (e.g., legumes) fix atmospheric nitrogen, reducing the need for synthetic fertilizers.	Nutrient availability. Decomposing cover crops can temporarily immobilize nitrogen or other nutrients, causing nutrient deficiencies for subsequent crops. Beware of the C/N ratio for C sequestration purposes.
Improved Water Retention. Their root systems enhance the soil's water-holding capacity, benefiting subsequent crops.	Water Usage. In water-scarce regions, cover crops may compete for soil moisture needed by the primary crops. Soil humidity is increased and in humid regions and seasons this can favour disease infections and spreading

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Attracting Beneficial Insects. Some cover crops provide habitat and food for beneficial insects, reducing pest pressure on cash crops.	
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1.8 Costs

Table 2 Costs for implementing cover crop in the farm

Type of costs	Cost (€/ha) (Costs are taken by agricultural contractors' price list)	How to reduce costs/negative impacts
Seeds	Variable: from 30 to 300	Producing seeds in the farm
Mechanical operations		
Primary tillage	$\cong$ 200 -300 (€/ha) ploughing $\cong$ 100 (€/ha) minimum tillage $\cong$ 200 (€/ha) minimum tillage +seeding	Optimising tillage operations, application of minimum tillage
Secondary tillage	$\cong$ 177-208 (€/ha) harrowing $\cong$ 150 (€/ha) milling	Reduce passes, use efficient equipment
Seeding	$\cong$ 100 (€/ha) $\cong$ 200 (€/ha) with combined machinery $\cong$ 130 (€/ha) sod seeding	Proper planning and calibration
Termination	From 80 (€/ha)	Minimise operations, leave biomass on the field

Source: http://caiaagromec.it/sites/unima.it/files/tariffari/tariffario_24-25_web.pdf



2. Soil tillage and cultivation

2.1 Definition

Tillage refers to the agricultural practice of preparing the soil for planting or growing crops. It involves mechanical manipulation of soil using tools or machinery to achieve various purposes, such as: enhance aeration and water infiltration, controlling weeds by uprooting them or burying their seeds, incorporating organic matter, fertilizers, or lime into the soil

Tillage can be classified into different types based on depth, purpose, or timing, such as:

- a) Primary Tillage: Breaks up compact soil and creates a rough surface (e.g., ploughing).
- b) Secondary Tillage: Follows primary tillage and creates a finer seedbed (e.g., harrowing).
- c) Conservation Tillage: Minimizes soil disturbance to reduce erosion and preserve moisture (e.g., no-till or reduced-till methods).

2.2 Description

Soil tillage has long been a fundament of agronomic practices, evolving over centuries to improve its efficiency. Tillage involves mechanical soil interventions designed to enhance conditions for crop growth. The primary aim is to create, restore, or sustain optimal soil conditions for plant roots by modifying various soil properties, particularly structure. Key tillage objectives include:

- Preparing a seedbed suited to seed burial and germination or the establishment of reproductive organs for cultivated plants.
- Promoting structural conditions for root penetration and efficient function.
- Enhancing soil permeability, controlling water flow, and reducing water stagnation, surface runoff, and erosion.
- Increasing the volume of soil explored by roots, which enhances water storage as a usable reserve, assisting plants during dry periods.
- Managing spontaneous vegetation and pests and disrupting capillary effects.
- Incorporating fertilizers and crop residues into the soil.

However, traditional tillage techniques can have significant drawbacks, such as:

- Compaction beneath the ploughing layer, impeding water and root penetration.
- Accelerated mineralization of organic matter, which speeds up nutrient recycling but compromises soil structure in organic matter-poor soils.
- Mixing soil layers, which is beneficial in some cases but harmful in others.
- Increased soil erosion due to water and wind.
- Over-deep burial of crop residues with deep ploughing (Toderi and Bonari, 1986).



D.1.3 Benefits and drawbacks of selected carbon farming actions

- Excessive use of non-renewable energy.

To address these issues, alternative methods have emerged:

- a) Minimum Tillage: Reduces mechanical intervention to the bare minimum, mitigating negative effects and conserving energy while maintaining suitable conditions for seed germination. This can be achieved through methods like disc harrowing, milling, or scarifying the surface layer before sowing.
- b) No Tillage ("Zero Tillage"): Avoids soil manipulation entirely, with seeds sown directly on untouched soil, including established grass.

The effectiveness of tillage techniques is influenced by soil characteristics, climate, and local conditions. Over time, it has become clear that excessive tillage, particularly deep ploughing, leads to a decline in soil organic matter (SOM), which impacts soil structure, water retention, and biodiversity (Lopez-Bellido et al., 2010; West and Post, 2002). Soil compaction further complicates water percolation and root growth, presenting a significant challenge. To counteract these negative effects, conservation agriculture (CA) practices, including no-tillage (NT), permanent organic soil cover, and crop diversification, have gained traction worldwide, particularly in Mediterranean climates (Kassam et al., 2022).

The adoption of NT is motivated by its benefits, such as reduced labour, fuel costs, and time savings, alongside its ability to maintain productivity. NT practices have demonstrated positive effects on soil health, such as improved soil organic carbon (SOC) preservation (Farina et al., 2024), enhanced water retention (Castellini et al., 2019), and better soil aggregation (Hernanz et al., 2002). Furthermore, these practices minimize disruptions to soil biological and biochemical processes, fostering healthier soil ecosystems (Farina et al., 2024).

However, NT systems face challenges, particularly with weed control. The absence of tillage alters weed dynamics, often leading to increased herbicide use to prevent crop yield losses (Nichols et al., 2015).

In NT systems, the persistence of organic matter, particularly organic carbon, is influenced by microbial access and interactions with soil minerals. The conservation of SOC in NT is attributed to reduced turnover of macroaggregates and the formation of stable microaggregates, where carbon remains sequestered for longer periods (Six et al., 1999; 2000). Long-term experiments are preferred for evaluating the impact of tillage on SOC trends, as the effects manifest gradually.

In Mediterranean rainfed regions, such as Italy, the decline in SOC, exacerbated by intensive farming and climate change, has led to a growing interest in NT practices. Efforts to assess NT's effects on SOC and soil biological properties have become a priority in these regions (Vanino et al., 2022).



In conclusion, while tillage remains a fundamental practice in agriculture, evolving towards more sustainable techniques like minimum and no-tillage methods is essential for preserving soil health, reducing erosion, and enhancing water retention. These approaches contribute to both environmental sustainability and long-term agricultural productivity.

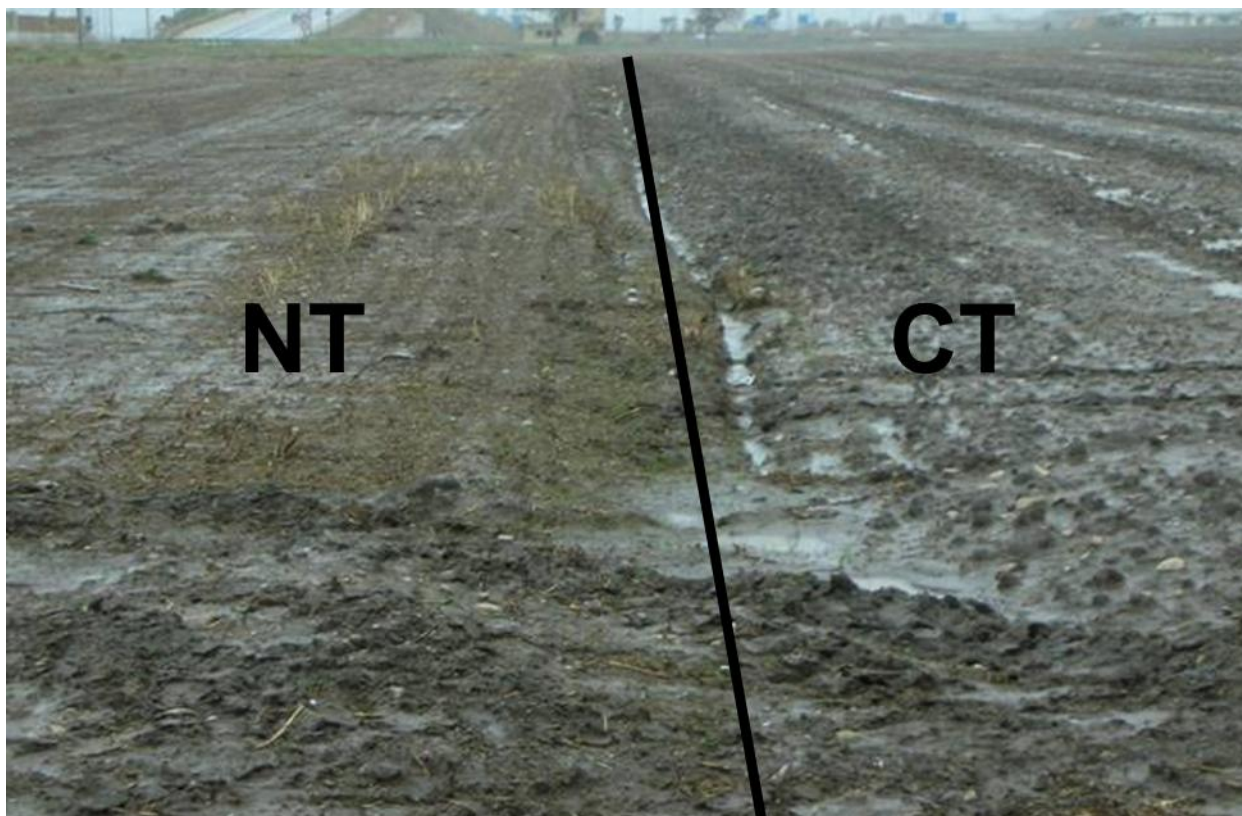


Fig. 7 Soil under conventional and no tillage (CT and NT) after an intense rainfall.

Photo from Roberta Farina's personal agriculture collection.

However, no tillage is not recommended as sole practice in soils prone to compaction and should be coupled with other sustainable management practices such as compost addition or cover crops and mulching thus it can be effective for SOC sequestration and stabilization over time (Fernandez-Soler, 2024).

2.3 Benefits and drawbacks of soil tillage

Table 3 Summary of benefits and drawback of soil tillage

	Benefits	Drawbacks
Conventional tillage	Weed control: disrupt weed growth	Soil erosion: in bare soils there is an increase of water and wind erosion
	Soil aeration: improves root penetration and microbial activity soon after the operation	Compaction: tillage can create a hardpan layer beneath the tillage depth
	Seedbed Preparation: Smooth, uniform soil for planting.	Moisture loss: tillage increase soil evaporation
	Pest management: can reduce some soil-born pests	Cost and Energy: Requires significant fuel, labour, and equipment
		Organic Matter Depletion: Speeds up breakdown of soil carbon with CO ₂ release.
		Change of soil microbiota composition favouring bacteria against fungi.
Minimum tillage	Preserves Soil Structure: Avoids disrupting natural layers, maintaining soil health.	Weed Control: Requires chemical or alternative methods as mechanical weed control is limited.
	Reduces Erosion: Disturbance is limited, minimizing soil vulnerability.	Specialized Equipment: Often necessitates tools like chisel plows or vertical tillage machines.
	Improved Water Retention: Less disruption leads to better infiltration and retention.	Potential for Compaction: Some areas may still compact if not managed carefully.
	Lower Costs: Requires less energy and fuel than traditional tillage.	Residue Management: Surface residues can complicate planting or harbour pests.
	Organic Matter Protection: Maintains residue on the soil surface to enhance fertility.	Biodiversity: Negative effect on biodiversity, since it decreases the presence of fungi, especially in permanent crops
No tillage	Erosion Control: Protects topsoil from water and wind erosion.	Weed Pressure: Often relies on herbicides.

D.1.3 Benefits and drawbacks of selected carbon farming actions

	Enhances Soil Health: Promotes long-term fertility and organic matter buildup.	Initial Investment: Requires specialized no-till seeders and training, not just for machinery use but also for crop cycle and calendar changes.
	Water Retention: Crop residues reduce evaporation and improve infiltration.	Residue Issues: Excess surface residues may harbour pests or hinder operations.
	Cost Efficiency: Lower fuel and labour requirements.	Long-Term Transition: Initial years may register variable yield outcomes before full benefits are realized.
	Biodiversity Support: Encourages diverse soil life and ecosystems.	

Table 4 Comparison between tillage, minimum tillage and no tillage in terms of environmental/agronomic effects

Environmental and agronomic effect	Tillage (with layers inversion)	Minimum tillage (20 cm, no layer inversion)	No tillage
Soil disturbance	High	Low	None
Erosion protection	None	Moderate	High
Moisture retention	Low	Moderate	High
Organic matter	Depletes	Maintains	Increase
Weed control	Mechanical (effective)	Partial (manual/chemical)	Low
Cost	High	Moderate	Low



3. Crop rotation and diversification

3.1 Definition

Crop rotation involves sequentially growing different plant species on the same land parcel in either a fixed or flexible order (Farina et al., 2018). Agronomically, it optimizes positive interactions and synergies between crops by managing crop succession. This traditional practice has been integral to agricultural diversification since the onset of intensive farming. Early observations revealed that continuous monocropping reduced yields. Following the Green Revolution, the extensive use of fertilizers and pesticides diminished the perceived benefits of rotation. However, as Karlen et al. (1994) emphasized, “...no amount of chemical fertilizer or pesticide can fully compensate for crop rotation effects.” Today, crop rotation is recognized as a cornerstone of sustainable farming. It helps reduce external inputs, disrupt pest cycles, prevent herbicide-resistant weeds, and enhance overall system resilience (Altieri et al., 2015). Rotations vary regionally, tailored to specific pedoclimatic and socio-economic conditions (Bruns, 2012). Diversification practices, can be successful adopted in regenerative agriculture, including also multi-cropping and intercropping. Multi-cropping entails growing two or more crops sequentially on the same field within a year or season.



Fig. 8 Examples of diversified Mediterranean crop mosaic landscape.

Photo from Roberta Farina's personal agriculture collection.

3.2 Description

Crop rotation increases yield and profit and allows for sustained production. Enhancing ecological (e.g., genetic and varietal), temporal and spatial diversity in cropping systems can improve crop productivity and resource use efficiency (Persiani et al, 2024). Crop rotation with legumes not only increases the cropping intensity but also increases the total food availability and the net return from selling it. The use of a legume cover in crop rotation can provide a substantial amount of nitrogen (N) to a succeeding crop. Crop rotation with species diversification contributes to the control of pests, diseases and weeds and improves soil fertility and conservation, which can lead to increased profitability in grain production systems (Fig. 3.1).

Agronomy traditionally distinguishes crops into 2 types, which must normally be alternated in order to apply an effective rotation:

- Improving crops: they improve soil fertility. These crops can improve the physical fertility of soil thanks to deep root systems (Brassicaceae) and/or the need for organic fertilization. There are also short cycle leguminous plants, which fix nitrogen.
- Worsening crops: they leave the soil in worse physical-chemical conditions than they found it, as they reduce the organic matter and nutrients present. This class normally includes winter cereals.

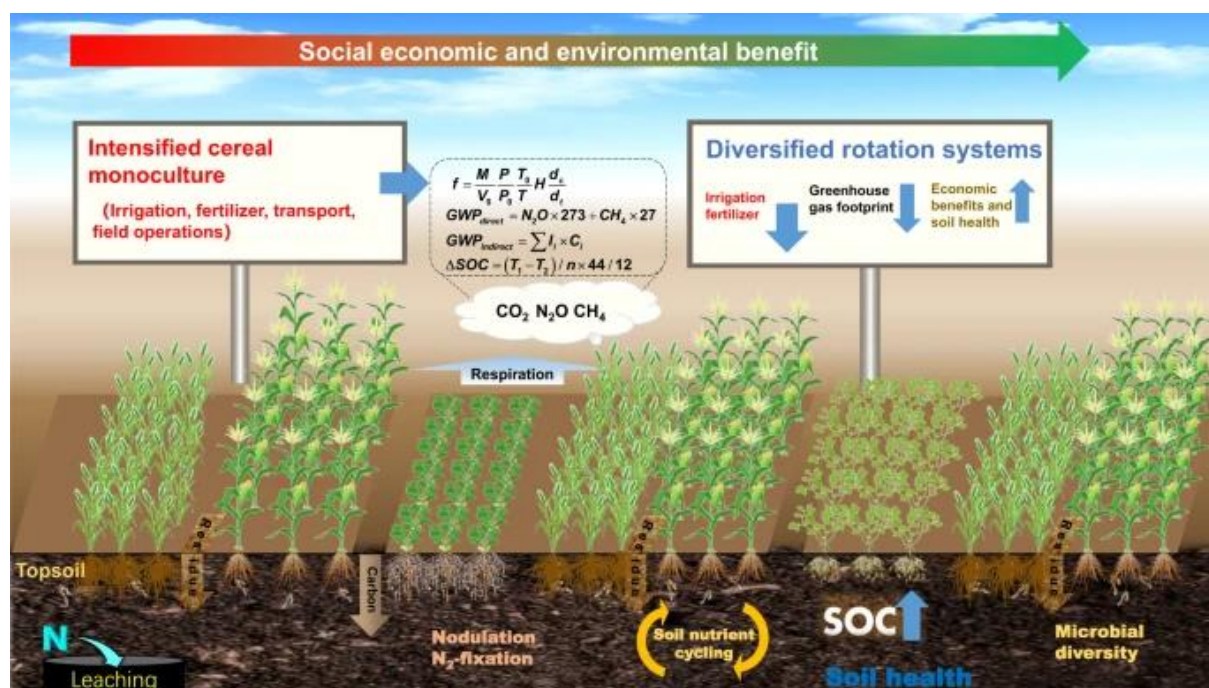
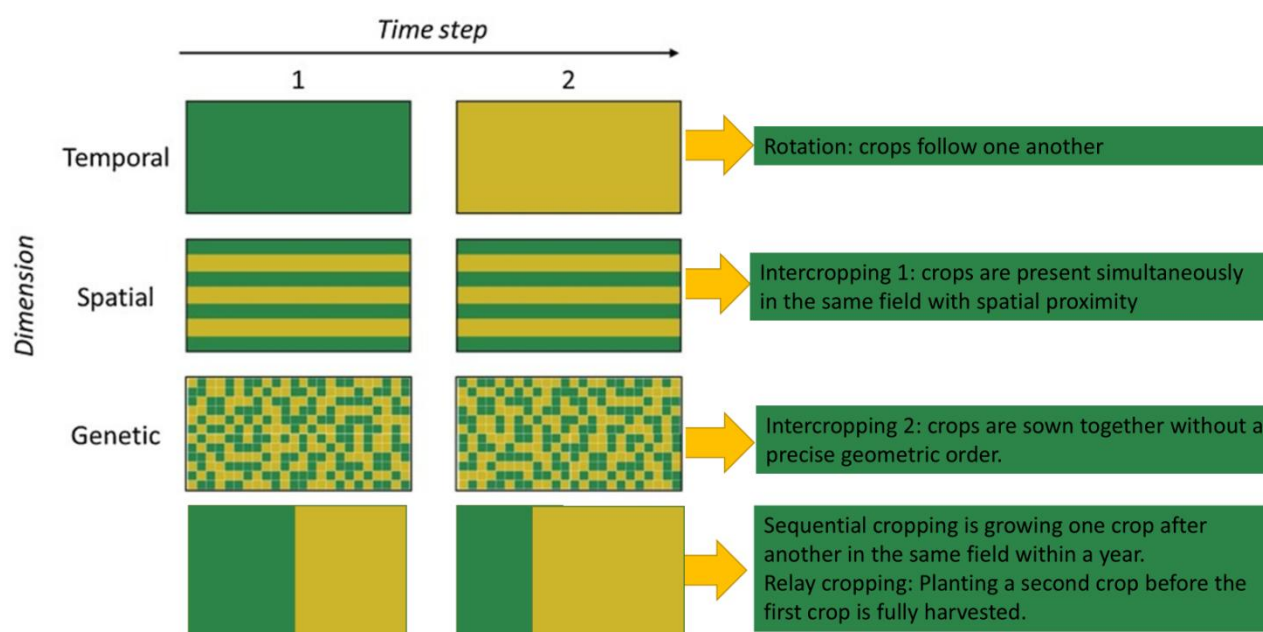


Fig. 9 Social economic and environmental benefits of crop diversification.

Source: Yang et al., 2024.

3.3 Crop rotations for regenerative farming

Crop rotations are normally adapted based on the farm feasibility to cultivate each crop/species considering the following factors: pedoclimatic conditions, farm machinery, attitude of the farmer, market requirement. In dryland cereal-based Mediterranean systems, representing often 50% of the agricultural area for Mediterranean countries, the selection of the crop to be included in a rotation is more difficult due to the pedoclimatic limitation. So, often, the farmers are discouraged to move from monoculture to a more resilient rotation. The strategy of including grain legumes (faba bean, beans, lentils, chickpea) and deep -root crops (i.e. sugar beet) should be considered, also for the expansion of the relative markets and interest. Possible alternative to the common annual (durum or winter) wheat is the use of perennial grains, a grain crop that lives and remains productive for two or more years, thus developing a notable root apparatus, that can contribute to a large extent to carbon sequestration to soil (DeHaan et al, 2023). Another crop that is gaining attention is buckwheat that can break the cereal monoculture. Intercropping systems vary widely, including strip cropping, alley cropping, mixed cropping, and windbreaks, each offering unique spatial arrangements and benefits (Pelzer et al., 2012). Intercropping involves growing multiple crops (annual or perennial) simultaneously on the same field for significant periods, each developing according to its growth patterns. Intercrops can be mixed entirely or arranged in rows or strips (Fig. 10).



9

Fig. 10. Schematic view of the differences between rotation and intercropping, considering the different dimension at which they act.

Adapted from Ditzler et al., 2021



Grass–legume intercrops, common in natural ecosystems, are valued for improving hay quality. Good experience of intercropping of cereals with legumes, considering the rapid growth of the legume in autumn and the slower but inexorable growth of wheat up to the interception of all lights, reducing the competition, can be a good strategy. Historically prevalent in tropical regions, intercropping has seen a resurgence in developed countries for reducing external inputs and better utilizing resources. Organic farming particularly benefits from its weed and disease suppression potential. In Mediterranean region, for the already mentioned scarcity of water during the late spring-summer season, multi cropping where, unlike intercropping, plants are cultivated one at a time, introducing temporal crop diversification, requires irrigation. If irrigation is available, the choice of crops to be inserted in the rotation is wide and includes all the horticultural crops.

3.4 Benefits and drawbacks of rotation and diversification

Table 5 Summary of benefits and drawbacks of crop rotation and diversification.

Benefits	Drawbacks
Improves soil health and fertility	As the number of species in rotation increase, requires complex management and planning
Breaks pest and disease cycles	May involve less profitable crops in the rotation
Supresses weeds through cover crops	Requires skilled labour and careful monitoring
Enhances biodiversity in soil and aboveground ecosystems	Tailoring rotations to regional conditions can be challenging
Optimizes nutrient and water use across cycles	Transition from monocropping can incur in higher costs
Reduces reliance on synthetic inputs, supporting sustainability	Potential short-term yield could decline during transition
Can increase the stock of carbon in soils	
Optimise the use of work and machinery within the farm	
Biodiversity Support: Encourages diverse soil life and ecosystems.	

4. Organic Inputs

4.1 Definition

Organic inputs are natural substances derived from living organisms or their by-products, used in agriculture to enhance soil fertility, improve crop growth, and support sustainable farming practices. These inputs can be classified into two main categories:

-Organic Fertilizers:

These provide essential nutrients (nitrogen, phosphorus, potassium, etc.) directly to plants for their growth. Examples include compost (repeated application), manure, bone meal, and fish emulsion. Organic fertilizers release nutrients slowly, ensuring long-term soil health and minimizing environmental harm (citation).

-Organic Soil Amendments:

These improve the physical, chemical, and biological properties of the soil, rather than serving as a direct source of plant nutrients. Common examples are biochar, green manure, crop residues, and different kinds of compost. Organic amendments long-lasting application help enhance soil structure, soil organic carbon and enzymatic activity, water retention, aeration, and microbial activity.

The following types of organic fertilizers are allowed in Europe (Regulation (EU) 2019/1009):

a) Manure and Compost

- Manure (from cattle, pigs, sheep, horses, poultry, etc.)
- Compost from organic waste (from separate collection, free of contaminants)
- Vermicompost (produced with earthworms)

b) Plant-Based Fertilizers

- Peat (though restricted due to environmental concerns)
- Crop residues and agro-industrial by-products (e.g., husks, grape pomace, olive pomace)
- Seaweed-based fertilizers

c) Fertilizers from Animal By-Products (Reg. EC 1069/2009)

- Bone and blood meal
- Processed manure and digestates
- Bat guano or seabird guano

d) Digestates from Biogas

- Separated liquid or solid digestate from biogas plants processing agricultural by-products

e) e) . Processed Livestock Effluents



- Treated slurry and livestock effluents (e.g., solid-liquid separation, composting)

All these fertilizers must comply with contaminant limits (heavy metals, pathogens) and can be used in conventional agriculture. For organic farming, they must follow Regulation (EU) 2018/848, which has stricter restrictions on certain fertilizers. Indeed, under organic farming the organic fertilizers and soil management include only natural and organic fertilizers such as:

- Compost, manure, and digestate (processed according to EU hygiene rules).
- Plant-based fertilizers (e.g., seaweed, green manure).
- Animal by-products (e.g., bone meal, blood meal), but only from organic livestock).

4.2 Description

Unlike synthetic fertilizers, which provide an immediate supply of nutrients, organic fertilizers must be broken down by soil microbes before plants can absorb them. This ensures a gradual and sustained nutrient supply. The following processes are taking place in the soil:

-Microbial decomposition: Soil bacteria and fungi break down organic matter into plant-available nutrients.

-Nutrient mineralization: Organic nitrogen (N) is converted into ammonium (NH_4^+) and nitrate (NO_3^-), which plants can absorb.

-Long-lasting effects: Organic fertilizers provide nutrients over weeks or months rather than a quick but short-lived boost.

For this reason, the application of these type of fertilisers, that can harm the environment if over applied or if might not fulfil the nutrients need of the crops, should be very careful.

4.3 Application

Applying organic fertilizers in regenerative agriculture requires a strategic approach to enhance soil health, improve nutrient cycling, and increase long-term productivity. Here are the key factors to consider:

a) Type of Organic Fertilizer

-Compost: Improves soil structure, microbial activity, and nutrient availability.

-Manure: Provides nitrogen, phosphorus, and potassium; requires proper composting to prevent pathogen risks.

- Green Manure & Cover Crops: Fix nitrogen, add organic matter, and prevent soil erosion.

- Biofertilizers : Enhance microbial activity and nutrient solubilization.

- Bone Meal, Fish Emulsion, and Seaweed Extracts: Provide slow-release nutrients and micronutrients.

b) Soil Conditions



D.1.3 Benefits and drawbacks of selected carbon farming actions

- Conduct a soil test to determine nutrient deficiencies and pH levels.
- Ensure proper soil texture and structure for optimal microbial activity.
- Improve soil organic matter to increase nutrient retention and reduce leaching.

c) Application Methods

- Surface Application: Works well for cover crops and compost but can lead to nutrient volatilization.
- Incorporation into Soil: Enhances microbial decomposition and nutrient uptake but can disturb soil life.
- Mulching: Helps retain moisture, reduce erosion, and gradually release nutrients.
- Liquid Application (Teas & Extracts): Provides a quick nutrient boost and enhances microbial diversity.

d) Timing of Application

Depends on the type of fertiliser.

- Apply in late summer or early autumn to allow the release of nutrients during the growing season, to match plant nutrient demand.
- Avoid application before heavy rains to prevent nutrient leaching and runoff.
- Use split applications for better nutrient absorption and reduced losses.

e) Crop Needs & Rotation

- Adapt fertilization to crop-specific nutrient demands.
- Integrate crop rotation and intercropping to optimize nutrient use efficiency.
- Combine organic fertilizers with cover crops to fix nitrogen and protect the soil.

f) Microbial Activity & Soil Biology

- Maintain a diverse soil microbiome to enhance nutrient cycling.
- Avoid excessive tillage to protect mycorrhizal fungi and beneficial bacteria.

Table 6 Summary of benefits and drawbacks of organic inputs

Benefits				Drawbacks
Improves	Soil	Health	–	Slower Nutrient Release – May not provide
Enhances	soil	structure,		immediate results, as decomposition takes
increases	microbial	activity,		time.
	and boosts	long-term	fertility.	



D.1.3 Benefits and drawbacks of selected carbon farming actions

Reduces reliance on synthetic chemicals and promotes a circular economy by recycling organic waste.	Variable Nutrient Content – Nutrient composition can be inconsistent compared to synthetic fertilisers.
Provides a steady supply of nutrients, reducing the risk of leaching and nutrient runoff.	Bulkier and More Expensive to Transport – Requires larger quantities to achieve similar nutrient levels as chemical fertilisers.
Improves the soil's ability to retain moisture, which benefits plant growth.	Lower Nutrient Concentration – Generally contains lower concentrations of essential nutrients (e.g., nitrogen, phosphorus, potassium) than synthetic options.
Lowers the risk of chemical accumulation in soil and prevents environmental pollution.	Organic fertilisers can be more expensive and less available than synthetic alternatives.
Encourages beneficial soil organisms, such as earthworms and mycorrhizal fungi.	Potential for Pathogens and Weeds – Poorly composted organic matter can introduce weed seeds or harmful pathogens.

TIPS to avoid the trade-offs associated with organic amendments in soil

-Proper Timing of Application: Apply organic amendments at times when soil microbial activity is optimal, such as during warm, dry conditions, to reduce the risk of excess nitrogen release.

-Incorporate Amendments with Soil: Mixing organic amendments into the soil rather than leaving them on the surface can help reduce nitrogen loss through volatilization and encourage more controlled nitrogen cycling.

-Balance Carbon-to-Nitrogen Ratio: Choose amendments with a balanced C:N ratio (e.g., composted manure) to avoid excessive nitrogen mineralization, which can lead to higher N₂O emissions.

-Use of Cover Crops: Plant cover crops to absorb excess nitrogen and prevent leaching, thus improving nitrogen retention in the soil.

-Monitor Soil Moisture: Ensure proper drainage and avoid waterlogged conditions, as excess moisture can enhance denitrification and N₂O emissions.

-Tailored Amendment Selection: Choose organic amendments based on the specific soil needs, ensuring that the nutrient release rates align with crop demand and avoid surplus nitrogen.

-Regular Soil Testing: Monitor nutrient levels to prevent over-application and ensure that organic amendments are being used efficiently.



5. Irrigation Management

5.1 Definition

Irrigation refers to the artificial application of water to agricultural lands to supplement low and irregular rainfall, ensuring stable crop production in a climate characterized by hot, dry summers and mild, wet winters. The disparity between water demand in summer and precipitation in Mediterranean regions is very well explained by the fig. 11, where both precipitation and temperature are reported.

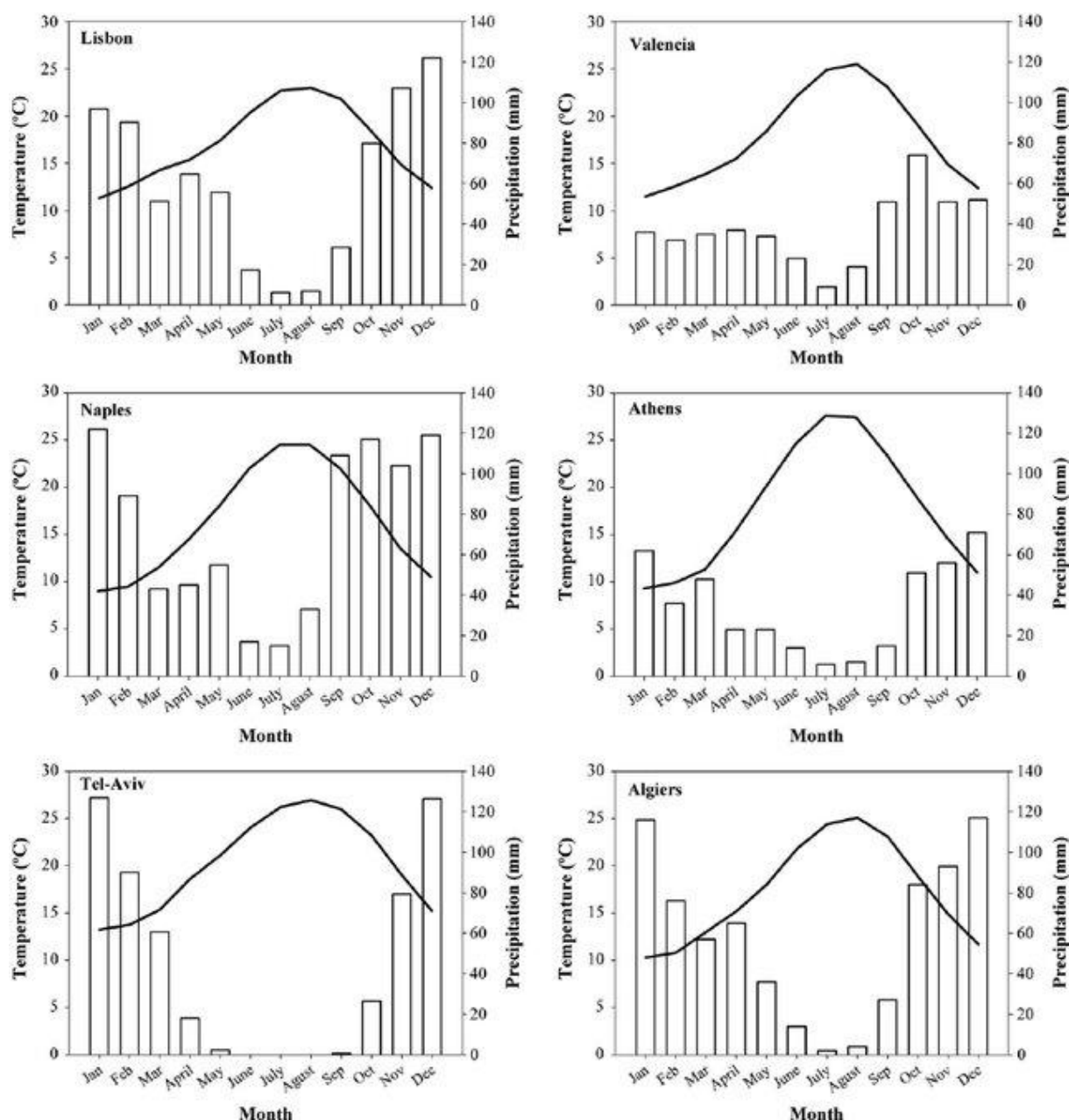


Fig. 11 Average monthly temperature and rainfall in six mediterranean sites

Source: García-Ruiz et al., 2013.

For this reason, in Mediterranean regions water supply is essential for cultivating summer crops and is often used in tree crops to ensure a good level of productivity (olive groves, vineyards, etc.).

5.2 Description

Irrigation is required when natural precipitation and soil moisture are insufficient to meet the water needs of crops. This need is assessed through the hydrological balance, which considers the inputs and outputs of water in the soil-plant-atmosphere system.

The hydrological balance equation can be expressed as:

$$P+I=ET+R+D+ \Delta S$$

where:

P = Precipitation (rainfall)

I= Irrigation applied

ET = Evapotranspiration (sum of plant transpiration and soil evaporation)

R = Surface runoff

D = Deep percolation (water lost below the root zone)

ΔS = Change in soil moisture storage

Irrigation is needed when the available soil moisture (ΔS) is insufficient to meet crop evapotranspiration demands (ETET), particularly during dry periods.

5.3 Application

Irrigation methods vary depending on water availability, soil type, and crop requirements. The main types of irrigation include:

- a) Surface Irrigation – Water is distributed over the soil by gravity, including furrow, basin, and border irrigation.
- b) Sprinkler Irrigation – Water is sprayed over crops using pressurized systems that mimic natural rainfall.
- c) Drip Irrigation – A highly efficient method where water is delivered directly to plant roots through a network of tubes and emitters, reducing waste.
- d) Subsurface Irrigation – Water is applied below the soil surface to reach plant roots with minimal evaporation.

Application in Mediterranean climate requires careful considerations of key irrigation factors including:



D.1.3 Benefits and drawbacks of selected carbon farming actions

- **Water Conservation:** due to water scarcity, efficient irrigation techniques like drip irrigation and deficit irrigation (applying water only during critical growth stages) are commonly used.
- **Soil Management:** maintaining soil moisture retention through mulching, cover crops, and organic amendments helps optimize irrigation efficiency.
- **Climate Adaptation:** selecting drought-resistant crops and adjusting irrigation schedules based on evapotranspiration rates ensures sustainability.
- **Use of Alternative Water Sources:** treated wastewater, desalinated water, and rainwater harvesting are increasingly integrated into irrigation systems

5.4 Benefits and drawbacks of irrigation management

Table 7 Summary of benefits and drawbacks of irrigation management

Aspect	Benefits	Drawbacks
Water Availability	Ensures crop growth during dry seasons	High dependence on limited water resources
Crop Yield	Increases productivity and economic returns	Over-irrigation can lead to waterlogging or salinization
Soil Health	Supports soil moisture balance and microbial activity	Risk of soil degradation and erosion if mismanaged
Climate Adaptation	Mitigates drought impacts on agriculture	High energy costs for water extraction and distribution
Water Efficiency	Can be optimized with modern irrigation techniques	Traditional methods may cause excessive water loss
Environmental Impact	Enables year-round farming in arid areas	Can deplete groundwater and affect natural ecosystems
Infrastructure Needs	Advanced systems improve water management	Requires investment in infrastructure and maintenance



6. Agroforestry

6.1 Definition

Agroforestry is an ancient land-use system in Europe. It is estimated to cover around 15.4 million ha, which is equivalent to 3.6% of the EU territorial area and 8.8% of the utilised agricultural area (Burgess, et al., 2018). The European Agroforestry Federation recognises nine different types of agroforestry, with a major distinction between agricultural land and forest land and between silvopastoral and silvo-arable systems. (Table 6.1)

Table. 6.1 The EURAF Agroforestry Typology (EURAF Policy Briefing #1)

Tree location	Agroforestry System	Agroforestry Practice	
		Agricultural Land	Forest Land
Trees inside parcels	Silvopastoral agroforestry	1 Wood pasture	10 Forest grazing
	Silvoarable agroforestry	2 Alley cropping 3 Alley coppice 4 Food forests	4 Food forests
	Permanent crop agroforestry	5 Orchard cropping, 6 Orchard grazing.	
	Agro-silvo-pasture	7 Agro-silvo-pasture	
Trees between parcels	Tree Landscape Features (protected by CAP Conditionality Rules)	8 Woody-landscape-features	
Trees in settlements	Urban agroforestry	9. Settlement agroforestry	

Agroforestation is not just tree planting in agricultural parcels. It involves intercrop management, ploughing, pruning, pollarding, thinning, mulching, and other management practices and proper design to increase yields and reduce above- and below-ground competition. It is a form of ecological intensification inspired by agroecological practices, which provides a safety net for nitrates, an aerial filter for ammonia, pesticides, and particulates, and a carbon pump to increase soil organic matter at depth—essential in conventional farming systems. It brings environmental and climate benefits and protects animals and crops from temperature extremes.

Carbon farming and agroforestry are interconnected in that they both aim to enhance carbon net removals. Agroforestry integrates trees and shrubs into agricultural systems, which increases carbon storage in vegetation and soil. This practice supports carbon farming by capturing more atmospheric CO₂, thus helping mitigate climate change while also improving farm productivity and biodiversity (EURAF, 2025) EURAF Policy Briefing #8 provides an



indication of the potential contribution of agroforestry to climate targets in the EU, and [Policy Briefing #20](#) includes a discussion on issues related to Monitoring Reporting and Verification of carbon certification projects.

The environmental advantages of agroforestry are outlined in the Brno Agroforestry Declaration ([EURAF, 2024](#)), and EURAF has published a recent vision document outlining the need for an emergency programme of new agroforestry planting and of restoration of old and often degraded agroforestry systems ([EURAF, 2024](#)).

7. Carbon removal potential

7.1 Cover crop

Cover cropping is a key strategy to increase net primary productivity (NPP) and provide high-quality plant residues for soil organic matter (SOM) formation. However, cover crop impacts on soil C stocks vary based on management practices and environmental conditions.

Overall, cover crops significantly increased soil C stocks by 12% -15.5%, providing an additional 1.11 – 1.54 Mg C ha⁻¹yr⁻¹ compared to no cover crops (McClelland et al, 2020, <https://doi.org/10.1002/eap.2278>). In woody crops, studies reported higher C fixation values for native species when compared to sowed cover crops. Cover crop mixture can produce more biomass than monocultures at intermediate N rates. The most influential factors include type of cover crop, cash crop type, soil texture planting and termination dates (growing window), annual biomass production, and soil clay content (Jian et al., 2020, <https://doi.org/10.1016/j.soilbio.2020.107735>). Vicente -Vicente et al. (2016) and Aguilera et al., (2013) after a meta-analysis, reported an increase of carbon after cover crop ranging from 0.5 to 7.3 Mg C ha⁻¹ yr⁻¹.

7.2 Soil tillage

Higher SOC levels in non-tilled soils compared to conventionally tilled soils have been frequently documented, particularly in semi-arid and Mediterranean climates. In the semi-arid region, a significant 58% increase in SOC content was reported at a depth of 0–10 cm after 10 years of NT, along with an overall 25% increase. In Italy an approximately 53% increase in SOC content under NT over a 22-year period in the 0–10 cm soil layer was observed with SOC accumulation in NT 10% higher than conventional tillage, highlighting its benefits for long-term SOC enhancement.

An extensive analysis (179 dataset) of literature reported an average increase of SOC of 0.43 Mg C ha⁻¹ yr⁻¹ and 0.32 under no tillage and minimum tillage respectively (Aguilera et al., 2013)



7.3 Rotation and diversification

Climate, soil texture and agronomic factors are the main drivers of SOC response to crop rotation. At global scale the crop rotation increased SOC content on average from 6 to 8% compared to monocropping, with the highest values registered in temperate climates (Liu et al., 2022, Zheng et al., 2023).

The figures on carbon sequestration potential are extremely variable and dependent from the type of crops inserted in rotation, they productivity, the residues treatment, and so on.

7.4 Organic inputs

Farina et al. (2018) investigated organic horticulture systems two years after compost application and found that soil organic carbon (SOC) stocks increased in all plots. The increase was +2.3 Mg C ha⁻¹ for plots receiving 15 Mg of compost and +4.9 Mg C ha⁻¹ for those receiving 30 Mg of compost. Similarly, Aguilera et al. (2013) conducted a comprehensive analysis of studies on Mediterranean soils and reported a significantly higher rate of carbon sequestration in average (1.34 Mg C ha⁻¹ yr⁻¹) in soils treated with organic amendments compared to those fertilized with minerals. The organic amendments category included a range of external organic matter sources, such as compost, manure, and agro-industrial residues. Organic amendments in soil can influence nitrogen (N) emissions by altering microbial activity and nutrient availability, often leading to increased nitrogen mineralization and potentially higher N₂O emissions, especially under conditions of excess moisture or poor aeration. The trade-off with organic amendments in soil lies in their ability to improve soil fertility and enhance carbon sequestration, but this benefit can be offset by the potential for increased nitrogen emissions, such as N₂O, a potent greenhouse gas, especially when nutrient cycling is not properly managed.

7.5 Irrigation

Irrigation can influence carbon sequestration in soils in several ways, both positively and negatively, depending on management practices and environmental conditions.

One positive impact is linked to improved plant growth, which leads to greater biomass production. This increases the amount of organic matter returned to the soil, potentially boosting soil carbon stocks and enhancing carbon sequestration. Irrigation can also stimulate soil microbial activity, facilitating the breakdown of organic matter and the formation of stable soil organic carbon, which contributes to long-term carbon storage.

The influence of irrigation is strongly dependent on climate and initial soil organic carbon content. In semiarid regions, irrigation has been shown to increase soil organic carbon by 11% to 35%. However, it can also lead to higher N₂O emissions, as noted in many studies (e.g., Trost et al., 2013). Therefore, in carbon farming, it is crucial to carefully assess this trade-off to ensure



that the benefits of carbon sequestration are not outweighed by the emissions of potent greenhouse gases.

7.6 Agroforestry

EURAF Policy Briefing #8, mentioned previously, reports on a wide range of European and global literature and shows that the total productivity of an agroforestry plantation ranges from 3.37 to 26.8 t CO₂/ha/yr. A recent study for the UK Woodland Trust, conducted by Cranfield University (Burgess, et al., 2022), modeled sequestration rates by the trees in two agroforestry systems (156–400 trees/ha) and predicted sequestration of 6 to 18 t CO₂/ha/yr over 30–40 years.

Taking data for poplar planted at 156 trees/ha and harvested after 30 years, using typical weather patterns for the English East Midlands, the model predicted an average annual biomass sequestration of 7.7 t CO₂/ha/yr over the rotation. Extrapolating this rate to the whole of Europe, and assuming that one million hectares of agroforestry could be planted annually from 2025 to 2050, indicates that this annual planting for 25 years could eventually provide 192 Mt CO₂/yr. The species, provenance, and clone used, along with the spacing and management, would be adapted to local climate and soil conditions and the management priorities of farmers.

8. Concluding remarks

Carbon farming applied in regenerative agriculture, and agroforestry enhances soil carbon sequestration and reduces greenhouse gas emissions through strategies such as cover cropping, no-tillage systems, crop rotation, organic amendments, irrigation management.

In summary:

- Cover Cropping: Increases soil carbon storage by 12%–15.5%, though effectiveness depends on crop type, environment, and management.

- Soil Tillage: No-tillage (NT) significantly improves SOC, particularly in semi-arid and Mediterranean climates, with recorded SOC increases of 53% over 22 years in Italy.

- Crop Rotation and Diversification: Crop rotations enhance SOC by 6%–8% compared to monocropping, with variability based on crop type and residue management.

- Organic Inputs: Compost and other organic amendments improve SOC but may increase N₂O emissions if mismanaged.

- Irrigation: Enhances plant growth and microbial activity, supporting SOC storage, though it can also increase N₂O emissions.

Benefits of Carbon Farming Actions

- Improved Soil Health: Enhances soil structure, fertility, and water retention, reducing erosion.

- Biodiversity Support: Agroforestry and diverse cropping systems create habitats and promote ecosystem resilience.

- Revenue Generation: Carbon credits offer an additional income source.

- Reduced Input Costs: Healthy soils lower reliance on fertilizers and irrigation.

- Climate Resilience: Improves adaptation to droughts and floods.

Challenges and Drawbacks

- Farmer Knowledge and Training: Transitioning to carbon farming requires new skills.

- High Initial Investment: Equipment and training costs can be barriers.

- Non-Permanence of Sequestration: SOC gains can be lost if practices are discontinued.

- Measurement Challenges: Carbon sequestration monitoring is costly and complex.

- Land Use Trade-offs: Some practices require land that could be used for food production.



-Equity Concerns: Carbon credit benefits may not be evenly distributed among farmers.

Conclusions

Implementing carbon farming practices in Mediterranean environments presents both significant opportunities and challenges. Given the region's arid and semi-arid conditions, soil carbon sequestration is inherently difficult due to high temperatures, low organic matter inputs, and frequent soil disturbances. However, regenerative agriculture and agroforestry offer viable solutions to enhance SOC (Soil Organic Carbon) storage while mitigating greenhouse gas emissions.

Key strategies such as cover cropping, no-tillage systems, crop rotation, organic amendments, and irrigation management have demonstrated measurable benefits. Cover cropping can enhance SOC by 12%–15.5%, though its effectiveness is influenced by crop selection and environmental factors. No-tillage practices are particularly promising in Mediterranean conditions, with long-term studies in Italy showing a 53% increase in SOC over 22 years. Crop diversification and rotation contribute to SOC improvements of 6%–8%, while organic amendments can significantly enhance soil fertility, albeit with the risk of increased N₂O emissions if mismanaged. Proper irrigation strategies further support carbon storage but must be balanced to minimize potential greenhouse gas emissions.

Beyond carbon sequestration, these practices improve overall soil health, enhance biodiversity, and contribute to climate resilience by increasing water retention and reducing erosion. Additionally, carbon credits present an emerging financial opportunity for farmers who adopt sustainable practices, potentially offsetting initial costs. However, the transition to carbon farming is not without challenges. High upfront investments, the need for specialized knowledge and training, the non-permanence of SOC gains, and the complexity of monitoring sequestration efforts pose significant barriers. Furthermore, land-use trade-offs and equity concerns surrounding carbon credit distribution must be addressed to ensure fair and sustainable adoption.

In conclusion, while the Mediterranean environment poses unique constraints to carbon accumulation, a well-designed carbon farming approach integrating agroecological principles can contribute to long-term soil sustainability and climate change mitigation. Future research and policy support should focus on optimizing these strategies to maximize carbon sequestration while ensuring economic and social viability for farmers in the region.



References

- Aguilera, E., Lassaletta, L., Gattinger, A., & Gimeno, B. S. (2013). Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, ecosystems & environment*, 168, 25-36. <https://doi.org/10.1016/j.agee.2013.02.003>
- Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for sustainable development*, 35(3), 869-890.
- Atangana A, Khasa D, Chang S, Degrande A. Definitions and Classification of Agroforestry Systems. In: Atangana A, Khasa D, Chang S, Degrande A, editors. *Tropical Agroforestry*. Dordrecht: Springer Netherlands; 2014. pp. 35–47.
- Bale, J. S., van Lenteren, J. C., & Bigler, F. (2008). Biological control and sustainable food production. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 761-776. <https://doi.org/10.1098/rstb.2007.2182>
- Blanco-Canqui, H., Lal, R. (2008). *Principles of Soil Conservation and Management*. Springer Science & Business Media. <https://doi.org/10.1007/978-1-4020-8709-7>
- Bruns, H. A. (2012). Concepts in crop rotations. *Agricultural Science*, 25-48.
- Burgess P., Graves A. (2022). The potential contribution of agroforestry to net zero objectives. Report for the Woodland Trust. Cranfield University; 2022 Nov. Available: <https://dspace.lib.cranfield.ac.uk/handle/1826/18664>
- Burgess PJ, Rosati A. (2018) Advances in European agroforestry: results from the AGFORWARD project. *Agrofor Syst*. 2018;92: 801–810.
- Cadillon, A., (2018). Choosing and managing cover crops in organic agricultural systems. Available at https://orgprints.org/id/eprint/30573/12/Fiches_Especes_EngraisVerts_ENG_2018.pdf, last accessed 16/12/2024
- Canali S., Diacono M., Campanelli G., Montemurro F. (2015). Organic no-till with roller crimpers: agroecosystem services and applications in organic Mediterranean vegetable productions. *Sustainable Agriculture Research* 4, No. 3: 66-75.
- Castellini, M.; Fornaro, F.; Garofalo, P.; Giglio, L.; Rinaldi, M.; Ventrella, D.; Vitti, C.; Vonella, A.V.,(2019). Effects of no-tillage and conventional tillage on physical and hydraulic properties of fine textured soils under winter wheat. *Water*, 11(3), 484. <https://doi.org/10.3390/w11030484>
- Chapagain, T., Lee, E. A., & Raizada, M. N. (2020). The potential of multi-species mixtures to diversify cover crop benefits. *Sustainability*, 12: 2058. <https://www.mdpi.com/2071-105..>
- Ciaccia, C., S. Canali, G. Campanelli, E. Testani, F. Montemurro, F. Leteo, and K. Delate (2016). Effect of roller-crimper technology on weed management in organic zucchini production in a Mediterranean climate zone. *Renewable Agriculture and Food Systems* 31 (2):11–21. doi:10.1017/S17421705150000460/12/5/2058
- Clark, S. (2014). Plant guide for bur clover (*Medicago polymorpha* L.) USDA-Natural Resources Conservation Service, Big Flats Plant Materials Center, Corning New York.
- De Baets, S., Poesen, J., Meersmans, J., & Serlet, L. (2011). Cover crops and their erosion-reducing effects during concentrated flow erosion. *CATENA*, 85(3), 237–244. <https://doi.org/10.1016/j.catena.2011.01.009>
- DeHaan, L. R., Anderson, J. A., Bajgain, P., Basche, A., Cattani, D. J., Crain, J., ... & Westerbergh, A. (2023). Discussion: Prioritize perennial grain development for sustainable food production and environmental benefits. *Science of The Total Environment*, 895, 164975.
- Delate, K., Cwach, D., & Chase, C. (2012). Organic no-tillage system effects on soybean, corn and irrigated tomato production and economic performance in Iowa, USA. *Renewable Agriculture and Food Systems*, 27(1), 49-59.



D.1.3 Benefits and drawbacks of selected carbon farming actions

Dial, H., & Wolf, M. (2020). Evaluation of Cool Season Cover Crops in Southern Arizona. United States Department of Agriculture.

Ditzler, L., Van Apeldoorn, D. F., Schulte, R. P., Tiftonell, P., Rossing, W. A. (2021). Redefining the field to mobilize three-dimensional diversity and ecosystem services on the arable farm. *European Journal of Agronomy*, 122, 126197.

Farina, R., Di Bene, C., Piccini, C., Marchetti, A., Troccoli, A., Francaviglia, R., (2018). Do Crop Rotations Improve the Adaptation of Agricultural Systems to Climate Change? A Modeling Approach to Predict the Effect of Durum Wheat-Based Rotations on Soil Organic Carbon and Nitrogen. *World Soil Resources Report No. 106. Soil Management and Climate Change: Effects on Organic Carbon, Nitrogen Dynamics, and Greenhouse Gas Emissions*, 2018, pp. 221-236

Farina, R., Piccini, C., Di Bene, C., Fornasier, F., Francaviglia, R., Pennelli, B., Vanino, S., Mario, R., Cerasuolo, M., & Troccoli, A. (2024). No tillage and leguminous cover crop improve soil quality in a typical rainfed Mediterranean system. *Canadian Journal of Soil Science*, 104(3), 257–272. <https://doi.org/10.1139/cjss-2023-0106>

Farina, R., Testani, E., Campanelli, G., Leteo, F., Napoli, R., Canali, S., Tittarelli, F. (2018). Potential carbon sequestration in a Mediterranean organic vegetable cropping system. A model approach for evaluating the effects of compost and Agro-ecological Service Crops (ASCs). *Agricultural Systems*, 2018, 162, pp. 239-248 <https://doi.org/10.1016/j.agsy.2018.02.002>

Fernández-Soler, C., García-Franco, N., Almagro, M., Díaz-Pereira, E., Luján, R., García, E., Martínez-Mena, M. (2024). Cover crops improve the long-term stabilization of soil organic carbon and total nitrogen through physico-chemical protection in rainfed semiarid Mediterranean woody crop systems. *Soil Use and Management*, 40(2), e13066.

García-Ruiz, J. M., Nadal-Romero, E., Lana-Renault, N., & Beguería, S. (2013). Erosion in Mediterranean landscapes: Changes and future challenges. *Geomorphology*, 198, 20-36.

Giller, K. E., Hijbeek, R., Andersson, J. A., & Sumberg, J. (2021). Regenerative agriculture: an agronomic perspective. *Outlook on agriculture*, 50(1), 13-25.

Hammermeister A.M., (2016). Organic weed management in perennial fruits. *Scientia Horticulturae*, 208: 28–42.

Hernanz, J.L.; López, R.; Navarrete, L.; Sanchez-Giron, V. , (2002). Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. *Soil Till Res.*, 66(2), 129-141. DOI: 10.1016/S0167-1987(02)00021-1

Ingels, C., (1994). Selecting the right cover crop gives multiple benefits. *Calif.Ag.* 48:43-48.

Ingels, C.A., R.L. Bugg, G.T. McGourty, Christensen L.P. (1998). *Cover Cropping in Vineyards: A Grower's Handbook*. University of California, Div. of Agriculture and Natural Resources.. Chapters on cover crop species, soil/water management, pest management, 12 growers. Charts of seeding rates, seed costs.

Jinshi Jian, Xuan Du, Mark S. Reiter, R. Stewart D. (2020). A meta-analysis of global cropland soil carbon changes due to cover cropping, *Soil Biology and Biochemistry*, Volume 143, 2020,107735, ISSN 0038-0717, <https://doi.org/10.1016/j.soilbio.2020.107735>.

Kabir, Z., & Koide, R. T. (2000). The effect of dandelion or a cover crop on mycorrhizal colonization and phosphorus uptake by maize in a no-till system. *Agriculture, Ecosystems & Environment*, 78(2), 167-174. [https://doi.org/10.1016/S0167-8809\(99\)00127-4](https://doi.org/10.1016/S0167-8809(99)00127-4)

Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., (1994). Crop Rotations for the 21st Century. *Adv. Agron.* 53(C), 1-45.

Kaspar, T. C., & Singer, J. W. (2011). The use of cover crops in sustainable agricultural systems. In *Sustainable Agriculture Reviews* (Vol. 5, pp. 143–164). Springer



D.1.3 Benefits and drawbacks of selected carbon farming actions

- Kassam, A., Friedrich, T., Derpsch, R. (2022). Successful experiences and lessons from conservation agriculture worldwide. *Agronomy*, 12(4), 769. <https://doi.org/10.3390/agronomy12040769>
- Leakey R. Definition of agroforestry revisited. *Agroforestry Today* (ICRAF). (1996). Available: <http://agris.fao.org/agris-search/search.do?recordID=QI9600003>
- López-Bellido, R.J.; Fontán, J.M.; López-Bellido, F.J.; López-Bellido, L. (2010). Carbon sequestration by tillage. rotation. and nitrogen fertilization in a Mediterranean Vertisol. *Agron J.*, 102(1), 310-318. <https://doi.org/10.2134/agronj2009.0165>
- Luppichini, M., Bini, M., Barsanti, M., Giannecchini, R., & Zanchetta, G. (2022). Seasonal rainfall trends of a key Mediterranean area in relation to large-scale atmospheric circulation: How does current global change affect the rainfall regime?. *Journal of Hydrology*, 612, 128233.
- Mazzoncini, M., Sapkota, T. B., Barberi, P., Antichi, D., & Risaliti, R. (2011). Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. *Soil and tillage research*, 114(2), 165-174.
- Mazzoncini, M.; Antichi, D., Di Bene, C., Risaliti, R., Petri, M., Bonari, E. (2016). Soil carbon and nitrogen changes after 28 years of no-tillage management under Mediterranean conditions. *European Journal of Agronomy*, 77, 156-165. <https://doi.org/10.1016/j.eja.2016.02.011>
- Montemurro, F., Persiani, A., & Diacono, M. (2020). Cover crop as living mulch: effects on energy flows in Mediterranean organic cropping systems. *Agronomy*, 10(5), 667.
- Montemurro, F.; Fiore, A.; Campanelli, G.; Tittarelli, F.; Ledda, L.; Canali, S. (2013) Organic fertilization, green manure, and vetch mulch to improve organic zucchini yield and quality. *HortScience* 2013, 48, 1027–1033. Natural Resources Conservation Service. PLANTS Database. United States Department of Agriculture. Accessed December 13, 2024, available at <https://plants.usda.gov>.
- Moyer, J. (2020). A time of reflection: a time for change. *Agriculture and Human Values*, 37, 581-582.
- Nichols, K., Omondi, E., Smith, A., Moyer J. (2017) GLOBAL SYMPOSIUM ON SOIL ORGANIC CARBON, Rome, Italy, 21-23 March 2017 Regenerative organic farm management practices mitigate agro-ecosystem vulnerability to climate change by sequestering carbon and building resilience.
- Nichols, V., Verhulst, N., Cox, R., & Govaerts, B. (2015). Weed dynamics and conservation agriculture principles: A review. *Field crops research*, 183, 56-68. <https://doi.org/10.1016/j.fcr.2015.07.012>
- Pelzer, E., Bazot, M., Makowski, D., Corre-Hellou, G., Naudin, C., Al Rifai, M., ... & Jeuffroy, M. H. (2012). Pea-wheat intercrops in low-input conditions combine high economic performances and low environmental impacts. *European Journal of Agronomy*, 40, 39-53.
- Persiani A., Diacono M., Montemurro F. (2024). The impact of long-term organic horticultural systems on energy outputs and carbon storages in relation to extreme rainfall events. *European Journal of Agronomy* 161 (2024) 127398.
- Peterson, G.A; De Paw, E., Payne, W.A., Mrabet, R.(2007). Drylands of the Mediterranean Zone: Chapter Biophysical Resources and Cropping Systems. DOI: 10.2134/agronmonogr23.2ed.c15
- Repullo-Ruibérriz de Torres, M. A., Veroz-González, Ó., Sánchez-Ruiz, F., Moreno-García, M., Ordóñez-Fernández, R., González-Sánchez, E. J., Carbonell-Bojollo, R. M. (2024). Carbon Sequestration Through Groundcovers and Pruning Residues in Sustainable Olive Orchards Under Different Edaphoclimatic Conditions. *Agriculture*, 14(12), 2118.
- Ruis, S. J., & Blanco-Canqui, H. (2017). Cover crops could offset crop residue removal effects on soil carbon and other properties: A review. *Agronomy Journal*, 109(5), 1785-1805. Liu et al., 2022, <https://doi.org/10.1016/j.agee.2022.108017>,



D.1.3 Benefits and drawbacks of selected carbon farming actions

- Sagris V, Wojda P, Milenov P, Devos W. (2013). The harmonised data model for assessing Land Parcel Identification Systems compliance with requirements of direct aid and agri-environmental schemes of the CAP. *J Environ Manage.* 2013;118: 40–48.
- Schreefel, L., Schulte, R. P., De Boer, I. J. M., Schrijver, A. P., & Van Zanten, H. H. E. (2020). Regenerative agriculture—the soil is the base. *Global Food Security*, 26, 100404.
- Six, J.; Elliott, E.T.; Paustian, K. (1999). Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Sci Soc Am J*, 63, 1350–1358. <https://doi.org/10.2136/sssaj1999.6351350x>
- Six, J.; Elliott, E.T.; Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biol Biochem*, 32(14), 2099-2103. [https://doi.org/10.1016/S0038-0717\(00\)00179-6](https://doi.org/10.1016/S0038-0717(00)00179-6)
- Soriano, M. A., Cabezas, J. M., & Gómez, J. A. (2023). Field evaluation of selected autochthonous herbaceous species for cover crops in Mediterranean woody crops. *European Journal of Agronomy*, 143, 126723.
- Sustainable Agriculture Research and Education (SARE) (2007). *Managing Cover Crops Profitably*, Third Edition. Available at <https://www.sare.org/wp-content/uploads/Managing-Cover-Crops-Profitably.pdf>, last accessed 16/12/2024
- Sustainable Agriculture Research and Education (SARE) (2019). *Cover Crop Economics. Opportunities to improve your bottom line in row crops*. Available at <https://www.sare.org/resources/cover-crop-economics/>
- Thorup-Kristensen, K., Magid, J., & Jensen, L. S. (2003). Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Advances in Agronomy*, 79, 227-302. [https://doi.org/10.1016/S0065-2113\(02\)79005-6](https://doi.org/10.1016/S0065-2113(02)79005-6)
- Tittarelli, F., Campanelli, G., Leteo, F., Farina, R., Napoli, R., Ciaccia, C., Canali, S. and Testani, E. (2018). Mulch Based No-Tillage and Compost Effects on Nitrogen Fertility in Organic Melon. *Agronomy Journal*, 110(4), pp.1482-1491.
- Todaro, V., D'Oria, M., Secci, D., Zanini, A., & Tanda, M. G. (2022). Climate change over the Mediterranean region: Local temperature and precipitation variations at five pilot sites. *Water*, 14(16), 2499.
- Toderi G., Bonari E., (1986). Lavorazioni del terreno: aspetti agronomici. I. Interazioni tra lavorazioni e terreno, clima, altre tecniche agronomiche. *Riv. Agron.*, 20 (2–3) (1986), pp. 85-105
- Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., & Baumecker, M. (2013). Irrigation, soil organic carbon and N₂O emissions. A review. *Agronomy for Sustainable Development*, 33, 733-749.
- Vanino S., Di Bene C., Piccini C., Gianni Fila, Bruno Pennelli, Raúl Zornoza, Virginia Sanchez-Navarro, Jorge Álvaro-Fuentes, Roman Hüppi, Johan Six, Roberta Farina, (2022). A comprehensive assessment of diversified cropping systems on agro-environmental sustainability in three Mediterranean long-term field experiments. *European Journal of Agronomy*, Volume 140, 2022, 126598, ISSN 1161-0301, <https://doi.org/10.1016/j.eja.2022.126598>.
- Vanino, S., Epifani, R., Baratella, V., De Leo, S., Farina, R. (2024). Technical Manual on "C stocking in vineyards - recommended practices"- English version. Zenodo. <https://doi.org/10.5281/zenodo.14245574>
- Vicente-Vicente, J. L., García-Ruiz, R., Francaviglia, R., Aguilera, E., Smith, P. (2016). Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. *Agriculture, Ecosystems & Environment*, 235, 204-214. <https://doi.org/10.1016/j.agee.2016.10.024>
- West, T.O.; Post, W.M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation. *Soil Sci Soc Am J*, 66(6), 1930-1946. <https://doi.org/10.2136/sssaj2002.1930>



D.1.3 Benefits and drawbacks of selected carbon farming actions

Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., ... ,Butterbach-Bahl, K. (2024). Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. *Nature Communications*, 15(1), 198.

Zheng, F., Liu, X., Ding, W., Song, X., Li, S., & Wu, X. (2023). Positive effects of crop rotation on soil aggregation and associated organic carbon are mainly controlled by climate and initial soil carbon content: A meta-analysis. *Agriculture, Ecosystems & Environment*, 355, 108600. <https://doi.org/10.1016/j.agee.2023.108600>.

