CarboNostrum

CLIMATE-SMART AGRICULTURE IN A CHANGING WORLD

# HandBook

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# Handbook for adapting Mediterranean Agriculture to Climate Change

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## CarboNostrum Handbook

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# Abstract

This handbook examines the complex interplay between agriculture, climate change, and desertification in the Mediterranean, emphasizing the urgent need for transformative agricultural practices. The guide provides an in-depth exploration of Climate-Smart Agriculture (CSA), a methodology focused on supporting agricultural productivity, building resilience to climate change, and minimizing greenhouse gas emissions. The handbook further elaborates on various sustainable farming practices, policy frameworks like the European Union's Common Agricultural Policy (CAP), and tools such as Geographic Information Systems (GIS) for its effective monitoring and implementation. Despite potential barriers such as upfront costs and technical expertise, the importance of community involvement and capacity building is underscored. By providing practical guidance and theoretical insights, this handbook aims to equip farmers and land managers in the Mediterranean region to adopt sustainable practices, contributing to a more resilient and environmentally responsible future for agriculture.


**Key Words:** Climate-Smart Agriculture, Desertification, Mediterranean Agriculture, Sustainable Practices, Agricultural Policy.

# Introduction

For the past 12,000 years, agriculture has been the backbone of civilization, starting from the Neolithic age. Throughout history, farmers have continually evolved their practices to ensure crop growth and production, playing a pivotal role in maintaining land productivity. However, it is crucial to remain vigilant about the long-term sustainability of these practices and their environmental impacts. This chapter will explore the potential detrimental effects of certain agricultural practices and the pressing need for sustainable alternatives. Moreover, we will delve into the critical nexus between agriculture and climate change, which calls for fresh perspectives and approaches.

Overwhelming evidence confirms climate change is a reality, largely influenced by human activities, particularly the emission of greenhouse gases (GHGs), with CO2 being the most significant contributor. The global scientific community strongly agrees with this correlation, which has immense implications for both the biosphere and humanity. Climate change profoundly affects the agri-food system, including crop production. Fluctuations in climate directly impact crop productivity, leading to reduced yields during droughts and other extreme weather events. Furthermore, agriculture and land use changes contribute to approximately 24% of total human GHG emissions, with an additional 10% coming from activities within the agri-food system, such as transportation and packaging. Hence, agriculture is a significant contributor to and a victim of climate change, underscoring the urgent need for agricultural sustainability.

The Mediterranean region, characterized by its distinctive climate and biodiversity, spans across 24 countries and is marked by hot, dry summers and mild, wet winters. Although this climate pattern, has facilitated the development of rich biodiversity and specific agricultural practices, it also presents significant challenges. These range from limited water availability, due to recurrent droughts and irregular rainfall, to fragile soils susceptible to erosion, desertification, and degradation. These unique and diverse ecosystems face serious threats under the weight of climate change. Current climate projections suggest that the region will experience intensified heatwaves, prolonged drought periods, and increased frequency of extreme weather events. These changes pose severe risks to the stability of ecosystems, agriculture, and human societies dependent on these resources. Specifically for agriculture, these climatic changes could lead to shifts in crop growing seasons, diminished yields, and increased pest and disease prevalence. Coupled with the existing water scarcity issues, these impacts could exacerbate the already precarious agricultural situation in the region. Given the potential severity of these climate change impacts, taking proactive steps towards mitigating these risks is crucial.

To address these pressing issues, the concept of Climate-Smart Agriculture (CSA) emerged, placing agriculture and related activities within the context of climate change. The Food and Agriculture Organization (FAO) introduced CSA in 2009, outlining three main pillars: sustainable increase in agricultural productivity and incomes, adaptation and resilience-building to climate change, and reduction or avoidance of GHG emissions. While CSA has gained significant attention, it is important to note that its definition and application have faced challenges, often tying into broader conversations about agricultural sustainability. A formal conceptual framework and implementation tools were developed later, but the term CSA had already gained widespread usage, leading to varied interpretations and controversies. In 2013, the FAO released a sourcebook outlining two key principles of CSA: increasing resource efficiency in agricultural systems and enhancing the resilience of systems and people involved in the agricultural sector.

This handbook primarily focuses on sustainable agricultural practices in the Mediterranean region, although it may also provide useful insights for other arid climatic contexts. The term "Mediterranean" refers to both a geographical area and a climate type characterized by a summer drought. The Mediterranean area, including regions such as California, central Chile, parts of South Africa, and southwestern Australia, faces significant challenges in terms of vegetation, soils, and agriculture due to the limited availability of water. The temperate zone amplifies the detrimental effects of drought, creating a fragile environment where maintaining long-term land productivity is particularly challenging and unstable. Given these circumstances, adopting sustainable practices becomes even more critical when considering the impending impact of climate change, which will exacerbate existing issues like water availability, soil quality, and extreme weather events.

The handbook is organized into three main sections. Section 1 provides an overview of general aspects, aiming to establish the broader context of modern agriculture, its environmental impacts, and its relationship with the surrounding landscape. This understanding is crucial for appreciating sustainable agricultural practices' description, purpose, and effectiveness. Section 2 delves into detailed descriptions of sustainable practices in the Mediterranean context, with a particular emphasis on CSA. While many of these practices draw inspiration from traditional techniques used for centuries, they are refined and adapted to incorporate newer perspectives such as the carbon cycle, climate change, and biodiversity importance. Each practice follows a structured format, covering aspects such as its name, type, description, illustrations, effects on soil conservation and biodiversity, implementation conditions, necessary resources, design and execution, relation to climate change, relation to the Common Agricultural Policy of the European Union, and references. Section 3 will dwell on Carbon Sequestration in Poor and Degraded Soils and aims to highlight some of the climate-smart techniques, which associate carbon sequestration rates and other impacts on agricultural activity. This section will cover carbon quantification and monitoring, as well as introduce the concept of carbon markets.

By exploring and implementing sustainable practices tailored to the Mediterranean's unique challenges, we can cultivate agricultural systems that are not only resilient but also environmentally responsible.

# GENERAL ASPECTS





## Agriculture: Trends, Impacts, and Benefits

Agriculture traces back around 12,000 years, marking a significant shift in human societies from nomadic hunter-gatherer lifestyles to settled farming communities. The advent of agriculture is believed to have been driven by several factors, including changes in climate, cultural advancements, and the need for stable and reliable food sources. From its inception, agriculture has grown in significance, shaping the societal and cultural fabric of civilizations globally and continues to play a pivotal role in the modern world.

Agriculture is thought to have originated independently in multiple parts of the world, including the Middle East's Fertile Crescent, China, Southeast Asia, the Ethiopian highlands, and the Andean highlands in South America. These early agricultural societies heralded a transition from transitory lifestyles to sedentary ones, marking the dawn of an era characterized by the establishment of permanent dwellings and the development of increasingly complex social structures.

The practice of agriculture catalysed significant societal advancements, including labour specialization and technological innovation. Initially, a large proportion of the global population was directly involved in agriculture. However, over time, the increased efficiency and intensification of agricultural practices led to fewer individuals needing to farm. In the present day, despite the global dependency on agricultural produce, farmers make up only about one-seventh of the global workforce.

In the European context, the Mediterranean region is of specific interest. Early evidence of agricultural practices in this region dates back to around 8500 BC. The

Mediterranean's unique climate, characterized by hot, dry summers and mild, wet winters, shaped agricultural systems that thrived on these conditions, leading to the cultivation of crops like olives, grapes, figs, and various cereals.

These agricultural systems are integral to the European agricultural framework, contributing significantly to the region's food supply and economy. They represent a diverse mosaic of cropping systems, pastoralism, and agroforestry, underpinned by thousands of years of agricultural history and cultural traditions. This region is a notable example of how agriculture can shape societal structures and landscapes, with far-reaching effects beyond food production, such as shaping cultural heritage, contributing to biodiversity, and playing a key role in the region's socio-economic dynamics.



## LAND FOOTPRINT AND INTENSIFICATION

Agriculture's spatial extent and influence on our planet are profound. Current estimates suggest that agricultural activities, including both arable and pastoral farming, occupy nearly five billion hectares of land globally. This accounts for an astounding 38% of the Earth's total terrestrial area, showcasing the considerable footprint of agricultural practices.

This agricultural land area has expanded dramatically over the past two centuries, with the conversion of natural ecosystems into farmland or pasture occurring at an accelerating pace. We have witnessed an almost threefold increase in the land designated for agriculture since the 18th century, significantly altering landscapes and ecosystems worldwide.

However, a notable shift has occurred over the last half-century. While the global population has more than doubled, increasing by over 100%, the total land area used for agriculture and pasture has expanded by less than 10%. This apparent disconnect between population growth and agricultural land expansion can be primarily attributed to agricultural intensification.

Agricultural intensification involves increasing the output of agricultural products, such as crops or livestock, from the same area of land. This increase is often achieved through more efficient use of inputs, advanced technologies, and improved farming practices. By enabling increased food production on less land, agricultural intensification has been pivotal in meeting the growing global demand for food, even as the physical footprint of agriculture grows more slowly.

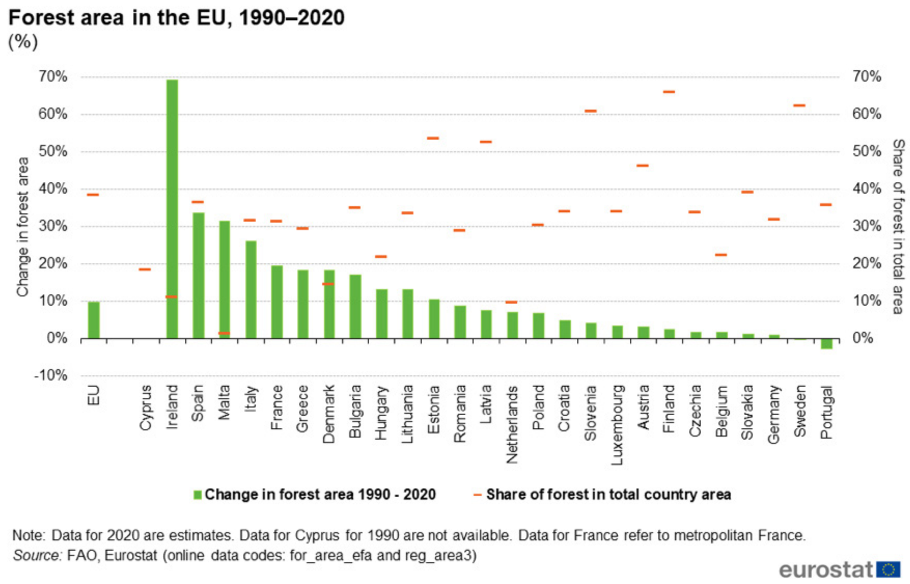


**Figure 1.** Increase of forest area in Europe (1990-2020). Source: Eurostat (2021)

In the context of the Mediterranean and European regions, agricultural land use and intensification reveal a distinct narrative. Over the past several decades, the Mediterranean region has seen a significant shift toward agricultural intensification, driven by the demand to increase productivity and meet growing food requirements.

Agricultural intensification, while instrumental in meeting the global food demand, has led to a range of environmental consequences of growing concern. The intensification process typically entails simplifying traditional agroecosystems and increasing reliance on external inputs such as synthetic fertilizers, pesticides, and energy resources. While these practices have boosted crop productivity and played a significant role in alleviating food scarcity, they have also triggered a series of environmental challenges.

One such consequence is the excessive consumption of resources. Intensive farming systems tend to require significant amounts of water, energy, and agrochemicals. These requirements can lead to over-extraction of water resources, contributing to water scarcity and excessive energy use, often associated with greenhouse gas emissions. Moreover, the heavy use of fertilizers and pesticides can lead to soil degradation and water pollution due to runoff, compromising both the quality of the environment and the sustainability of agricultural practices.

Furthermore, agricultural intensification often involves a shift in farming practices and land use patterns, including monoculture farming and landscape simplification. These changes can disrupt local biodiversity and alter ecosystems' structure and function. As biodiversity declines, so does ecosystem resilience, potentially leading to lower productivity and stability in the long run.

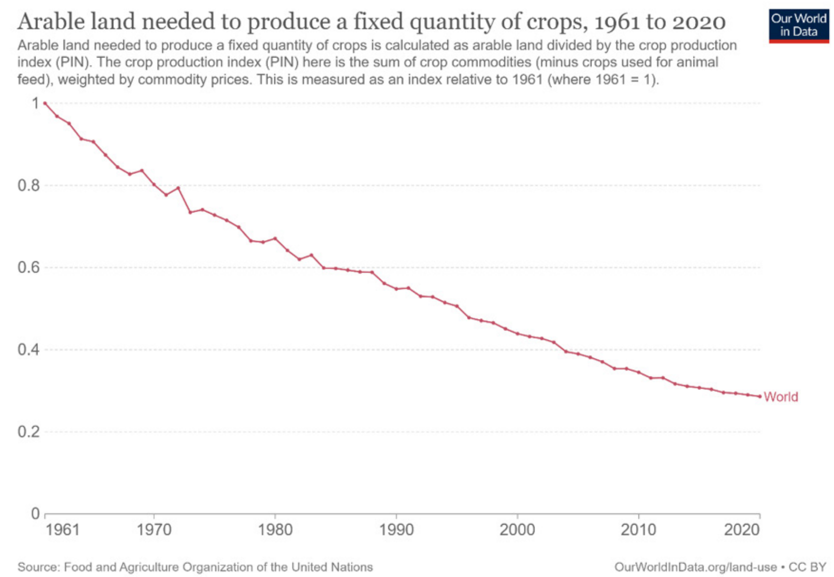


**Figure 2.** Arable Land necessary to produce one unit of agrarian production (1961 =1; 1961-2014). Source: ourworldindata.org, based on data from FAO (2023).

These issues are particularly pertinent in the Mediterranean region, where the agricultural landscape is already strained due to limited water availability, fragile soils, and increasing climate variability. The region's agricultural intensification has often led to the overuse of resources, soil degradation, and the loss of traditional, biodiversity-friendly farming practices.

Furthermore, the widespread adoption of monocultures, particularly in parts of Southern Europe, has simplified landscapes and disturbed the region's rich biodiversity. This not only jeopardizes local flora and fauna but also undermines the agroecological resilience of the region, making it more vulnerable to pests, diseases, and climatic extremes.

Balancing the demands for increased agricultural output with the urgency of environmental conservation and resilience is a complex task. It necessitates a keen understanding of local contexts and systemic thinking. This handbook delves into this crucial issue, focusing on strategies for fostering a sustainable, resilient, and productive agricultural future in the Mediterranean and other regions grappling with similar challenges.

## THE VALUE OF ECOSYSTEM SERVICES

Ecosystem services are integral to human wellbeing, with their benefits extending across various aspects of our lives. These services are products, conditions, and processes that natural ecosystems provide, benefiting humans directly or indirectly. They can be categorized into four broad types: supporting, regulating, provisioning, and cultural services (Millennium Ecosystem Assessment, 2005).

- Supporting services are the fundamental ecological functions that underpin all other ecosystem services. They include nutrient cycling, soil formation, and primary production, providing the basic ecosystem productivity upon which all species, including humans, depend.
- Regulating services refer to the natural processes regulated by ecosystems, such as climate regulation, flood control, disease regulation, and water purification. For instance, forests regulate climate by absorbing CO2, a greenhouse gas, and releasing oxygen (Foley et al., 2005).
- Provisioning services include tangible products provided by ecosystems, such as food, fresh water, wood, fibre, and medicinal plants. Agriculture is a primary example of a provisioning service, providing various food products across the globe.
- Lastly, cultural services encompass the non-material benefits people obtain from ecosystems. These include aesthetic enjoyment, spiritual fulfilment, intellectual development, recreation, and ecotourism opportunities (Daniel et al., 2012).

In a seminal study by Costanza et al. (1997), the total global value of these ecosystem services was estimated to exceed the global gross national product (GNP), underscoring their tremendous economic significance.

However, these invaluable ecosystem services are under threat due to factors associated with agricultural intensification. Excessive use of agrochemicals can degrade water quality and soil health, negatively affecting both provisioning and regulating services (Matson et al., 1997). Furthermore, landscape simplification—a common characteristic of intensified agricultural systems—can lead to biodiversity loss, thus degrading supporting and cultural services (Tscharntke et al., 2005).

Protecting and enhancing ecosystem services is not just an environmental issue but a necessity for sustainable agricultural production and overall societal wellbeing. As such, the need for agriculture that respects and harnesses ecosystem services rather than degrading them is more urgent than ever.



# Climate change: What is Happening and How it Affects Agriculture in the Mediterranean

Climate change, supported by a consensus among scientists, is a reality that is happening now and is projected to worsen in the future, even with aggressive greenhouse gas emission cuts. Globally, land temperatures have risen by about 1.2°C since the late 19th century, with the most significant increase occurring in the last four decades. Most of this warming has happened in the last four decades, showing that our industrial activities have escalated the pace of climate change, exacerbating the natural greenhouse effect of the earth's atmosphere.

Temperature rise has not been uniformed across the globe, with some regions experiencing more severe increases than others. A case in point is the Mediterranean region, which is bearing the brunt of the effects of climate change more intensely. Temperatures in this area have surged to approximately 1.7°C higher than in the late 19th century.

The Mediterranean region's warming rate is faster than the global average, which is a cause of serious concern as it already leads to, and will continue to cause, severe social, economic, and ecological impacts. The heat is causing longer and more intense heatwaves and wildfires, reducing water availability, threatening agriculture, and causing widespread ecosystem damage.

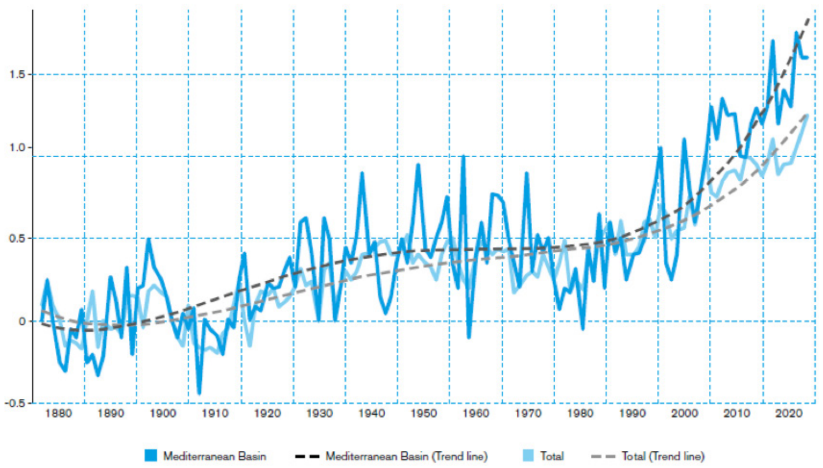


**Figure 3.** Change in global surface temperature on Earth and in the Mediterranean Basin (1880-2020). Source: Cramer et al. (2018)

The changes in global temperature and atmospheric patterns caused by climate change critically impact factors like precipitation, temperature, and the frequency and severity of extreme weather events, which in turn affect crop productivity and food security.

One significant effect of climate change on agriculture relates to desertification in dry regions. Human activities like overgrazing, deforestation, and inappropriate farming practices degrade the soil and vegetation cover, leading to the expansion of desert-like conditions. On top of this, increasing global temperatures can intensify the evaporation rates, further contributing to the drying out of these areas.

If global temperatures continue to rise without a corresponding increase in rainfall, the phenomenon of aridity (the degree to which a climate lacks effective, life-promoting moisture) will be heightened. This growth will lead to the expansion of arid and semi-arid areas, putting more regions at risk of desertification. This expansion can reduce the land area suitable for farming, thereby threatening food security.

Moreover, climate change is likely to alter the distribution and intensity of rainfall due to shifts in atmospheric patterns. These alterations can lead to a more complex set of aridification patterns globally. Some areas may experience more frequent and severe droughts, while others may face erratic and intense rainfall, both of which can detrimentally impact agricultural productivity.

Such shifts in rainfall patterns and increased temperatures could render current crop adaptations unsuitable for their respective regions. Different crops have different climatic requirements for optimum growth, and these requirements are based on the current climate. Changes in temperature and precipitation patterns could mean that crops that were once suitable for a particular area may no longer thrive under the new climatic conditions.

Farmers may need to switch to more resilient crop varieties or entirely different crops, practices which entail significant costs and risks. This also raises the spectre of losing crop diversity if traditional varieties become untenable under the new climatic conditions. Such shifts also increase the likelihood of pest and disease outbreaks as changing climate conditions can alter the life cycles of insects and pathogens.

Beyond crop production, climate change also poses significant challenges to livestock farming. Rising temperatures can cause heat stress in animals, reducing productivity and increasing mortality rates. Changes in the availability and quality of feed due to altered rainfall patterns can also affect livestock health and productivity.

## THE MEDITERRANEAN CLIMATE AND ITS VULNERABILITIES

The Mediterranean climate is distinctively characterized by its hot, dry summers and mild, wet winters, which it owes to its location between the subtropical high-pressure and polar front. The annual rainfall is typically low, and the climate sees high inter-annual variability, meaning there can be significant variations in rainfall and temperature from one year to the next.

While most Mediterranean regions, such as southern California, Spain, Australia, Chile, and Northern Italy, endure predominantly dry conditions, some areas are subjected to high rainfall, particularly during winter. These periodic heavy rainfalls can lead to rapid growth of vegetation, which then dries out in the hot, dry summer months, often leading to an increased risk of wildfires.

Drought conditions during the hot summer months are a common phenomenon in the Mediterranean climate. This makes water stress a critical factor affecting both natural ecosystems and agricultural practices. The region's plants and animals have evolved to survive with limited water availability during summer, but persistent and severe droughts can still cause significant ecological damage.

Recent climatic trends have indicated a general decrease in annual rainfall in these Mediterranean regions. For instance, some areas are even experiencing reduced rain during the summer. This, combined with the high temperatures' characteristic of the Mediterranean summers, could exacerbate water scarcity, leading to severe agricultural droughts and increased vulnerability to wildfires.

Climate change adds another layer of complexity to the situation. Global warming due to the increasing concentration of greenhouse gases in the atmosphere is projected to intensify the aridity of the Mediterranean climate. Rising temperatures lead to increased evaporation rates, which can further reduce the availability of surface water and groundwater reserves. This would make the already dry summers even drier and potentially extend the dry season into the typically wetter winter months.

In addition to the increase in temperatures, climate change is also expected to influence rainfall patterns. While the overall trend is towards reduced rainfall, the distribution of rainfall might also become more uneven, with more intense rain events separated by longer dry periods. This increased rainfall seasonality can lead to more frequent and severe flooding during the wet periods and more intense droughts during the dry periods.

These climatic changes are exacerbating the vulnerability of Mediterranean lands to desertification, a process where fertile lands become increasingly arid and lose their productivity. This could have severe implications for agriculture, biodiversity, and human settlements in the region.

The Mediterranean region's vulnerabilities to climate change highlight the urgent need for adaptation and mitigation strategies. These could include improved water management, developing drought-resistant crops, reforestation to prevent soil erosion, and reducing greenhouse gas emissions. Moreover, there is a need for rigorous climate modelling to predict future changes and plan for them accordingly.

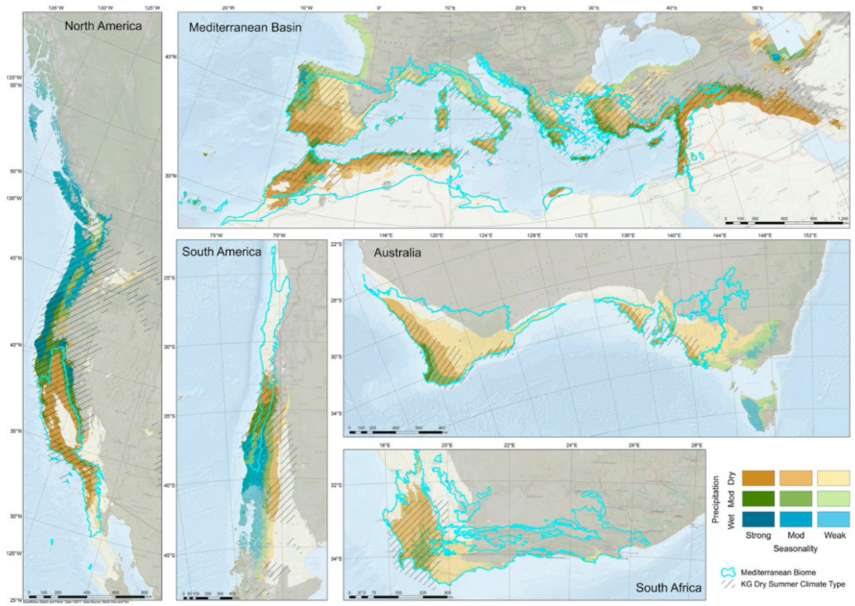


**Figure 4.** Distribution of Mediterranean climates globally. The blue line defines Mediterranean biomes, with the transversal lines indicating areas of dry summer. Colours indicate rainfall regime, and colour intensity represents seasonality. Source: Deitch et al. (2017)

The Mediterranean Sea, like many other marine ecosystems around the globe, is experiencing the adverse effects of climate change. Observational data from 1982-2018 indicates a steady increase in its temperature by approximately 0.04°C per annum. Although this increment might appear trivial, it has resulted in the sea becoming over 1.5°C warmer than it was in the early 1980s. This consistent warming is consequential to the Mediterranean Sea's delicate ecological balance, affecting biodiversity, fishing industries, and the regional climate.

One notable aspect of this warming trend is the geographic disparity across the Mediterranean Sea. The eastern Mediterranean is warming more rapidly than the western part, which is connected to the Atlantic Ocean. This spatial variability in warming rates can influence the distribution of marine species, potentially impacting local ecosystems and the fishing industry. Some species may move towards the cooler western regions, while others may not be able to survive the increased temperatures at all, leading to changes in local biodiversity.

The temperature of the Mediterranean Sea exerts a significant influence on regional weather patterns. One such example is the heavy autumn rains typically experienced in the region. The warmer the sea, the more evaporation occurs, and this added moisture can fuel heavier rainfall. This intense precipitation, particularly after the dry summer months, can lead to severe soil erosion, damaging agricultural lands and increasing the risk of landslides in hilly areas.

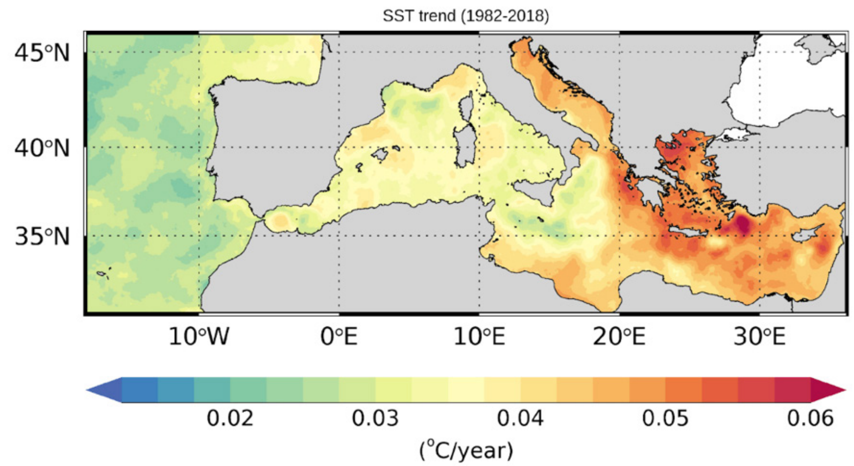


**Figure 5.** Warming trends in the Mediterranean Sea. Source: Pisano et al. (2020)

Climate models provide insights into the potential impact of climate change on agricultural activity. The Mediterranean region is particularly vulnerable due to its unique climatic characteristics and heavy reliance on agriculture. As cited by the Institut Europeu de la Mediterrània in 2018, forecasts predict that even with emission reduction efforts, the average temperature in the Mediterranean could rise by 2°C by mid-century (RCP 4.5). However, a more alarming "business as usual" scenario suggests a potential increase of 3.5°C-4°C (RCP 8.5).

RCP stands for Representative Concentration Pathways. They are scenarios that the climate research community uses to project the potential future of greenhouse gas concentrations in our atmosphere. These scenarios, or pathways, are defined based on their total radiative forcing (measured in watts per square meter) by the year 2100 relative to pre-industrial values.

- **RCP 4.5** represents a "stabilization scenario" where policies are enacted to stabilize radiative forcing shortly after the year 2100, leading to an increase of 4.5 $W/m^2$ (watts per square meter) at the end of the century. In this scenario, greenhouse gas emissions peak around 2040, then decline. It is often considered an intermediate scenario, as it assumes considerable reductions in emissions yet is less ambitious than some of the other RCPs.
- **RCP 8.5** is a "business as usual" scenario with no specific policies to reduce greenhouse gas emissions. It represents the highest greenhouse gas concentration trajectory among the RCPs. The radiative forcing value reaches 8.5 $W/m^2$ by the year 2100. In this scenario, greenhouse gas emissions will continue to rise throughout the 21st century, and atmospheric CO2 concentrations will reach around 950 parts per million (ppm) by 2100, more than double the concentration of about 400 ppm in 2015.

These pathways are used in climate models to project the possible impacts of climate change, including temperature rise, precipitation changes, sea level rise, and other factors, under different emissions scenarios. They help policymakers and scientists understand the range of possible futures and plan for different potential climate outcomes.





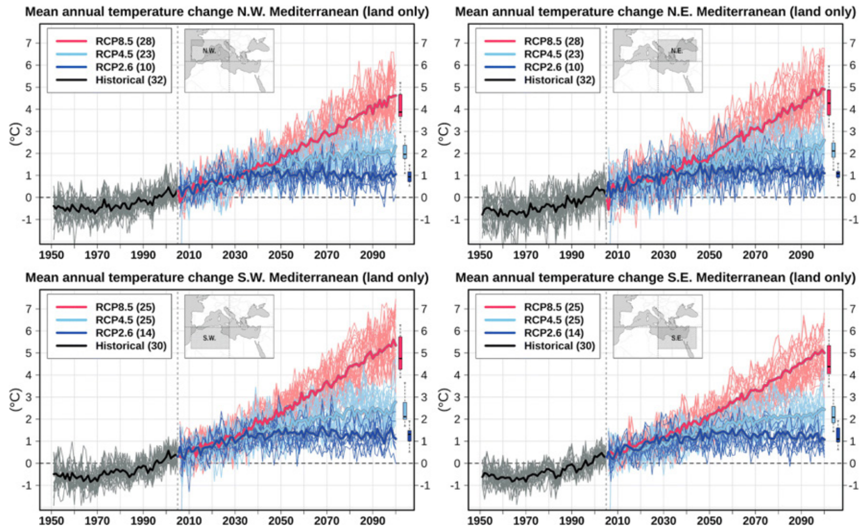


**Figure 6.** Forecasted changes in mean annual temperature in land surrounding the Mediterranean. RCP2.6 is a scenario of strict control of emissions; RCP4.5 increase emissions until 2040 and then decrease; RCP8.5 is 'business as usual' with no control of emissions. Source: Zittis et al. (2019)

This shift in temperature is not an isolated phenomenon. Precipitation patterns are also projected to undergo considerable transformation. Most notably, reductions in winter rainfall are anticipated. Regions such as the Maghreb and the Eastern Mediterranean are of particular concern, where significant decreases in rainfall could have dire implications for water availability, soil moisture, and agricultural productivity.

The hotter, drier summers in the Mediterranean, as a result of climate change, pose a series of challenges for agriculture. Staple crops in the region, such as olives, grapes, and various cereals, may face stress from heatwaves and insufficient water. Reduced water availability affects not only the yield but also the quality of the produce. Moreover, the increased frequency of extreme weather events like droughts can erode soil, decreasing its fertility over time.

Interestingly, while some regions may witness decreased precipitation, the global hydrological cycle is expected to intensify, meaning that certain areas might experience increased rainfall. However, this could mean more concentrated, heavy rainfalls for the Mediterranean rather than steady, beneficial rain spread over time. Such sporadic and intense rain events might lead to flash floods, which can wash away topsoil and damage crops instead of replenishing water reserves.

The effects on crop dynamics have implications for crop yields and suitability in the Mediterranean. For instance, simulations suggest that sunflower cultivation in certain soil types in Southern Spain may become partially unsuitable, leading to reduced crop production by 2100. Olive cultivation also faces challenges, with projected yield decreases of up to 45% in Western Europe due to increased temperatures and decreased precipitation. Vineyards and olives, other vital Mediterranean crops, may experience changes in phenological events, affecting both quantity and quality.

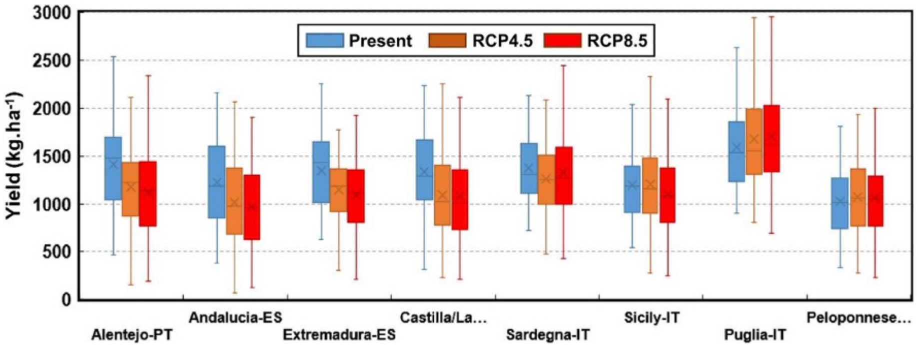


**Figure 7.** Olive yields under different climate change scenarios across de Mediterranean. Source: Fraga et al. (2019)

Furthermore, the impacts on the hydrological cycle will affect the supply and demand of water, leading to challenges for irrigated agriculture as droughts will be a more frequent phenomenon. Adding to this and intensified by climate change, the Mediterranean is also highly susceptible to desertification, which further aggravates the impacts of climate change and the agricultural activities in the Mediterranean.

# Desertification in the Mediterranean

Desertification is the degradation of land in arid, semi-arid, and dry sub-humid regions due to various factors, including climatic variations and human activities. It affects about one-third of the world's land surface and over a billion people globally. Contrary to popular belief, desertification does not refer to the expansion of existing deserts but rather the creation of desert-like conditions in previously non-desert areas. It occurs due to a long-term imbalance between the demand for and supply of ecosystem services, resulting in decreased land productivity.

**Figure 8.** Example of a critical area of desertification susceptibility in Serra de Mértola, Alentejo, Portugal – Credit: Henrique Cerqueira



## VULNERABILITY OF THE MEDITERRANEAN TO DESERTIFICATION

The Mediterranean Basin, with its unique climate characterized by wet winters and hot, dry summers, is one of the region's most vulnerable to desertification. Approximately 75% of the land in southern Europe, according to the European Environment Agency (EEA, 2008), is prone to desertification. Studies indicate an increased risk of desertification in the Mediterranean over recent decades, primarily due to climate change and human-induced factors such as land overexploitation, overgrazing, and deforestation. These factors contribute to soil erosion, loss of vegetation cover, and land degradation, furthering the process of desertification.

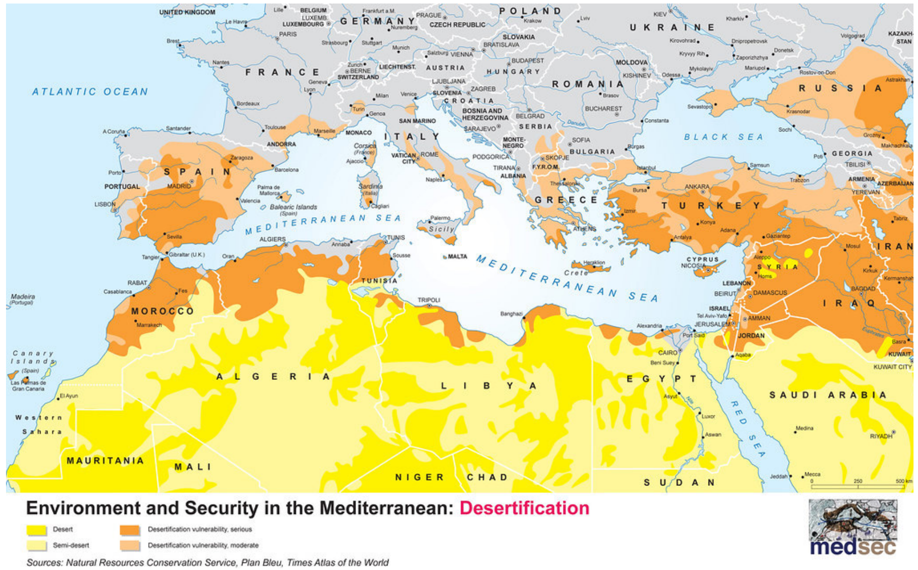


**Figure 9.** Vulnerability to desertification in the Mediterranean basin.
Source: Emmanuelle Bournay and Matthias Beilstein, Zoï Environment Network (2013).

## INDICATORS AND IMPACTS OF DESERTIFICATION

Recognizing the early signs of desertification is crucial for mitigating its impacts. Key indicators include vegetation changes, soil quality degradation, water scarcity, altered climate patterns, and socio-economic indicators such as declining agricultural productivity and increased rural poverty. Desertification in the Mediterranean region has several implications, including:

1. **Agricultural Productivity:** Desertification significantly impacts agricultural productivity. Soil degradation and water scarcity lead to declining crop yields. Olive groves, vineyards, and grain production, which are vital for the Mediterranean region, are particularly at risk. Decreased agricultural productivity can result in food insecurity and economic instability, given the sector's importance to the region's economy.
2. **Biodiversity Loss:** The Mediterranean Basin is a biodiversity hotspot, hosting a significant number of plant species, many of which are unique to the region. Desertification threatens biodiversity, leading to the loss of species and impacting the health and resilience of ecosystems.
3. **Water Scarcity:** Reduced rainfall and increased evaporation rates due to higher temperatures contribute to water scarcity. This affects agricultural water use and the availability of drinking water, exacerbating existing water stress in the region.
4. **Socio-economic Consequences:** Decreased agricultural productivity and increased costs caused by water scarcity and soil infertility can lead to rural unemployment, increased poverty, and, potentially, forced migration as people seek livelihoods elsewhere. The socio-economic consequences of desertification are significant and can have long-lasting impacts on local communities.

## MITIGATION AND ADAPTATION STRATEGIES

Desertification is not inevitable, and measures can be taken to mitigate its impacts. Sustainable land management practices, such as regenerative agriculture, agroforestry, and sustainable irrigation practices, can help restore degraded lands and enhance resilience to desertification. Early warning systems and adaptation strategies, including the cultivating drought-tolerant crops and efficient water management, can assist farmers in coping with changing conditions.

Desertification poses a significant threat to the Mediterranean region, with climate change and human activities exacerbating the risk. Recognizing the indicators of desertification and implementing appropriate mitigation and adaptation strategies are essential for preserving agricultural productivity, biodiversity, and the socio-economic stability of the Mediterranean. Promoting sustainable land management practices and adopting resilient agricultural approaches can mitigate the impacts of desertification and build a more sustainable future for the region.

# Agroecosystems and the surrounding landscapes

Agroecosystems are unique ecosystems intentionally designed and managed by humans for agricultural purposes. These systems encompass various components, including crops, livestock, soils, water, climate, and the diverse living organisms within the environment. Unlike natural ecosystems, which operate independently, agroecosystems are carefully structured to optimize productivity and economic profit. Figure 10 shows, on the left, a moderately streamlined landscape. On the right is an extensively streamlined landscape. Human involvement emerges as a key influence in reshaping the spatial framework of the environment. When activity is moderate, the landscape's diversification is promoted, whereas intense human involvement leads to a heightened simplification.

**Figure 10.** Management of Agricultural Scenery of two farming ecosystems in northern Spain. Source: G. Clemente-Orta (2019).



## THE IMPORTANCE OF AGROECOSYSTEMS

Agroecosystems play a crucial role in sustaining human life and supporting socio-economic development. They are responsible for producing most of the world's food, including staple crops like grains, fruits, and vegetables, and essential protein sources such as meat, milk, and eggs. Beyond food production, agroecosystems offer a wide range of ecosystem services, including water purification, carbon sequestration, habitat creation for biodiversity, and visually appealing landscapes. Moreover, agroecosystems facilitate agriculture, providing employment for over a billion people worldwide and contributing significantly to global economic development and poverty reduction.

Agroecosystems do not exist in isolation: they interact with and are influenced by surrounding natural ecosystems in various ways. Agricultural landscapes often serve as habitats for wildlife, and enhancing habitat diversity within agroecosystems can support biodiversity conservation efforts. Agroecosystems also influence nutrient and water cycles within their surrounding landscapes, impact climate regulation by sequestering carbon in soils and vegetation, rely on pollination services from surrounding natural habitats, and contribute to landscape connectivity, facilitating wildlife movement and gene flow.

Understanding the intricate relationships between agroecosystems and their surrounding ecosystems is critical for effective landscape-level planning and management. By striking a balance between agricultural production and environmental and biodiversity conservation, we can foster sustainable agriculture. This involves adopting sustainable farming practices, preserving biodiversity, valuing cultural heritage, and ensuring the long-term resilience and productivity of agroecosystems while safeguarding the natural environment.

While agroecosystems provide numerous benefits, it is important to address the trade-offs associated with unsustainable agriculture. Practices associated with land degradation, biodiversity loss, and environmental pollution can have detrimental effects on the long-term viability of agroecosystems. Therefore, the key to achieving both food security and environmental conservation lies in the sustainable management of these systems.

The Mediterranean region is renowned for its diverse agroecosystems, shaped by its unique climate, topography, and rich historical-cultural influences. The Mediterranean hosts a rich agricultural heritage, from the picturesque olive groves, vineyards, and citrus orchards along the coasts to the productive cereal fields, rangelands, and livestock systems in the interior. Notably, traditional agroecosystems like the Dehesa in Spain or Montado in Portugal, characterized by a combination of agriculture, forestry, and pastoral practices, are globally recognized for their high biodiversity and cultural value.

In recent decades, Mediterranean agroecosystems have faced significant challenges. Urbanization, land abandonment, intensified agriculture, climate change, and desertification have all posed threats to the sustainability of these systems. A transition towards more sustainable farming practices is imperative to overcome these challenges. This transition involves preserving the Mediterranean's unique biodiversity and cultural heritage while ensuring food security and the well-being of local communities.

# Agricultural and ecological intensification

Agricultural and ecological intensification are two contrasting approaches to enhancing agricultural productivity. Agricultural intensification focuses on maximizing yields through increased inputs and advanced technologies. In contrast, ecological intensification aims to achieve productivity gains while minimizing negative environmental impacts by optimizing ecosystem services and promoting biodiversity.

In the Mediterranean region, agricultural intensification has been prevalent due to the growing demand for food and the pursuit of higher profitability. This has led to a shift from traditional low-input farming systems to more intensive monocultural practices heavily reliant on synthetic inputs and mechanization. However, the negative consequences of agricultural intensification, such as biodiversity loss, soil degradation, water pollution, and greenhouse gas emissions, have prompted a shift towards ecological intensification.

**Figure 11.** Super intensive Olive production in Alqueva Region, Alentejo. Source: Miguel Manso (2019), Público.

Intensification is driven by the need to feed a growing population, technological advancements, market forces, and government policies. Nevertheless, while food production increases, it also causes significant environmental damage.

Ecological intensification offers a more sustainable alternative by focusing on biodiversity conservation, soil health improvement, and reducing chemical inputs. This approach aligns with several Sustainable Development Goals, including food security, climate change mitigation, and biodiversity conservation.

**Figure 12.** Cover Crop Cultivation in Olive Farming in Turkey. Source: The Turkish Foundation for Combating Soil Erosion, for Reforestation and the Protection of Natural Habitats, TEMA (n.d).

The key difference between agricultural and ecological intensification lies in their approaches to increasing productivity. Agricultural intensification heavily relies on external inputs, leading to environmental degradation, whereas ecological intensification harnesses ecological processes to enhance productivity and sustainability. However, ecological intensification faces challenges such as shifting farming practices, increased understanding of ecological processes, and policy support to incentivize sustainable approaches.

In the Mediterranean region, ecological intensification offers numerous benefits. By optimizing ecosystem services and promoting biodiversity, it enhances the resilience of agroecosystems in the face of climate change and environmental stressors. It also preserves the region's agrobiodiversity and cultural landscapes shaped by traditional farming practices. Furthermore, by reducing the use of synthetic inputs, ecological intensification helps mitigate environmental pollution and the associated health risks related to chemical residues in food.

By embracing ecological intensification, the Mediterranean region can achieve both increased agricultural productivity and environmental sustainability. This transition requires a holistic approach that integrates ecological principles, farmer knowledge, and supportive policies to create a resilient and sustainable agricultural system for the future.

# The carbon cycle in agricultural systems

The carbon cycle is a fundamental process involving carbon exchange between the Earth's biosphere, geosphere, hydrosphere, and atmosphere. It plays a vital role in regulating the Earth's climate and supporting ecosystem productivity. Understanding and leveraging the carbon cycle in agricultural systems is crucial for enhancing soil fertility, mitigating climate change, and building resilience.

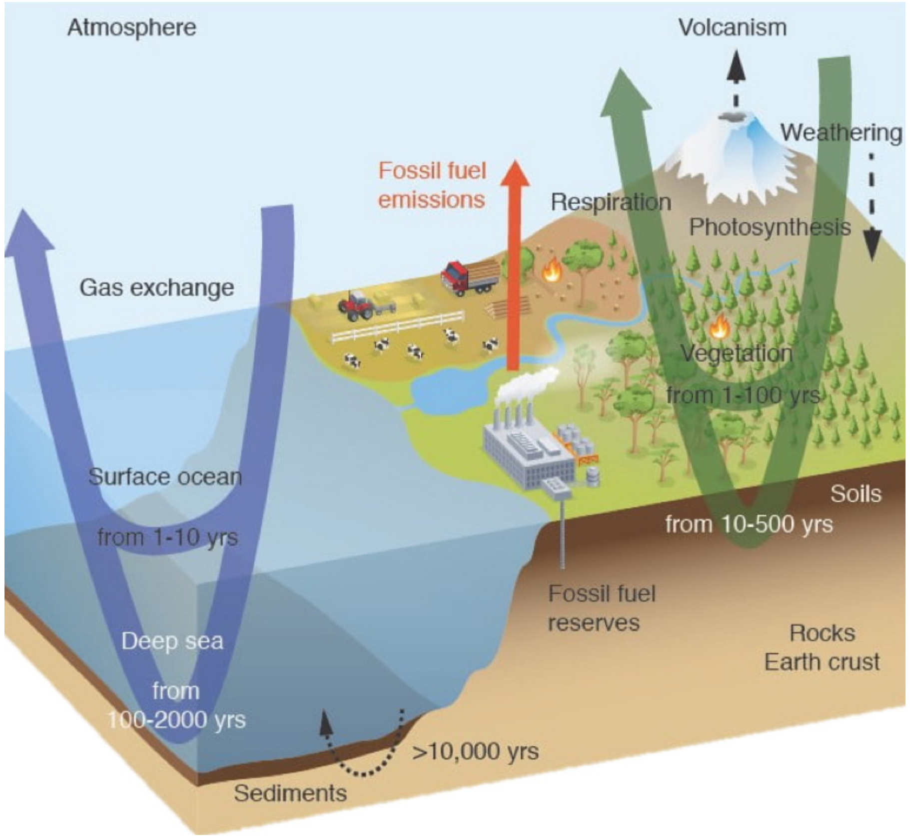


**Figure 13.** Simplified schematic of the global carbon cycle showing the typical turnover time scales for carbon transfers through the major reservoirs. Source: IPCC (2013)

The carbon cycle begins with photosynthesis, where green plants and phytoplankton convert carbon dioxide into organic compounds using solar energy. This process forms the basis of the food chain, with carbon being transferred from primary producers to herbivores and carnivores. When organisms die, their bodies decompose, releasing carbon back into the atmosphere through respiration by microbes. Combustion, both natural and human-induced, also releases carbon dioxide into the atmosphere.

Human activities such as deforestation, burning fossil fuels, and changes in land use disrupt the carbon cycle, leading to increased carbon dioxide concentrations in the atmosphere and contributing to climate change. Agricultural systems, in particular, can be affected by these disruptions. Practices like overgrazing, excessive tillage, and monoculture cropping can reduce soil organic carbon and degrade soil health. These practices not only impact soil fertility but also increases carbon dioxide emissions.

The carbon cycle plays a significant role in agroecosystems by enhancing soil fertility and mitigating climate change. Carbon is a key component of soil organic matter, which improves soil structure, water retention, and nutrient cycling. Additionally, agroecosystems can act as carbon sinks when managed appropriately.

Promoting a healthy carbon cycle in agroecosystems contributes to their resilience in the face of environmental changes. Soils rich in organic carbon can better retain water, reducing vulnerability to drought. These soils also buffer against nutrient losses, maintaining productivity under changing conditions.

Several strategies can be implemented to leverage the carbon cycle in agroecosystems. Carbon sequestration in soils can be achieved through practices like cover cropping and conservation tillage. Agroforestry, which integrates trees into agricultural landscapes, not only sequesters carbon but also provides additional benefits such as shade and habitat for beneficial species. Organic farming practices, including composting and green manuring, enhance soil organic carbon content and reduce reliance on synthetic fertilizers. Crop diversification and rotations contribute to soil health and increase carbon sequestration.

# Mitigating Impacts and Climate-Smart Agriculture (CSA)

Climate-Smart Agriculture (CSA) is a holistic approach that addresses the complex interplay of agricultural development, climate responsiveness, and emission reductions. It is geared towards transforming and reorienting agricultural systems to support sustainable development and ensure food security under the new realities of climate change. Given the undeniable impacts of climate change on Mediterranean agriculture – rising temperatures, decreased rainfall, and more frequent and intense extreme weather events – CSA's principles are highly pertinent.

Successful examples of sustainable practices already exist in landscapes such as the "Montado" in Portugal, "Dehesa" in Spain, and traditional irrigated floodplains in Eastern Spain. While cultivated, these landscapes maintain high levels of ecosystem services, including carbon sequestration, water filtration, and the preservation of biodiversity. They serve as models of how agriculture can be compatible with environmental conservation and resilience.

The adoption of CSA practices can help to mitigate the environmental impacts of agriculture in a variety of ways:

- **Adaptation to climate change:** CSA promotes the adaptation of agricultural systems to changing climatic conditions. This involves developing and implementing of new farming practices, crop varieties, and technologies that are resilient to climate extremes, such as drought-tolerant crop varieties, precision irrigation systems, and agroforestry systems.
- **Mitigation of greenhouse gases:** CSA seeks to reduce greenhouse gas emissions from agriculture, which contribute significantly to global

warming. This can be achieved by implementing practices such as efficient use of fertilizers, integrated pest management, conservation tillage, and organic farming.

- **Sustainable intensification of food production:** CSA aims to increase food production to meet the growing global demand while minimizing negative environmental impacts. This can be achieved through practices such as precision farming, intercropping, and agroecology, which increase yield per unit of land while maintaining or even improving soil health and biodiversity.

In addition to these three pillars, CSA emphasizes the importance of an enabling policy environment and strong institutions that can facilitate the adoption of CSA practices. This includes policies that incentivize sustainable farming practices, capacity-building programs for farmers, and robust agricultural research and extension systems.

Overall, Climate-Smart Agriculture provides a comprehensive and flexible framework for addressing the challenges posed by climate change to Mediterranean agriculture. By adopting CSA practices, it is possible to ensure the resilience and sustainability of agriculture in this region while also contributing to global efforts to mitigate climate change. This will involve not only farmers but all stakeholders in the food system, from policy-makers and researchers to consumers. The transition to CSA is both an environmental necessity and an opportunity for innovation, improved productivity, and sustainable rural development. By adopting these CSA practices, farmers can contribute to climate change mitigation while improving the productivity and sustainability of their agroecosystems. Understanding and harnessing the carbon cycle, the relationship of the different components of agroecosystems, and the challenges that affect them is essential for achieving both environmental and agricultural benefits.



# Understanding the Common Agricultural Policy

The Common Agricultural Policy (CAP) plays a crucial role in shaping agriculture in the European Union (EU) and has undergone reforms to address evolving challenges and priorities. While the CAP has traditionally focused on ensuring a fair standard of living for farmers, stabilizing markets, and ensuring food supply, there has been a growing recognition of the need to integrate environmental considerations and promote sustainable agricultural practices.

Climate change and desertification have emerged as pressing challenges with significant implications for the sustainability of agriculture in the EU. In response, the CAP has incorporated environmental and climate objectives into its framework. The concept of "greening" has been introduced, which involves the provision of direct payments to farmers conditional on their adherence to various environment and climate-friendly farming practices. These practices include crop diversification, the maintenance of permanent grassland, and the allocation of a certain percentage of arable land to environmentally beneficial elements, known as "ecological focus areas."

Furthermore, the CAP provides funding for rural development, which includes measures aimed at climate change mitigation and adaptation, as well as combating desertification. Initiatives such as organic farming, agroforestry, and improved water management are supported under these programs. The aim is to incentivize farmers to adopt practices that reduce greenhouse gas emissions, enhance carbon sequestration, improve water efficiency, and promote overall environmental sustainability.

The CAP's measures aim to promote sustainable land management practices in regions particularly vulnerable to desertification, such as Southern Europe and the Mediterranean. This is essential to prevent soil degradation, maintain biodiversity, and protect valuable ecosystems. By encouraging practices like agroforestry, conservation agriculture, and cover crops, the CAP seeks to enhance soil health, conserve water resources, and improve the overall resilience of agroecosystems in these regions.

In recent years, there has been a growing interest in emerging agricultural approaches, such as regenerative agriculture and climate-smart agriculture. These approaches emphasize building soil organic matter, restoring soil biodiversity, increasing carbon sequestration, and enhancing resilience to climate change. While the CAP has made progress in supporting sustainable practices through its agri-environment-climate measures (AECMs), critics argue that the current structure and focus of the CAP still fall short in promoting such practices to the extent necessary.

To address these concerns, there is a need for further evolution of the CAP to better align with the principles of sustainability and resilience. This includes greater emphasis on supporting agroecological approaches, encouraging the adoption of innovative technologies and practices, and providing incentives for farmers to transition to more sustainable and climate-resilient farming systems. By embracing these changes, the CAP can contribute to the development of more sustainable and environmentally friendly agricultural systems, ensuring a balance between food production, environmental protection, and the well-being of farmers and rural communities.

# MANAGEMENT PRACTICES





## Crop Residue Management

**NAME OF THE TECHNIQUE:** Shredding of Crop Residues

**OTHER NAMES:** Crop Residue Management, Management of Pruning Residues, Mulching, Organic Cover

**TYPE:** Crop Management

**DESCRIPTION:**

This technique, known as the shredding of crop residues, has been used in agriculture for many years. It is a part of Conservation Agriculture, which is widely practiced in various regions of the world, particularly the Americas, where extensive herbaceous crops like cereals, sunflowers, corn, and soybeans are grown. The technique involves shredding or chopping the leftover plant materials on the field surface and distributing them over the soil. These residues include the parts of herbaceous plants left after harvesting and the branches and small trunks remaining after pruning woody crops. It is important to note that organic waste generated within the agricultural system should not be considered residues but rather a by-product that can be reintroduced into the agricultural production system.

In Spain, citrus and fruit tree producers, especially in the Region of Murcia, have increasingly adopted these techniques in their main production areas. Similar practices are also employed for woody species like olive trees in Andalusia and grapevine residues, offering an alternative to burning the pruning waste. Over time, when left on the ground surface, these residues decompose and form a layer of organic material known as mulch. The thickness of the mulch can vary depending on the tree species and their age, with mature lemon and orange orchards reaching up to 20cm in thickness. This technique is often combined with minimum or no tillage, as practiced in the Americas. The advantages of using these residues are further enhanced when combined with other techniques such as contour tillage, minimum tillage, reduced tillage, direct sowing, and plant covers.

The primary objective of shredding plant residues is to help farmers overcome the challenge of managing these leftover materials and avoid burning them. Burning woody crop residues, such as almond, citrus, fruit trees, grapevines, and vines, has caused concerns in Spanish society, even though the volume of residues burned is relatively small and mostly occurs in small-scale agricultural operations where access to shredding systems or residue managers is limited. As a result, significant changes in the law have been implemented in recent years, leading to the practical prohibition or highly restricted burning of agricultural waste, thereby highlighting the importance of shredding residues for soil incorporation.

The mulch created by this technique serves as a protective layer for the soil and acts as an organic amendment rich in cellulosic components. This technique has gained prominence in the past 15 years, particularly in organic agriculture, which is rapidly expanding in the Region of Murcia. It has become a common practice in modern orchards of citrus and stone fruits, even in smaller-sized operations. In regions like the Guadalentin Valley and the Campo de Cartagena, where vegetable crops are prevalent, the leftover green residues are often used as livestock feed. The remaining trunk and root parts are then chopped and added to the soil. However, this practice may result in only a small amount of residue being left in the soil, thus diminishing the benefits of mulching.

In some cases, it is possible to combine the use of crop residues with green fertilizers or annual green covers. However, the impact may be limited due to the suppressive effect of the existing organic layer. Therefore, adjustments in management practices need to be considered, and the results may not be as effective as when the technique is applied independently.

**Figure 14:** Residue mulch on the surface, crop residues can be incorporated or retained to protect the soil against erosion and disturbance. Source: Ghasal et al., 2016.

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

Shredding of crop residues has various impacts on the soil: Physical Effects: The mulching layer, when it reaches a minimum thickness of around 5cm, provides significant protection to the soil. It reduces the impact of raindrops on soil particles, minimizing their tendency to break apart. Additionally, the layer of chopped wood acts like a sponge, retaining water from the initial rainfall. Once saturated, it slows down the flow of water, controlling runoff and reducing soil erosion.

Improvements in Soil Properties: Over time, the continuous addition and decomposition of organic matter create a gradient of humic substances within the soil profile. This enhances soil properties in various ways. Physically, it improves soil permeability and stability of soil aggregates. Chemically, it returns some of the nutrients extracted by the crops back into the soil, which needs to be considered when calculating the nitrogen balance. The increase in humic substances and their interaction with soil mineral particles also enhances the soil's cation exchange capacity. Moreover, the presence of mulch helps the soil retain or break down any phytosanitary residues used in the crop, preventing their movement into water sources.

Reduction in Water Evaporation: Mulching, particularly this type, reduces water evaporation by creating air pockets within the mulch layer that limit water vapor loss to the atmosphere. The insulation properties of the mulch layer also contribute to a more stable soil temperature, reducing sudden temperature fluctuations.

Enhancement of Biological Activity: Mulching fosters a diverse community of microorganisms, saprophytic organisms, and decomposer arthropods, creating a favourable habitat for them similar to a forest environment. This increases the trophic levels and interrelations within the ecosystem, benefiting the overall health of the crop. The presence of these organisms also competes with pathogens, limiting their expansion and providing an antagonistic effect that helps protect the crop.

Suppression of Adventitious Plants: One unforeseen yet desirable effect of mulching, particularly with thicker layers, is the suppression of weed growth. The mulch layer acts as a barrier, making it difficult for unwanted plants to emerge. Additionally, the use of mulch improves the soil's physical properties, making it more suitable for machinery and workers, even after heavy rainfall.

## RECOMMENDED APPLICATION CONDITIONS:

The shredding or chopping of plant residues can be applied in terrains with slight or moderate slopes, but more is needed for steep slopes. On steep slopes, the flow of rainwater could potentially carry these residues outside the agricultural fields. In such cases, combining this technique with other systems that reduce water flow and help maintain the organic cover is necessary. There are no limitations regarding soil type, as this organic material significantly improves soil structure, cohesion, and porosity.

There are, however, operational limitations to consider. The arrangement of the crop, dimensions of the orchard or plantation, and accessibility can pose challenges for the use of necessary equipment such as shredders or choppers. For instance, narrow or irregularly spaced plantations or orchards, as well as small vegetable gardens located in hard-to-reach areas, may present difficulties.

Perhaps the most crucial factor that could limit or discourage this technique is the presence of fungal or bacterial diseases that could severely impact the crop. Wood-borne diseases, who's reproductive and dispersal cycles could be favoured by organic residues, are of particular concern. In such cases, mulching is strongly discouraged from a plant health perspective. Controlled burning for immediate elimination would be the recommended action in these specific cases, despite concerns from certain sectors. Unfortunately, numerous fungal diseases, and to a lesser extent, bacterial diseases, can be found. Examples include *Esca* and *Eutypa lata* in vines, *gummosis* in citrus, *bacterial fungi* in pears, *molinia*, and *Fusicoccum* in almonds and stone fruits, among others. Additionally, various arthropods may not be effectively eliminated or dispersed when this practice is not carried out adequately (e.g., pear blight beetle or woodborer).

Another alternative concerning the aforementioned problem is the immediate incorporation of freshly shredded residues into the soil using a seeder or cultivator. However, this approach would result in the loss of some protective properties provided by the organic blanket. Before choosing this option, it is important to gather sufficient information about the specific disease in question to assess its viability.

From a regulatory perspective, the codes of good agricultural practices for preventing water contamination with nitrates from agricultural sources recommend this practice due to the prohibition of burning crop residues.

## REQUIRED RESOURCES:

When working with woody crops, using a pruned wood shredder or chopper is essential. While static equipment similar to those used in city gardens and green areas is possible, these are not practical or cost-effective for regular agricultural operations. Such equipment would require double the work, first collecting the residues and then shredding them before distributing them in the field. The most efficient use of this equipment would be in composting along with other organic residues like animal manure, but that would involve a different technique.

Mobile equipment offers more flexibility, with tractor-mounted implements being the most commonly used. Depending on the crop type and wood characteristics, various working widths and shredding systems are available (hammers, sweeps, tines, etc.). It is important to select the equipment that best suits the specific operation, ensuring fine shredding of the pruned pieces to avoid pest problems and facilitate their subsequent decomposition. Some equipment also includes distribution or guidance systems for collecting or placing the residues. Additionally, if the intention is to incorporate the residues into the soil, equipment suited for that task should be selected, aligning with the overall soil conservation strategy.

On the other hand, the need for specialized machinery for herbaceous crops depends on the species and the characteristics of the stubble produced. In some cases, conventional tilling may be sufficient to adequately shred the residue. However, in other cases, specific equipment, such as a rotavator or similar implement, may be required to achieve the necessary degree of shredding.

## DESIGN, EXECUTION AND MAINTENANCE:

As for the design, there is little to add, except that for woody crops in newly established plantations, it is important to consider the equipment that will be used to shred the future pruning residues. This will help optimize the operation in terms of cost and performance, considering that expenses will be associated with the crop.

During execution, the goal is to achieve thorough and fine shredding of the residues, with diameters typically ranging from 1-3 cm. smaller pieces facilitate faster decomposition. In citrus crops, there is the additional consideration of thorns in the wood, making adequate shredding crucial to avoid the risk of tire punctures or harm to operators.

The usual practice is to leave the pruning residues in the middle row, where they are subsequently shredded by passing shredders, and then the mulch is distributed across the field. the wood chips can be buried using a harvester or similar machinery to address pest concerns.

In terms of maintenance, two aspects should be noted. First, there may be a need to incorporate accumulated residues into the soil after several years, particularly for certain species and mature plantations. This can be accomplished using a harvester or similar equipment. Second, with young plantations with limited biomass, supplementing with herbicide application may be necessary to control the growth of adventitious plants near the young trees until the residue layer becomes sufficient for effective weed control.

### CLIMATE CHANGE MITIGATION POTENTIAL:

Its effect on climate is twofold. Firstly, the reduced or eliminated tillage associated with this technique contributes to carbon sequestration in the soil. The stable storage of carbon in the residues over an extended period further supports this. Secondly, it should be acknowledged that shredding itself is energy-intensive. However, when compared to the alternative of burning, which releases CO2 into the atmosphere, the balance is positive despite the use of fuel. The same consideration applies when comparing it to the transport and disposal of residues to composting centres or landfills, especially if the distances involved are substantial due to the large volume occupied by these residues.

In addition to the direct effects on CO2 emissions and storage, the technique's indirect effects on soil fertility, nutrient recovery for the crop, and erosion reduction should be considered. These factors can potentially decrease the need for fertilization and improve overall performance.

### CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

The Common Agricultural Policy (CAP) explicitly prohibits the burning of residues as a requirement under the "Good Agricultural and Environmental Conditions (GAEC)" general requirements. This prohibition is also included in the latest CAP plans, including the new CAP 2023-2027 under the "Reinforced Conditionality." It applies to all farmers or growers receiving direct payments, regardless of CAP funding.

# Hedges and Copses

**NAME OF THE TECHNIQUE:** Hedges and Copses

**OTHER NAMES:** Plant Barriers, Living Fences, Plant Conservation Structures, Living Enclosures, Copses and Boundaries

**TYPE:** Plant Structure

### DESCRIPTION:

Hedges are linear plant structures, often formed by both naturally occurring and cultivated species, usually woody (trees or shrubs). However, larger herbaceous species can also be incorporated. Traditionally, hedges are arranged along the edges of farmlands or individual cultivation plots. In the past, especially in Southeastern Spain, it was common to plant fruit species like mulberry, fig, quince, medlar, pear, apple, plum, apricot, lemon, orange, and others like olive or almond trees. Date palm, prickly pear, laurel, aromatic plants like lemongrass, rosemary, sage, and ornamental species like rose bushes, and some forest species (poplars, cypresses, pines, willows, etc.) were also planted. The purpose of these hedges varies: they can serve as windbreaks, physical barriers, or simply for landscaping. Nowadays, these hedges are also planted between crops (intercropped) for more effective erosion control or to attract beneficial insects.

In traditional Spanish agriculture, narrow strips of land, often on the margins of cultivation plots, roadsides traverse the farm, terraced land embankments, hills, etc., where farming or tilling is typically not performed, are referred to as slopes. These slopes teem with shrubby and small xerophytic herbaceous vegetation. Due to their origin and species, they are more aligned with this category than strips, which are specifically created with herbaceous species for a distinct purpose.

On the other hand, copses are irregular plant structures composed of spontaneous or forest species, which can be tree-like, shrubby, or herbaceous. Usually found along rivers, dry riverbeds, irrigation or drainage canals, or any other waterway, copses are often arranged longitudinally in the direction of the slope or, to be more accurate, in line with the water flow. They commonly appear in valleys or ravines, sometimes forming small forests. Primarily, their function is to protect these margins or banks. However, they also serve as important refuges, feeding and breeding areas for wildlife, acting as ecological corridors.

Many of these hedges, especially the riverside copses, are remnants of the area's natural arboreal and shrubby vegetation, left behind after centuries of land clearing for cultivation. These copses have been preserved primarily as separators between farms or due to the unsuitability of the land for agriculture (e.g., high flood risk or rocky terrain). In some cases, they result from spontaneous vegetation growth on crop edges, margins, slopes, or elevation differences between farmland and terraces.

Historically, many hedges and copses in rural areas were lost due to intensified farming practices, mainly because of mechanization, which made the land more uniform and easier to cultivate. Such a productivity-focused approach was so prevalent that these areas were once considered eligible for direct payments to farmers. Fortunately, this trend has reversed significantly in recent years, primarily due to the recognition by the EU of these areas as key components of the landscape that play a crucial role in soil and water conservation and biodiversity preservation. Nowadays, the Common Agricultural Policy (CAP) recognizes them as areas of ecological interest, often included in farmers' aid calculations, or as direct beneficiaries of specific conservation-promotion aid (Fernández, M.A., 2015).

From an integrated pest management perspective, hedges and copses are being recognized as crucial elements of the agroecosystem, contributing to the conservation and enhancement of crop arthropod biodiversity. This, in turn, improves the integrated pest management on farms. Organic farming pioneers recognized the benefits of these landscape elements in various aspects of agricultural production, particularly their ability to attract beneficial insects.

Today, hedges are frequently employed worldwide to control runoff and soil loss in sloping areas. For this, they should be established as perpendicularly as possible to the line of maximum slope, following the contour lines. Copses, on the other hand, are typically used to correct hydrological issues when intense erosion occurs on farms or to mitigate diffuse contamination from the use of agrochemicals in crops. Despite their benefits, these living structures are still limited or cautiously adopted by technicians and farmers, mainly due to a lack of understanding or confidence in their advantages. Similar to the earlier hesitance towards the release of natural enemies for biological control, these structures are now considered an integral tool in crop protection.

**Figure 15:** Hedge acting as a wind break to protect the field. Source: Michael Patterson (2006)

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

Primarily, this technique significantly enhances both plant and animal diversity. Initially, the variety of plant species rises due to the plants introduced by the farmer. Over time, local spontaneous species increase as they take advantage of these undisturbed soil surfaces. Eventually, animals (both vertebrates and invertebrates) colonize these mini-ecosystems in search of new feeding grounds, shelter, or breeding areas. As such, there is a substantial increase in species diversity on farms where these structures are established compared to their prior state.

Another critical aspect is their role as connecting elements between existing natural spaces (ecological corridors), particularly for copses found in watercourses. Furthermore, these hedges are extensively used as conservation plant structures in integrated pest management strategies due to their excellent ability to harbour beneficial arthropods (natural enemies of plants or pollinators).

In terms of soil conservation, the establishment of these living structures offers significant benefits:

Primarily, they effectively control runoff, reducing the erosion of fertile soil, particularly nutrients and organic matter. Likewise, their root system and the slowing of surface water flow can retain part of these nutrients and excess circulating water, largely being absorbed by these plants. They also decrease the diffuse contamination from phytosanitary products through drift and runoff. Finally, these areas become sites where abundant biomass is produced, part of which is returned to the soil. This, combined with the absence of treatments and tillage in these areas, fosters the proliferation of decomposing microorganisms and plant symbionts.



## RECOMMENDED APPLICATION CONDITIONS:

These stable structures can be used in all types of soils and crops. The main limitations are economic factors (implementation cost) and space availability for their establishment.

In fact, using these barriers is highly beneficial when the land has steep slopes and other tillage-related techniques are insufficient for controlling runoff.

Lastly, this technique can be easily combined with other soil conservation methods (such as terraces and contour tillage, among others).

## REQUIRED RESOURCES:

The first requirement is the seeds or plants for the hedge or copse. The quantity of these plants is crucial. Sometimes, the species may not be readily available in nurseries, making it difficult to obtain the necessary quantities. Therefore, it is vital to plan ahead to acquire these plants. Requesting a confirmed supply when needed is a good strategy, though allowing them to acclimatize to the local environmental conditions before transplantation is recommended.

In some cases, farms may have plant materials suitable for propagation in hedges. This common practice can lead to significant cost savings. However, it is essential to ensure that the source plants are healthy.

Regarding equipment, we can utilize tools already available on the farm to apply this technique. For instance, a moldboard plow with sweeps can be used to create a deep furrow to prepare the land, which is critical for good root development.

During land preparation, if possible, it would be beneficial to apply organic amendments or even deep fertilizers.

In warmer regions with low rainfall, supplemental irrigation may be required. This can be achieved using a lateral drip irrigation line if available or, alternatively, by distributing water with a tank.

In the early stages, managing spontaneous species that could compete with the planted ones may be necessary. For this, a string mower could be used, or manual weeding could be done if the area isn't too large. Optionally, biodegradable plastic mulch could be used, making small holes for the seedlings, although this isn't typically required.

Lastly, depending on the species planted, it may be necessary to manage the growth of the plants. This could be done through manual pruning or, more efficiently, with a saw or a specialized mechanical hedge trimmer.

## DESIGN, EXECUTION AND MAINTENANCE:

Designing the plant structures offers a wide range of options. First, it is essential to determine the main objectives of these structures. Depending on whether the purpose is to plant hedges as windbreaks, reduce runoff and prevent soil erosion, implement integrated pest management, enhance the agricultural landscape, create ecological corridors, achieve additional production for self-consumption, or simply define property boundaries or enclosures for livestock, the design requirements will vary significantly. While it is possible to integrate multiple objectives, factors such as surface area, arrangement, geometry, choice of species, and densities will differ considerably. Hence, specific guidelines cannot be provided in this summarized technical sheet. However, it is crucial to analyse this information in advance and consult the available literature for specific examples that can aid in designing custom hedgerows. This technique allows for extensive customization based on personal preferences and criteria, utilizing fundamental concepts.

Typically, different types of hedges are positioned around the farm or individual parcels, with particular attention given to sides that traverse slopes to control streams or small dry riverbeds. In such cases, their primary function is to serve as cost-effective and long-lasting property boundaries, act as windbreaks to protect crops, enhance the landscape, or promote self-consumption. For terraced agricultural land, hedges are placed atop the terraces to facilitate the conservation of these structures. The planted vegetation's roots play a crucial role in stabilizing and anchoring the surrounding soil, preventing erosion caused by runoff. To maximize the diversity and quantity of natural enemies or useful insects like pollinators, as well as minimize soil erosion, hedges should not only be established along the perimeter but also within the cultivation plots. It is important to determine the appropriate spacing between hedges for effective biological control, considering the crop, selected plant species for the hedge, and the range of movement or target of natural enemies inhabiting the hedges. The goal is to enable these insects to control specific pests. Therefore, opting for a diverse mix of species and maintaining distances between hedges ranging from 20 to a maximum of 50 meters is recommended.

In terms of water erosion control, hedges should ideally be planted at specific intervals along contour lines. The appropriate interval depends on several key factors, including the crop type, chosen plant species, hedge width, slope, and length. These intervals influence the cumulative effect of water's kinetic energy during runoff. Indicative figures are available for guidance. A larger effective surface area covered by these structures yields more significant effects. For biological control, the hedge occupies around 5-7% of the surface area. However, for erosion control, starting with a minimum coverage of this percentage is advisable, which can increase up to 50% for steep slopes. In such cases, terracing the area is recommended.

Another vital aspect to consider is the density of sowing and/or planting. A high planting density is necessary for establishing functional hedges quickly. However, certain large species should not be planted too close together to avoid competition for space and resources, which can lead to viability issues or favour harmful pests and diseases.

Regarding the hedge width, narrower hedges of 1 to 2 meters are suitable for promoting natural enemies, utilizing herbaceous and shrub species. For erosion control purposes, slightly wider hedges ranging from 2 to 4 meters are preferred, utilizing larger species, including trees.

When selecting plant species, conducting preliminary studies or gather information to determine important characteristics is essential. These characteristics include root depth and type, development (diameter and height), growth rate, adaptation to the local climate (hardiness), flowering time, fruit and seed production, and potential invasiveness. Species' ability to host natural enemies and potential pests affecting the crop must also be taken into account. Ongoing research and testing aim to identify species and their mutualistic relationships with these insects. Web applications and mobile apps are available for this purpose. Generally, a mixture of at least five different species is used, incorporating woody species with shrubs or herbaceous species. However, in horticultural crops, selecting only shrubby and herbaceous species is common, excluding trees to avoid issues such as excessive shading, leaf drop in crops, or limited space for machinery. The species selection process is crucial due to the many options available. Making an inappropriate choice can lead to maintenance difficulties or the entry of pests that could harm the crop for an extended period.

It is important to assess the potential negative impact of selected species, particularly when a species serves as an ideal host for a pest or disease affecting the crop. Specialized pest websites can provide guidance on this matter. To minimize this issue, avoid planting species from the same botanical family or even the same genus as the crop, as they may share common pests or diseases. By utilizing a diverse mix of species rather than relying on a single species, it is possible to prevent any one species from dominating the structure. Consider that for natural enemies to thrive in these hedges, a small population of the pests themselves or similar species must be present to sustain these insects during periods when the crop is not infected.

Determining the layout of the plantings on the ground often involves following set planting patterns, with a certain order or planting module repeated throughout the hedge. For example, a continuous module may consist of repeatedly planting three rosemary, one oleander, one atriplex, and one mastic. However, it is recommended to create a random mix unless a technical justification calls for a specific pattern. This approach results in a more natural and favourable outcome.

A unique scenario involves designing hedges as windbreaks. In this case, the prevailing winds and the risk of frost due to inversion should be analysed to prevent cold damage to the crop. The arrangement of windbreaks must not act as a barrier to cold air that accumulates during thermal inversion, such as at the end of a mountain slope. Therefore, the orientation of windbreaks can differ significantly from other types of hedges. Additionally, the degree of protection or area of influence provided by windbreaks, determined by the maximum height of the trees planted (which is typically around ten times their height), must be taken into account. When selecting plant species for windbreaks, it is essential to focus on trees with a known protective effect. Moreover, planting density should be appropriate for the chosen species, considering their final size. The windbreak should not be overly compact, allowing air to pass through in a controlled manner to prevent adverse effects caused by strong eddies on the leeward side of the hedge.

For riverside or valley copses, irregular planting with alternating species is ideal to create a more natural appearance. To enhance their filtering and bank protection functions, herbaceous species should be positioned upstream, followed by shrubs, with trees closer to the bank. Over time, natural vegetation will recolonize parts of these margins, resulting in the typical appearance of riverside forests. However, in cases where local hydrological correction is required due to uncontrolled gullies or streams on the farm, engineering interventions are necessary. These interventions, accompanied by plantings to achieve greater stability and naturalness through copses, fall beyond the scope of this handbook.

Proper soil preparation is crucial when planting hedges. This involves thorough soil cultivation to eliminate any hardpan. Depending on the species to be planted, preparation can be accomplished through continuously planted trenches using appropriate implements like a sweep, moldboard, or subsoiler. Alternatively, individual planting holes can be created using a backhoe or an auger. Adding organic matter and deeply applying mineral fertilizer is advisable. Finally, the soil is mounded and compacted. Leaving one side of the hedges planted below the plantation (upstream) or creating a small parallel ditch can enhance rainwater retention during the early stages of planting. Alternatively, a small mound parallel to the hedge downstream can serve the same purpose. In some cases, the hedge may be elevated higher than the ground, creating a small plateau or hill to enhance erosion control, particularly during the initial years of plant development.

In extremely arid areas, additional irrigation support may be necessary depending on the planting season and the hardiness of the selected species. Temporary irrigation systems or water tanks can provide supplemental water. However, it is crucial to gradually reduce or eliminate irrigation to allow proper root establishment and self-sufficiency in soil stabilization.

Regarding maintenance, periodic pruning and removal of branches may be necessary to maintain the desired size of the hedge without encroaching on the crop or to replace ageing plants. Importantly, these surfaces should not be subjected to subsequent fertilization or treatments, especially when hedges are established to promote and conserve beneficial fauna (natural enemies), as such treatments can be detrimental to their survival.

Lastly, it is essential to consider the potential regulatory regulations that may impact the establishment of hedges in certain locations.

Gathering information on legal aspects is highly recommended to ensure proper design and avoid future setbacks. For example, according to Article 5 of the Spanish Forest Law, after a certain period (typically ten years or less for copses), shrubby or wooded surfaces may be classified as surface forests. These areas are considered “forest enclaves on agricultural land” by the forestry authority of the Autonomous Community. Such classification can impose limitations in the future, affecting landscape or biodiversity-related aid, and may require specific authorization for removal.

## CLIMATE CHANGE MITIGATION POTENTIAL:

The use of these plant structures offers two key benefits to climate change. Firstly, they contribute to improved soil fertility by reducing soil and nutrient losses. Additionally, they can store significant amounts of CO2 through the generation of biomass. This storage capacity can be particularly high when trees are involved, reaching levels comparable to forests. Moreover, the area influenced by the hedge experiences a substantial increase in organic matter content, surpassing the actual width of the structure.

Furthermore, the reduced fertilizer losses and localized increase in organic matter resulting from the presence of these structures can contribute to a certain extent in reducing the dependence on fertilizers. Additionally, their planting, especially when interspersed within the plantation, leads to a decrease in tillage, resulting in fuel savings over time, albeit modest.

Overall, these plant structures have a positive impact on carbon sequestration, making them valuable as carbon sinks.

## CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

In the past, the multifunctional aspects of these elements in the agricultural landscape were not adequately recognized within the EU Common Agricultural Policy (CAP) model. Consequently, the amounts paid to farmers for these areas were reduced, considering them “non-productive.” Fortunately, the European authorities now acknowledge the significance of these elements as integral components of the diverse rural areas across Europe. Recognizing their benefits for biodiversity and climate change, they are now strongly incorporated into the requirements for direct payments to farmers (reinforced conditionality) and basic payment aid.

Moreover, many regions have already included measures related to these elements in their previous rural development programs, both for their conservation and for new plantings, making them a mandatory requirement for receiving agro-environmental aid (Fernández, M.A., 2015).

Finally, it is worth mentioning that the costs associated with planting these conservation plant structures can be offset through the operational funds of the Producer Organizations for Fruit and Horticultural Products (OPFH). These structures are considered part of the compulsory environmental measures to be implemented within these funds.

# Rotation and Alternation of Crops

**NAME OF THE TECHNIQUE:** Rotation and Alternation of Crops

**TYPE:** Crop Management

**DESCRIPTION:**

Crop rotation is a traditional method utilized since antiquity to preserve natural soil fertility and safeguard farm crops, particularly horticultural varieties, from undesirable plant health issues arising from repeatedly planting the same crops.

This approach centres around creating a sequence or rotation of crops on the same piece of land over a specific period, usually 1 to 3 years. This duration depends on the intensity and lifespan of each crop. The method involves using plant species that can coexist for a time while having unique characteristics. These distinct features enable them to break the lifecycle of specific pests, tap into various soil profiles, possess different root systems, boost atmospheric nitrogen fixation, and offer other useful traits.

It is recommended to include at least two, ideally three, crops or variants within this rotation. These could involve fallow periods (times of rest for the soil) or the use of green manure. This technique can also be paired with sensible livestock management. Leftover crop residues or certain grazing plants beneficial to livestock can even be incorporated into the crop rotation cycle.

Despite the numerous advantages offered by crop rotation, the intensification of agriculture — characterized by the advent of fertilizers and plant health products and the focus on certain export-oriented crops in specific regions like Campo de Cartagena or the Valley of Guadalentin — has led to the decline of this practice. This occurred because crop diversification made farm management difficult due to the small size of many farms. This was not conducive for fruit and vegetable companies requiring large volumes of a specific product year-round to meet commercial demand.

However, the growing popularity of Organic Agriculture in the Region of Murcia, the emergence of certain plant health problems with limited control measures, and new regulatory requirements are beginning to shift this trend. As a result, many large agricultural businesses, along with smaller-scale producers, have started to incorporate some form of rotation or alternation in their production cycle. This includes the use of temporary fallow periods, cereals, beans, sunflowers, potatoes, and more, which are alternated with some of the region's most commonly grown crops.

In the United States and elsewhere in the Americas, crop rotations also serve the purpose of soil conservation. They achieve this by introducing specific species capable of enhancing the soil-plant system's resilience against erosion caused by wind or water.

**Figure 16:** Pea and wheat crop rotation plots. Source: Mervin St. Luce (2022).

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

Crop rotation can have a significant effect on soil preservation and biodiversity in several ways:

Firstly, one key benefit of crop rotation how it disrupts the reproductive cycle of various pests and diseases that are potentially harmful to specific crops. This is achievable by rotating different crop species from distinct botanical families or incorporating fallow periods of certain lengths. For instance, this method is beneficial for brassicas (like broccoli, cauliflower, and cabbage) that are often infested by nematodes from the *Heterodera genus*, lettuce affected by the *Sclerotinia fungus*, or cereals impacted by *Septoria* or the cereal mosquito.

Additionally, crop rotation encourages biodiversity by introducing new plant species. This increase in biodiversity results not just from the new crop species themselves but also from the pests or natural enemies associated with these crops and the microbiota that benefit from their residues in the soil. On a smaller scale, having a wider variety of crops also diversifies the food sources for smaller fauna, such as birds and rodents.

Another vital aspect of crop rotation is the variation it introduces to the soil profile. By selecting crops with different root systems that operate at varying soil depths and absorb nutrients and water differently, crop rotation allows the soil and its nutrient reserves to rest and recover naturally.

Regarding soil erosion, some crops like cereals can directly enhance soil protection against sheet erosion. This is due to their dense growth, root system, and the stubble they leave behind, which can enhance soil porosity and organic matter content. Similarly, green manures or pastures can also combat erosion, especially when combined with other techniques like contour or minimum tillage, strips, hedges, or terraces. Lastly, the use of crop rotation generally reduces the duration for which the soil is left exposed and unprotected, as time would be better utilized for growing these alternating crops.

## RECOMMENDED APPLICATION CONDITIONS:

This technique is ideally suited for herbaceous crops, typically annual or biennial, and can be effectively utilized on all types of soil used in cultivation fields. The benefits of rotating crops—avoiding planting the same crop year after year—help prevent significant soil issues that could ultimately impact crop yield.

From a regulatory perspective, the codes for good agricultural practices to control nitrate pollution from agricultural sources typically recommend crop rotation.

## REQUIRED RESOURCES:

Implementing crop rotations might necessitate additional resources, such as increased equipment for planting, transplanting, tilling, and/or harvesting, or even storage for crop residues for livestock feeding.

Often, the primary challenge or limiting factor is time, as the transition between crops, as well as their time in the ground, must be carefully managed. Therefore, it is important to thoroughly plan the selection of crops used in the rotation, bearing in mind that weather conditions can significantly alter these timelines, requiring farmers to adapt and respond to potential unforeseen situations.

As the number of crops or plant species increases, the resources needed may vary. When uncommon regional species are introduced, farmers will need to plan or anticipate procuring new seed species for the rotation. To assist with this, germplasm banks, which are being established in many countries, can provide plant material that may be useful. This material often includes traditional cultivars that might be better adapted to the local environmental conditions of the crops.

## DESIGN, EXECUTION AND MAINTENANCE:

In crop rotation, the sequence of crops is treated as a single production unit. However, another approach involves applying this sequence across different units or plots. This strategy, known as alternation, involves dividing the farm into several units or plots (also called "leaves"). In each leaf, crops are planted in sequence, including periods of fallow and green manures. The crops change with each cycle, moving to another plot in a systematic way. After a certain period, the crops return to the original plot where the rotation began. The number and size of the leaves must be determined based on production needs (types of crops and yield) and the time frame considered for this alternation. This will depend on the growth periods of each species, along with the time necessary for planting and preparatory work.

Regarding the design of crop rotation, the selection of species or alternative crops to include in the rotation is a critical step. Several factors or parameters should be considered, which may include some or all of the following:

1. Select species of significant economic interest to the farmer or the marketing company.
2. Ensure compatibility with other crops concerning planting and harvesting times. The goal is to plant a new species right after harvesting the previous one or to choose species with short production cycles that would make them compatible with others.
3. The sequence of crops should align with the seasons in the area.
4. Utilize species from different botanical families, as some pests or diseases can affect entire genera.
5. Include species with different root systems, such as fasciculate, taproot, fibrous, etc., or with different depths.
6. Avoid species that share major pests or diseases.
7. To opt for species with varied nutritional needs.
8. Choose crops that can tolerate certain soil conditions, like salinity, clayey, or heavy soils, if present.
9. Consider species that can fix atmospheric nitrogen, such as legumes.
10. Including a species with low water needs to balance the higher consumption of another.
11. Consider species with beneficial allelopathic effects; that is, those whose presence or residues can repel certain pests.
12. Select crops beneficial for livestock feeding, either directly or after harvest.
13. In case of erosion problems, consider species that provide greater erosion control.

A commonly used rotation involves a main horticultural crop, followed by fallow, cereal, and/or green manure, or two main horticultural crops from different families for different seasons, with fallow or green compost/cereal periods in between. There is abundant literature detailing good combinations for both dryland herbaceous crops and irrigated horticultural crops.

## CLIMATE CHANGE MITIGATION POTENTIAL:

Crop rotations can help lessen the need for mineral fertilizers overall. Moreover, certain species that might be included in the rotation may require less fertilization or tillage (as with some cereals), reducing fuel or energy usage. If legumes are also included in the rotation, the need for nitrogen-based fertilizers will be significantly lessened, thereby lowering fertilizer costs.

Complementarily, although moderately, the CO2 storage capacity can also increase when the organic matter content increases due to the increased amount of crop residues.

### CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

In previous periods of Rural Development Programmes (RDPs) in many regions of Spain, agro-environmental measures like crop rotations, environmental fallows, or the use of green manures were included (Fernández, M.A. 2015). Organic Agriculture, which makes crop rotations essential for a more sustainable agricultural system, is becoming a key measure in these kinds of aids.

Moreover, the new Common Agricultural Policy includes, within the Good Agricultural and Environmental Conditions (GAEC), the compulsory use of a minimum number of rotations under the strengthened Conditionality. These rotations must include fallow periods and the use of nitrogen-fixing species. Such requirements are mandatory for direct payments to farmers, an aspect already required in the previous period in the greening component of the basic farmer payment.



# Minimum Tillage, No Tillage and Fallow

**NAME OF THE TECHNIQUE:** Minimum Tilling, No Tilling and Fallow

**OTHER NAMES:** Reduced Tilling, Direct Sowing, Zero Tilling, Conservation Tilling

**TYPE:** Tilling Management

### DESCRIPTION:

Minimum tillage, also known as reduced tillage, involves reducing the frequency or intensity of tillage compared to conventional practices in a given region. This is achieved by decreasing the number of tasks performed on the soil. It can also involve using implements that cause less disruption to the soil profile, such as those that minimally alter it (inversion of the profile) or work at a shallower depth (superficial work).

In the case of woody crops the primary objective of no-tillage is to completely avoid any ploughing on the soil, as it exposes the surface to erosional processes. For herbaceous crops, the equivalent practice is called direct sowing. In direct sowing, seeds or transplants are directly planted on the soil, with some residue from the previous crop (stubble) left in place. Minimal initial soil preparation work is conducted during planting or transplanting. This technique has emerged as a more sustainable alternative to burning stubble, which was found to be harmful to soil fertility and resulted in increased carbon dioxide emissions.

Another alternative, commonly used in specific agro-environmental aid programs within the CAP (Common Agricultural Policy) in Spain, involves restricting tillage during certain times of the year, usually in periods of heavy rainfall risk (spring or autumn) or in designated bird protection areas (ZEPA) on cereal surfaces during breeding seasons of species of interest. This restriction effectively reduces tillage over time. Extending this approach further, the fallow technique involves leaving the soil completely uncultivated for a period ranging from a few months to a full year. This traditional practice, widely employed in the past when fertilizers and pesticides were not available, was essential for restoring minimal soil fertility and controlling crop pests and pathogens, particularly in rainfed crops. Today, the fallow technique is being revived as a requirement within CAP regulations and Rural Development Programs (RDPs), as well as due to the increasing adoption of Organic Agriculture, which restricts the use of agrochemicals. The fallow technique is considered a component of crop rotations, which are described in another section of this manual.

## EXAMPLES:

**Figure 17:** Corn plantation with no tillage technique. Source: Shutterstock (n.d)

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

Tillage practices have various negative effects on the soil, including the breakdown of soil structure, increased mineralization of organic matter when exposed to air and desiccation, the formation of hardpan (a hardened layer due to machinery passage and implement cutting), and significant alterations in the soil microbiota due to solarization. Therefore, any technique that minimizes tillage by reducing the frequency, depth, or degree of soil turning will have a positive effect by mitigating the potential impact of these practices. Leaving the land fallow for an adequate period or at opportune moments can further enhance these benefits.

In conclusion, implementing these cultivation techniques can lead to improved soil structure, increased permeability, enhanced water infiltration capacity, higher organic matter content, and greater biological activity in most cases. Direct seeding and fallow periods, in particular, contribute to the incorporation of a significant amount of biomass into the soil cycle through microbial action. These practices enhance soil resilience against erosion and improve its agronomic quality.

However, specific adverse effects may occur under certain conditions and soil types. These can include excessive soil compaction, the emergence of crop-specific pathogens (especially without proper crop rotation), loss of fertilizers due to delayed incorporation into the soil, and the formation of a surface crust that hampers seed emergence. For instance, in the case of minimum tillage in woody crops like olive groves, some producers have resorted to herbicide application for weed control, which can lead to herbicide contamination in the soil or runoff translocation. This technique has been heavily promoted by companies marketing such products. Fortunately, an increasing number of people are opting for alternative methods such as mowing, cutting, crushing the spontaneous vegetation, or utilizing it for livestock grazing.

Despite the initial yield decrease in rainfed crops during the early years of implementing no-tillage, long-term studies indicate that these techniques gradually improve yields, reaching or even surpassing the levels of conventional cropping. Additionally, significant energy savings are achieved, resulting in reduced farming costs.

## RECOMMENDED APPLICATION CONDITIONS:

These practices are generally suitable for most soil types, except for soils with specific physical issues such as crusting or high clay content. In these cases, the practices may provide temporary improvements by enhancing soil infiltration capacity. Another consideration is the slope of the land, as the application of these practices alone is not recommended for slopes between 5-10% without additional conservation structures.

Minimum tillage or no-tillage is particularly well-suited for woody crops, while in herbaceous crops, it can be relatively easily implemented in more extensive crops like corn, sunflower, and cereals. However, it may less feasible in horticultural crops due to the need for certain soil preparation tasks, such as the removal of adventitious weeds. This aspect is more closely related to direct sowing practices.

When implementing reduced tillage, it is important to choose appropriate periods for the work, avoiding the most intense rainy seasons. Alternatively, fallow periods can be applied, which is especially recommended for horticultural crops.

In terms of crop rotations, continuous and repetitive planting of horticultural species over time can lead to the emergence of diseases that cause significant damage, reducing productivity and increasing control costs. In extreme cases, it can result in soil problems specific to that crop. This issue has been observed in recent years with certain fungi or nematodes affecting crops such as lettuce or brassica species (cabbage, cauliflower, or broccoli) in the Guadalentin Valley or Campo de Cartagena in Murcia.

These techniques can be combined with other soil conservation practices such as contour tillage, rotations, green roofs, terraces, and crushing of plant remains to achieve cumulative benefits through their integrated use.

## REQUIRED RESOURCES:

The primary requirement for minimal or reduced tillage is to have suitable tools that can perform tillage with minimal impact on the ground. Examples include selecting specific sweeps positioned on a moldboard, using a cultivator with shorter tine length, employing blades for mowing grass, etc.

In the case of direct sowing, more specialized machinery is necessary. This machinery combines automatic sowing or transplanting capabilities with minimal labour to create optimal conditions for plant development. It may also include features for the placement of deep fertilizers.

To successfully implement these techniques, farmers will need access to the appropriate tools and machinery based on the specific method chosen, ensuring efficient and effective execution of minimal or no-tillage practices as well as direct sowing.

## DESIGN, EXECUTION AND MAINTENANCE:

When it comes to design, the first step is to evaluate the most suitable and compatible technical alternative based on factors such as the desired crops or existing ones (for woody plants), soil physical and physicochemical properties, machinery availability, and other relevant considerations. Once this evaluation is done, decisions can be made on how to minimize tillage while avoiding or minimizing any potential adverse effects, all while considering the production requirements of the agricultural operation.

Regarding execution, not much can be said except when reducing the number of tillage events. In such cases, the key decision is to choose the phenological stages of the crop or weather conditions that maximize the benefits of tillage while minimizing the risk of erosion. For instance, in a typical rainfed almond crop in the Region of Murcia, up to five passes may be made, but this number can be reduced to just a couple of tasks. On the other hand, in citrus or fruit crops with localized irrigation, it is relatively easy to eliminate or minimize tillage (e.g., no-tillage or once every one or two years) by incorporating organic matter and breaking up any hardpan that may have formed if there is no plant cover.

When applying minimum tillage or no-tillage to woody crops, managing the growth of plant cover may be necessary at certain points. Traditionally, this has been done using herbicides, but more recently, alternatives such as mowing at a specific height or shredding along with pruning residues are being adopted. In critical periods, where the plant cover needs to be completely eliminated (such as during the summer months), the entire ground can be mowed using a weeder or flush passes with a blade, although it is important to ensure that the ground is well levelled.

For fallow periods in cereal and other extensive herbaceous crops, preparatory work can coincide with the onset of the rainy season (early autumn or spring). The goal is to capture as much water as possible to ensure optimal emergence and growth of the crops in the first few months. Therefore, it is crucial to implement contour tillage alongside other techniques like non-till strips, hedges, etc., to mitigate erosion risks.

## CLIMATE CHANGE MITIGATION POTENTIAL:

These techniques have significant positive implications for climate change. Firstly, they contribute to a reduction in fuel consumption required for regular farming activities, resulting in a notable decrease in $CO_2$ emissions. Secondly, by minimizing soil disturbance, they enhance the soil's capacity to store organic carbon in the form of compounds like humus and support a healthier microbiota. Lastly, the reduced soil and nutrient losses also lead to a decrease in mineral fertilizer usage, positively impacting indirect emissions associated with fertilizer production.

## CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

The Common Agricultural Policy (CAP) considers these practices mandatory in sloping areas as part of the general requirements for "Good Agricultural and Environmental Conditions (GAEC)." Compliance with these conditions is necessary to qualify for most direct farm aids. Additionally, in the upcoming programming period for Spain as a whole and specifically in Murcia, one of the eco-regimes will be implemented within the direct payment schemes for farmers, emphasizing crop rotation and direct sowing practices in farmlands.

# Contour Tillage

**NAME OF THE TECHNIQUE:** Contour Tillage

**OTHER NAMES:** Levelling Tillage

**TYPE:** Management of Tillage

**DESCRIPTION:**

Contour tillage involves working on the land along the contour lines as closely as possible, regardless of the agricultural task or implementation used. This means working perpendicular to the line of maximum slope, creating furrows and ridges that slow down runoff and retain water in small channels (furrows) within the soil. By reducing water erosion and increasing water accumulation in the soil profile, this technique enhances water utilization by crops. Contour tillage is often associated with establishing terraces, which also serve as reference points for implementing this practice during crop development.

This traditional practice is widely used in rainfed crops, particularly in regions with extended periods of low rainfall. its purpose is to optimize rainfall usage during the rainy season. Contour tillage has been traditionally employed, almost as a requirement, in Mediterranean areas with hillsides, slopes, or ravines featuring gentle to moderate slopes. It is utilized for both herbaceous crops (such as cereals, sunflowers, and legumes) and woody crops like olive or almond trees. However, due to the mechanization and expansion of crops, this practice has declined. Vertical tillage along the slope became more popular as it was more convenient and faster than contour tillage. Moreover, the increased use of fertilizers reduced the significance of the soil's natural fertility from the farmer's perspective.

It is important to note that while contour tillage can control erosion in herbaceous crops, it may work against us on steep slopes, areas with intense rainfall in short periods, or on soils with low permeability (clayey or loamy). In such cases, it can lead to the generation of streams when working in favour of the slope. Additionally, horticultural crops may face the additional challenge of increased incidence of fungal diseases due to prolonged soil saturation.

In woody crops, contour tillage can be combined with reduced tillage to minimize the frequency of tillage per year. Alternatively, a portion of the middle row, between the tree rows, can be left untilled, reducing the area that requires tilling. Both approaches significantly enhance erosion control. Planting uncultivated areas as conservation strips would be even more beneficial, as conservation strips are highly effective in soil conservation.

Over time, re-tilling following the contour of the row middles in woody crops can create gentle ridges around the base of the tree trunk due to gravity. This increases terrain irregularity and makes moderate erosive processes more challenging.

## EXAMPLES:

**Figure 18:** Example of contour tilling of a field in Georgia a U.S.A.
Source: Jeff Vanuga / USDA Natural Resources Conservation Service (2011),

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

Contour tillage creates furrows in the soil perpendicular to the flow of runoff, resulting in ground irregularities that partially reduce the kinetic energy of water and its erosive capacity (known as the local lamination effect). Simultaneously, it promotes water accumulation on a small scale, along the entire length, and to a certain depth depending on the implement used. This can significantly reduce the initial drainage volume and the risk of stream formation while enhancing water infiltration.

However, a recent study conducted under Mediterranean conditions in central Spain indicated that contour tillage may lead to increased erosion compared to tillage in the direction of the slope, particularly during intense rain episodes in short time periods (Cermeño, I. 2018). This reveals the limitations of this technique concerning the slope of the land where it is applied and the presence or absence of other measures that enhance the terrain's resilience against such extreme episodes with higher erosive potential.

On the other hand, more recent studies suggest that contour tillage has a greater impact on mechanical erosion, which refers to erosion caused by the movement of soil particles resulting from re-tiling and the effect of gravity. As a conservation tillage method, it is more favourable for reducing mechanical erosion compared to tillage in the direction of the slope.

Regarding biodiversity, contour tillage does not have a notable direct impact but indirectly contributes to soil, nutrient, and organic matter retention. This helps maintain the soil's quality and ability to support plant, animal, and microbial life.

Finally, it is important to note that contour tillage is not a permanent technique. Its effects last only a few months, after which it needs to be repeated in woody crops (at least once a year) or when preparing the land for sowing or planting in herbaceous crops. In the case of horticultural crops, it should be performed whenever tillage is necessary to control weeds or break up the hardened surface.

## RECOMMENDED APPLICATION CONDITIONS:

Contour tillage is generally considered suitable for all soil types and crops. It is highly effective in retaining water after moderate rainfall, particularly on gentle slopes ranging from 1% to 10%. In the case of woody species, slopes up to 15% are manageable. However, it is important to note that this technique alone may not be sufficient to prevent runoff after heavy rain or on steeper slopes. Therefore, it is recommended to combine contour tillage with other conservation techniques. Alternative methods such as terraces, hills, plant strips, and/or hedges are more advisable for very steep slopes where tractor manoeuvrability is challenging.

Typically, the orientation of herbaceous crop planting or tree planting aligns with the direction of tillage to facilitate cultivation. Currently, in many woody crop plantations, this type of work is carried out using plantation plateaus, particularly in the case of citrus in Eastern Spain or terraces in olive groves, orchards, vineyards, or almond orchards.

While the fundamental principle of contour tillage is to follow the contours closely, there may be cases where adverse topography (ravines, gullies, rocks, etc.), limited manoeuvring space, or a natural runoff flow different from the slope's direction make it impractical or unhelpful to strictly adhere to this rule in certain sections.

From a regulatory standpoint, codes of good agricultural practices generally consider contour tillage as recommended or mandatory, depending on the slope of the land.

## REQUIRED RESOURCES:

Contour tillage does not require specialized machinery or equipment, except for farms with high slopes where the tractor used must be suitable for working in this direction without the risk of overturning or slipping, ensuring operator safety. GPS-enabled equipment is highly advantageous, as it allows for more precise tillage implementation, especially for herbaceous crops.

Geographic Information Systems (GIS) currently provide accurate maps with contour lines or high-altitude precision for the targeted area. In the absence of modern tools like GPS, theodolites, or total stations for topographic surveys, topographic maps of the terrain can be directly used. Alternatively, older methods can be employed to define contour lines. Another relatively simple approach to approximating the lines of the maximum slope is by using applications like Google Earth™, which provides altimetric values of the terrain, enabling the creation of terrain profiles along specific routes, albeit with potentially lower precision.

In the case of woody crops, careful consideration must be given to the placement of planting lines since adjustments cannot be easily made afterwards, unlike in herbaceous plant farms.

## DESIGN, EXECUTION AND MAINTENANCE:

In terms of design, there are few specific guidelines for contour tillage apart from the fundamental requirement of closely aligning the tillage lines with the contour lines.

One limiting factor to consider is the slope of the land, which should not be steep. It is recommended that the slope is at most 3-5% for herbaceous plants, while for woody plants, it should not exceed 7-10% if contour tillage is applied alone without the support of other complementary techniques. This is particularly important when dealing with less permeable soils.

When implementing contour tillage during land preparation for sowing or planting, the following considerations should be taken into account:

Line spacing depends on the specific crop or intended crop. Generally, a greater depth and width of the furrow will increase its water retention capacity. However, this may be limited by the physical properties of the soil, such as permeability and structure.

The width of the furrow typically has a minimum distance of 25 cm between ridge tops, while the depth should be at least 20 cm during land preparation. However, the actual depth may vary depending on the available implements on the farm, such as moldboards, harrows, discs, and sweeps.

If excess water drainage is controlled, such as through a drainage channel, the tillage lines can be established with a slight 1.5-2% slope. This facilitates the drainage of excess water that could otherwise result in uncontrolled streams and phytosanitary problems, especially in horticultural crops. Such a design is particularly important in soils with low permeability, such as clayey or loamy soils.

In areas prone to heavy rain episodes, especially on steep slopes, additional structures should be incorporated to enhance water retention or facilitate controlled drainage. Therefore, it is recommended that the maximum length of crop strips does not exceed 50-100 meters without the insertion of these structures. However, this recommendation may vary depending on the slope of the hillside and the specific crop being cultivated.

To facilitate the establishment of contour tillage, it is beneficial to create a preliminary plan and/or reconsider land use. This can be achieved by using markers, such as stakes, spaced at regular intervals of 10-15 meters or more in the case of woody crops. These markers serve as reference lines from which tillage will be conducted along the contour lines.

In terms of implements, using those that perform vertical work without turning, such as spiked or chisel plows, sweeps, discs, or subsoilers is recommended. Traditional moldboard plows should be avoided.

Maintenance for contour tillage is not necessary as it does not involve permanent physical structures. The work is renewed with each new herbaceous crop or on an annual basis for woody crops. However, deeper subsoiling can be conducted to improve soil infiltration capacity, especially after many years of tillage. The use of a "subsoiler" type implement is particularly effective as it breaks up the hardpan formed by tillage and helps create deep drainage channels.

## CLIMATE CHANGE MITIGATION POTENTIAL:

Implementing contour tillage may pose some challenges or discomfort for farmers, but it can contribute to reducing fuel consumption slightly. This is because the tractor movement does not involve traversing from higher to lower levels and vice versa, as is the case with tillage following the slope.

Furthermore, contour tillage helps decrease soil and nutrient loss, which can result in slightly higher yields per hectare in the long term compared to tillage following the slope. Additionally, the need for mineral fertilizers may be slightly reduced.

Importantly, contour tillage also helps prevent the loss of the topsoil layer (fertile layer) that can occur in long-term slope tillage. Preserving this layer is crucial for maintaining the land's capacity to support crop growth, particularly in extreme cases.

## CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

For many years, the Common Agricultural Policy has regarded contour tillage as a requirement for sloping areas under the "Good Agricultural and Environmental Conditions (GAEC)" general requirements. It is included in the latest program as part of Conditionality, and compliance is necessary for most direct aids provided to farmers.

# Plant Strips

**NAME OF THE TECHNIQUE:** Plant Strips

**OTHER NAMES:** Strip Cropping, Contour Protection Strips

**TYPE:** Management of Tillage; Plant Cover

## DESCRIPTION:

Plant Strips are an extremely effective soil conservation strategy widely adopted in Spain for many years (Andreu, J. 1945). It entails setting up slender rows or "strips" of perennial herbaceous plants, usually grasses, that follow the slope of the land. These strips serve as intermittent vegetation cover and are typically situated between rows of crops.

While this method is frequently employed with herbaceous crops, it also shows effectiveness with woody crops, particularly when complete plant cover is not required. The herbaceous species are densely planted; if the strips are preserved, spontaneous species may naturally proliferate over time. The breadth and distance between these strips can be constant or variable, ideally decided based on the slope of the terrain and the type of crop being grown.

The standard procedure involves tilling the land along its contours to plant these strips. However, a different crop alignment can be determined when dealing with a gentler slope or wider strip spacing.

One alternative approach is to use these strips as long-term fallow areas, alternating with crop rotation. In this method, the herbaceous strips are ploughed for crop cultivation after a significant duration, while the previously cultivated area is set up as the new strips. In such cases, the strips would cover 50% of the cultivated area, and agriculturally beneficial species like cereals would be chosen.

Another possibility is to utilize these strips as grazing fields for livestock, integrated with the main crop. To ensure their continued effectiveness, livestock density should be managed, or grazing should be periodically paused, to allow for natural regeneration of the ecosystem.

**Figure 19:** Example of strip cropping with inter cropping in the United States. Source: Tin Man (2021), The Combien Forum.

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

The establishment of plant strips can have a profoundly positive impact on soil conservation. These undisturbed surfaces with vegetative cover are highly capable of retaining water and nutrients such as nitrates, thereby mitigating soil loss and minimizing the formation of streams. The effectiveness of these strips is directly proportional to their width and the frequency of their use. Furthermore, the regions occupied by the strips typically exhibit higher organic matter content, a greater presence of microorganisms, and increased biodiversity compared to cultivated areas. This biodiversity can be even richer if the vegetative cover arises spontaneously rather than being intentionally planted. That said, a planted species could prove beneficial for agronomic reasons, such as the incorporation of green manure into the rotation or the promotion of beneficial insects like pollinators or natural predators associated with the crop.

When plant strips of substantial width (spanning several or even tens of meters) are created, they can act as significant ecological corridors for local wildlife. As with many conservation practices, the longer these strips are maintained, the more beneficial their effects become.

## RECOMMENDED APPLICATION CONDITIONS:

Plant strips are usually associated with extensive herbaceous crops, such as cereals, or industrial crops like soybean, sunflower, and corn. In scenarios involving significant slopes, the technique can also be applied to woody crop plantations if the farm layout provides adequate space for the strips.

In terms of soil compatibility, there are no specific restrictions, although steep slopes might necessitate incorporating additional conservation structures to prevent the formation of streams or gullies.

At the regulatory level, the codes of good agricultural practices often view the use of plant strips as advisable or even mandatory, depending largely on the gradient of the land.

## REQUIRED RESOURCES:

The necessary resources are similar to those required for contour tillage, including a seeder and a roller for planting the selected species in these strips. Additionally, a mower or weeding machine is necessary for their upkeep, or a combine harvester may be used if the strips are of cereal crops or similar.

## DESIGN, EXECUTION AND MAINTENANCE:

In designing the strips, they are typically established longitudinally, running continuously along the contour lines. If other conservation structures like terraces or banks are present, these strips are generally placed upstream from them, allowing the slopes to host protective vegetation (either natural or planted) to enhance stability and erosion protection.

For woody species, planting is usually done close to the line of trees, typically upstream. However, the strips are sometimes planted in the middle of the lane as cover. Unlike herbaceous crops, these strips are not applied to all lanes but follow an alternating pattern as needed.

Two key considerations during planting are the width of the strip and the frequency of their distribution, or the space between them, in relation to their positioning.

The recommended design approach places a cultivated plot at the highest part of the slope, followed by a strip downstream. This sequence is repeated, moving in a descending direction. Ideally, a final wider strip should be established at the lower boundary of the plantation, especially if there is a watercourse or drainage channel below that could receive runoff.

When the cultivated lands are part of the Natura 2000 Network and close to wooded or bushy areas, the strips can be designed to connect these natural elements, functioning as ecological corridors for wildlife.

In terms of strip frequency or ground spacing, the limiting factor would be the width of the machinery needed for farm work and crop harvesting. The crop width between protective strips must at least exceed the maximum width of any implements or equipment used. Strips should be spaced approximately 25 m apart at a minimum, and no more than 100 m apart at most. However, for wider strips, greater distances can be considered. A practical method for determining this distance would be to observe the maximum distance at which runoff and rill formation begin to occur on the land and crop. This observed distance should be the maximum considered.

The width of the strips can greatly vary. They should be at least 2-3 m wide to retain water effectively, but not wider than half the length of the crop row where it is placed. For instance, in low-slope cereal crops, strips can be as wide as 5-10 m, but they should be widely spaced. The total surface area occupied should be between 7-50%, depending on the slope.

A variety of plant species can be used for these strips, including herbaceous species with agronomic interest, such as legumes, cereals, other grasses or composites, or their mixtures; species with possible allelopathic effects (insect attraction or repellence); or refuge for useful insects. Over time, the initially established species could be allowed to recede in favour of local herbaceous species that gradually recolonize these areas. Nonetheless, grasses are generally the most suitable in semi-arid conditions aimed at reducing erosion and improving soil retention.

When planting the selected species, itis important to consider the periods of the year when the main rainfall occurs in the area to ensure adequate growth of these strips. If rainfall is scarce, some irrigation might be necessary.

Maintenance may include reseeding for annual species with low self-seeding capacity or mowing, shredding, or grazing for perennial species to prevent excessive growth or proliferation of shrub species. The interval between each intervention depends on the plant species in the strips, their growth rate, and weather conditions. Notably, these surfaces can be used as nesting areas for birds, so nesting periods should be avoided to prevent harm. Some agro-environmental aids from the CAP contemplate temporary restrictions on harvest periods.

In cases of significant sediment accumulation on these surfaces, redistributing this sediment every few years may be advisable. If not redistributed, mounds or terraces may form, offering additional benefits in soil conservation.

## CLIMATE CHANGE MITIGATION POTENTIAL:

Although this technique effectively reduces the cultivated surface area, it also proportionately or even more significantly reduces fuel consumption due to the contour tillage implemented. Soil and nutrient loss decrease, potentially increasing long-term yields per hectare for the actual cultivated area, even if this is not the case for the total area. Consequently, fertilizer requirements are also significantly reduced.

Importantly, this method enhances the organic matter content in the implemented areas. This is achieved by reducing losses from tillage and through the biomass accumulated in these strips from the planted herbaceous plants' residues. The combined effect results in lower $CO_2$ emissions and increased organic carbon.

## CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

For many years, the Common Agricultural Policy has mandated this practice in areas with slopes under the 'Good Agricultural and Environmental Conditions (GAEC)' general requirements. In the latest programming under 'Conditionality,' this practice is a requirement for most direct aid.

# Associated Crops

**NAME OF THE TECHNIQUE:** Associated Crops

**OTHER NAMES:** Mixed Crops, Interspaced, Multiple or Accompanying, Strip Cropping, Mixed Crops, Polycrops

**TYPE:** Crop Management

## DESCRIPTION:

Unlike crop rotation, intercropping embodies the simultaneous cultivation of different plant species within the same field, partitioned into smaller or thoroughly mixed sub-units. Typically, two different crops are interplanted, although the number can be increased, thereby contributing to the biodiversity of the agricultural ecosystem. This technique aims to diversify the crop population in a field, mitigating issues related to monoculture and encouraging natural pest enemies by providing alternative feeding opportunities or pest refuges. Some farmers also note potential yield increases when employing intercropping as opposed to cultivating individual crops.

In many cases, intercropped plants are arranged in a particular geometric distribution, such as expansive cultivation strips or a combination of tree species with herbaceous ones following a linear pattern, like cultivation rows of the taller species. There may also be fewer regular designs, and in some instances, a total mix of species can be seen, as with crops destined for animal fodder or forage.

Urban vegetable farmers using intercropping can deliver a wider range of products to their customers thanks to this cultivation technique. For woody crops, intercropping offers an economic boost, particularly when the trees are still young and leave an open surface that can be utilized for a specific period with this practice by growing vegetables or other crops of interest. In some instances, we see rows of trees or plants allowed to grow when the original woody plantation was replaced by another crop, which is often seen in vegetable cultivation.

Intercropping is also employed for a variety of other reasons, such as the use of some species to enhance soil quality and assist the primary crop, to moderate excessive soil nutrients (like nitrogen), or traditionally, the use of certain species for personal consumption (e.g., fruit trees, olives), or small-scale production of artisanal products like canned food, soaps, etc. In the latter case, these crops are more akin to hedges than actual crops.

**Figure 20:** Wild asparagus and other crops in olive orchards in Italy. Source: Adolfo Rosati (2017).

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

The impact of this farming technique on biodiversity is noteworthy, as increasing the variety of species within a single plantation inherently expands the number of related organisms such as arthropods, microorganisms, etc. Naturally, if more farmers adopt this cultivation method, its effect will be amplified.

Moreover, richer plant stratification occurs when herbaceous and woody species are combined. This leads to more areas for shelter or reproduction and new food sources, greatly encouraging the emergence of other species quite different from the intercropped ones compared to each crop grown separately.

This diversity also benefits the soil. Depending on the species used, it can enhance soil protection and increase the organic matter content.

One key advantage of intercropping is its potential for pest or disease control. The discontinuities created, for instance, by alternating strips, hinder the spread of any plant health issues. Some plants, like tall trees or herbaceous species, can even offer physical protection (acting as barriers) against pests for other crops. In addition, certain cultivated species exhibit allelopathic traits, functioning as repellents (many aromatic species), attractants (trap crops), or fostering the growth of natural enemies or competitors that help control pest development. An example of this is the cultivation of cereals alongside citrus trees. Aphid infestations in the cereal crop can trigger the appearance of predators and parasitoids, which may then move to the citrus trees, helping control the different aphid species that attack them. This Integrated Pest Management (IPM) strategy could effectively reduce the usage of plant protection products.

Furthermore, some plants can attract pollinators, which can assist in pollinating other crops. For instance, this is seen when almonds and cherry trees are intercropped with labiate and composite species and fruit vegetables like peppers or tomatoes.



## RECOMMENDED APPLICATION CONDITIONS:

There are few constraints to this technique, and in general, it can be tailored to fit nearly all crops, whether they are herbaceous, horticultural, or woody species. The main exception is the size of the operation, as in very small plantations, intercropping is not practical, and the subdivision of production into various crops is not profitable. For these scenarios, it can still be applied but on a smaller scale or for personal consumption.

In the case of woody crops, if the plantation layout is too dense, managing the herbaceous or horticultural crop that is planted can be challenging.

Another hurdle comes from managing the intercropped plants themselves. Often, they have different fertilization or watering needs, which can complicate the use of this technique. The application of plant protection products should also be considered. In many cases, certain active ingredients are not approved for both crops, and their proximity increases the risk of contamination due to product drift or runoff. Therefore, Organic Farming is more conducive to this technique, as the few approved active compounds tend to be more generic. Alternatively, there may not be any available products to combat some of these pests.

## REQUIRED RESOURCES:

The implementation of intercropping may necessitate an increase in equipment for tasks such as planting, transplanting, tending, and harvesting, similar to crop rotation, although the effect is less significant. However, another challenge at the professional level is the need to assess the compatibility of the associated crops. It is essential to ensure these crops are adapted to the crop cycles, management and mechanization, fertilization and irrigation, pest treatments, etc., to prevent any management issues. Because of this, the use of intercropping has grown in

Organic Farming systems. Nonetheless, with careful planning, some beneficial crop combinations could also be introduced into more intensive agricultural systems, considering the precautions above.

## DESIGN, EXECUTION, AND MANAGEMENT:

Various designs can be used to implement intercropping. Typically, relatively large strips interspersed with the primary crop are used. The size of these strips depends on the goal and the species to be combined with the main crop. In some instances, when both crops are of equal importance, the farm should be split into two equal parts with different shapes, with the crops placed alternatively. For woody crops, the herbaceous crop is placed in rows between the tree lines. In the case of vegetable crops, it is common to use one species more frequently, often as perimeter hedges around the property's boundaries.

Another approach, popular for small organic gardens or for producing grasses, is a random mixture of species over the same area. This approach can enhance the interplay between species in terms of allelopathic activities, nutrition support, nitrogen fixation, and more. It can also be used in plantations designed to produce quality fodder for livestock.

The species selection will depend on the farmer's interests regarding commercial viability, profitability, or other desired benefits or effects.

In terms of maintenance, nothing significant stands out other than the need for effective management of the intercropped plants, which is understandably more complex than managing a monoculture.

## CLIMATE CHANGE MITIGATION POTENTIAL:

Crop association may not be renowned for its environmental benefits, but it does offer some advantages regarding climate change. For instance, as mentioned before, using crop association can help reduce the occurrence of key pests, which may lead to less use of plant protection products. This reduction could subsequently decrease costs and fuel usage due to fewer required interventions.

Depending on the types of plants that are grown, certain herbaceous species might help improve soil fertility and boost the capacity for CO2 storage. Furthermore, pairing a crop with a soil-protecting species offers a practical option. In this situation, soil erosion could be diminished, leading to enhanced fertility, lower fertilizer costs due to decreased nutrient loss, and increased organic storage.

## CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

Even though crop association is an intriguing practice that aligns well with various production approaches and is increasingly being adopted, agro-environmental support measures have not yet been considered to promote this technique, unlike crop rotations. However, it has been incorporated into the good agricultural or environmental practices of the Common Agricultural Policies (CAP). In relation to crop diversification found in the greening requirements, these are now included in the new CAP within the Good Agricultural and Environmental Conditions (GAEC) of the Enhanced Conditionality. This inclusion implies that crop association could be a potential alternative to meet the requirements for direct payments from the CAP.

# Cover Crops

**NAME OF THE TECHNIQUE:** Cover Crops

**OTHER NAMES:** Green or Live Covers, Vegetation Cover, Green Fertilizers, Spontaneous or Natural Covers

**TYPE:** Plant Cover

## DESCRIPTION:

As in other techniques described, the present section integrates techniques that are somewhat different in their focus or aim but whose final result is very similar in their overall effects. Plant covers involve establishing a permanent presence of one or more herbaceous, annual, or perennial species, either sown by the farmer or naturally occurring local species. When there is no tilling or use of herbicides in woody crops, these plant covers envelop either part or the entire surface of the crop. Their growth is typically controlled through mowing or livestock grazing.

At present, these covers are highly valued for their contribution to integrated pest management. They offer benefits such as the preservation of natural predators of pests that damage crops, including aphids, mites, whiteflies, and others. However, their main advantage lies in protecting soil against erosion caused by water or wind. In southeast Spain, plant covers are increasingly used in olive groves, citrus plantations, stone fruit and pome fruit orchards, and occasionally vineyards. Their usage is a critical component of organic farming operations.

In many cases, these covers create an expansive green layer over the land, usually planted in the spaces between rows of trees, with a gap maintained around the base of the tree trunks. Occasionally, they are planted around the base of the tree, leaving the middle of the row open for tilling. However, in some regions, the cover extends over the entire crop surface, appearing like a meadow. This is still visible across various parts of Europe, such as in dryland plantations used for pasture and in well-known groves of holm oak. It is also observed in almond, olive, or carob groves and some fruit tree species in Central Europe. Traditional irrigated flatland areas in the south and southeast of Spain still exhibit small citrus orchards with permanent covers throughout, composed predominantly of herbs like wood sorrel (Oxalis sp.).

Common practice often involves sowing one or more selected species for a specific benefit, such as atmospheric nitrogen fixation (in the case of legumes), resulting in what is known as green manures. The Common Agricultural Policy (CAP) strongly promotes these, and their importance in conserving beneficial insects to combat pests is growing. There is also a rising trend in using covers of local herbs and spontaneous flowers, which gradually establish themselves in the plantation through selective mowing. One must consider the rainfall in the area as the amount and distribution of rain can be a limiting factor for many grass species, whether sown or naturally occurring. In Mediterranean conditions, some irrigation is advisable to support initial growth or to provide relief during droughts in spring and summer, though it is not ideal.

So far, we have primarily discussed plant covers in woody crops, which are the main focus. However, they can also be applied to herbaceous crops, particularly vegetables. Introducing improving species like legumes (green manure) or cereals is increasingly common within the yearly crop rotations. The primary difference with woody species is that these covers tend to be annual rather than permanent to align with crop cycles. In certain situations, such as excess soil nitrogen or the presence of a pathogen, it may be beneficial to establish a cover that mitigates the problem, enabling the growth of commercially valuable species. Regardless, in both woody and herbaceous crops, the ultimate objective is to ensure the soil is effectively protected by a herbaceous cover, minimizing periods of partially or entirely bare soil and realizing the various other benefits they offer.

**Figure 21:** Cover crops used in a vineyard for pest control. Source: Jacqueline Macou (2016).

## IMPACT ON SOIL CONSERVATION AND BIODIVERSITY:

Implementing plant covers produces effects akin to those brought about by plant strips but with greater intensity, given the larger coverage area. The key benefits include significant improvements in water and nutrient retention capacity, specifically for Nitrogen (N) and Phosphorus (P). Simultaneously, they reduce reliance on plant protection products, curbing potential environmental losses. Additionally, they encourage the layering of runoff, thereby substantially minimizing soil loss and the formation of streams.

Soil fertility, particularly in terms of organic matter content, microorganism presence, and overall biodiversity, witness a considerable boost. Spontaneously grown, local species-based covers yield much higher biodiversity. Though some intentionally sown species may offer specific benefits, like acting as green manure, impacting the crop, or promoting beneficial insects (pollinators or natural enemies), it is generally observed that both types of covers significantly augment the number of natural enemies (predators and parasitoids) in a mature plant cover. This results in notable savings on specific insecticides typically required for pest control in conventional plantations.

On the policy front, apart from the aforementioned role of integrated pest management in the sustainable use of plant protection products, the codes of good agricultural practices established for controlling diffuse pollution from nitrates of agricultural origin often recommend or mandate this practice, starting from a specific slope of the woody crop terrain.

Finally, it has been observed in practice that plant covers significantly decrease the likelihood of flooding in the terrain, thanks to increased soil porosity and improved structure. These provide indirect benefits to the farmer by enabling field traversal post-rainfall and reducing the incidence of fungal diseases.

## RECOMMENDED APPLICATION CONDITIONS:

As previously stated, plant covers are primarily applied to woody crops. However, herbaceous crops (particularly vegetables) are utilized as green manure and other beneficial herbaceous species, which could also fall under this category.

Typically, these covers can be implemented in any soil type or slope, with the primary limiting factors being the minimum precipitation necessary for the successful growth of the chosen herbaceous species and the space available between trees for their establishment and subsequent management. However, soil quality and local weather conditions can significantly influence the development of certain species of planted covers due to their specific requirements. As such, they may not be recommended under certain circumstances, such as for species that require a particular temperature range or those negatively affected by calcareous soils.

These covers readily adapt to pre-established designs in mature plantations, an advantage amplified if the plantation was initially designed with plant covers in mind, whether aligned with or against the slope. This characteristic renders this technique highly suitable and versatile compared to other techniques, which may present more limitations in this respect.

## REQUIRED RESOURCES:

Certain equipment is necessary to implement these plant covers. First, one or two pieces of machinery are required to prepare the terrain for sowing. A seeder and a roller are also needed to flatten the surface, ensuring good contact between the seeds and soil particles. Optionally, you might want to apply an organic amendment for soil enrichment. Furthermore, a substantial quantity of seeds of the chosen species is required for planting.

Lastly, for maintenance, it would be prudent to have a mower, shredder, or weeder. In relation to this, there are now precision mowers equipped with articulated arms and sensors, which facilitate mowing between tree trunks without causing them any damage.

## DESIGN, EXECUTION AND MAINTENANCE:

An important aspect to decide is the total area of the cover relative to the crop. For instance, in many fruit tree orchards or vineyards, the cover crops often occupy the entire lane between rows of trees, with only a small area near the trunk, between 20-100 cm, remaining cover-free. This cover-free area is typically either mechanically controlled through mowing or chemically controlled with herbicides. For other crops with lower and denser branches, like citrus or olive groves, the cover-free space might be slightly larger, leaving the area directly under the tree canopy exposed. In older plantations such as plains, it's common to find complete cover crops reaching the tree trunks.

As previously noted, traditional farming systems in Spain and Italy, especially in dryland wood crops, often use pasture farming. Here, the plant cover is typically spontaneous, allowing its growth to create surfaces suitable for grazing livestock with a reduced livestock load suitable for the local climate. These covers can be enhanced by sowing species that provide benefits for the livestock.

While the competition for water and nutrients between the cover crops and the main crop is generally minimal due to the nature of tree crops, the decision to implement cover crops should be based on additional management aspects. These may include localized irrigation in plantations, the presence of plateaus in citrus groves, and support structures in vineyards, among others.

The next consideration is the type of cover crop to establish, taking into account the local climate, soil conditions, and the specific benefits sought from this technique. The cost-effectiveness of each type of cover crop should also be considered, comparing the cost of sown versus spontaneous cover crops.

Despite the scarcity of extensive information on this topic, recent years have seen numerous studies and trials to test the behaviour and effects of specific species and their management depending on the crop type. In Spain, information is particularly abundant for olive trees, although interest is growing for other significant species such as citrus, vineyards, or almonds. Among the cover crop species sown, we find legumes like vetch and fodder clover, grasses like oats or barley, and various lawn species like Festuca sp., Hordeum sp., Bromus sp., etc., as well as species from the cruciferous family. Many trials have investigated combinations of species to combine or add benefits, such as a cereal/legume combination to improve the Carbon/Nitrogen ratio when their remains are humified.

Among these benefits, the nitrogen-fixation ability of legume species is well-known, which contributes significant amounts to the soil. This helps in reducing the need for mineral fertilization, leading to savings. Cases of allelopathic effects (attraction or repulsion of insects) and antagonistic effects (such as rye and soil nematodes) have also been observed. In other cases, physical soil improvements are notable; grasses typically improve soil permeability due to their root systems.

Moreover, with the decrease in the availability of phytosanitary products for use in woody crops to combat pests, some crop protection research teams have sought to understand the biological implications of planting cover crops with specific herbaceous species. These teams aim to identify which natural enemies can be attracted by these covers to enhance natural pest control, a practice known as conservation biological control. While still in the early stages, there have already been instances providing added value to this biological control approach in crops, such as the use of Festuca sp. in citrus orchards.

Currently, seed-based products from various species are commercially available for use as cover crops in specific crops. However, farmers might find it beneficial to create their own species mix based on specific needs and interests.

Sowing should occur in anticipation of the rainy seasons, with proper soil preparation and seeding a few days before expected rainfall to ensure good seed germination. In Spain, sowing usually occurs in spring or autumn. If rainfall is insufficient following sowing, supportive irrigation may be required using a tank or cistern dragged through the lanes. The seeding dose (number of seeds per area) may vary based on the herbaceous species but a dense sowing is generally recommended due to the high potential of non-germination and the need to maximize erosion control on steep slopes.

When the goal is to establish a spontaneous cover of natural vegetation, it is common to start the process at the same time as the planting of the main crop, when the trees are young, and plenty of vertical space and light are available. The freshly tilled soil also allows plants to germinate more easily. An alternative approach could be to initially sow a plant or a mixture that can help protect the soil at first but eventually allow natural grasses to colonize the area.

Maintenance may require periodic reseeding if the species struggle to propagate or if the cover crop ages (renewal). The growth of cover crops is typically managed to prevent them from growing too tall or competing for water. Thus, they are often mowed or crushed, or even grazed by livestock from time to time. The frequency of these interventions will depend on the growth rate of the plant species and the local weather conditions. Many researchers recommend that in Mediterranean conditions, cover crops should be mowed during their flowering period (between late March and April). However, in regions like Murcia, mowing might need to occur earlier due to lower rainfall. Observations in plantations with spontaneous covers reveal that the existing species are small and require little water, so their management is seldom necessary.

Over time, in these spontaneous covers, a species selection process occurs after mowing or clearing and cultivation work. This process shifts the flora from initial annual, opportunistic, nitrophilous, and invasive species (in the case of crucifers) to more perennial ones with slower, creeping growth (like grasses, legumes, etc.).

Once the cover crop is well-established, shallow tilling can be performed every year or two. This process removes a small portion of the surface layer of the cover crop, aiding in self-sowing, improving aeration, and facilitating the incorporation of organic remains into the soil. This work can also be done alternately, on every other lane each year.

## CLIMATE CHANGE MITIGATION POTENTIAL:

Employing cover cropping techniques in woody crops significantly curtails the necessity for frequent tillage. This practice reduces it to mowing approximately once or twice per year, supplemented by occasional surface and vertical tillage. The latter method is used to aid in the effective incorporation of organic matter produced by the cover crops and to soften the soil's surface for natural self-seeding processes. This practice greatly reduces fuel consumption in agricultural operations, thereby contributing to environmental conservation.

The implementation of cover crops leads to a decrease in soil and nutrient loss. This has a dual positive effect: it enhances the yield of the crops and reduces the necessity for artificial fertilizers. In addition, due to the decreased mineralization and the increase in biomass incorporated into the soil by the cover crops, there is a substantial rise in the accumulation of organic matter. This increase in organic matter, in turn, has a very positive effect on the carbon dioxide storage capacity of the soil, contributing to efforts to mitigate climate change.

## CONNECTION WITH THE COMMON AGRICULTURAL POLICY:

For many years, the CAP has deemed the implementation of cover crops as an obligatory practice in areas with steep slopes. This requirement falls under the "Good Agricultural and Environmental Conditions (GAEC)" general prerequisites and has been incorporated into the most recent program under the Conditionality clause, forming a requirement for most forms of direct aid. More recently, this practice has been particularly required in the obligatory measures within the green payment, "greening," concerning minimum soil coverage and designating areas of ecological interest. In fact, the newly updated CAP for the years 2023-2027 includes a Reinforced Conditionality clause.

# CARBON SEQUESTRATION IN POOR AND DEGRADED SOILS





Carbon sequestration in the soil is crucial in addressing climate change and ensuring sustainable soil management. Carbon sequestration refers to the process of assimilating atmospheric carbon dioxide through primary production and storing it within biomass and soil. In this chapter, we will explore the relevance of carbon sequestration in poor and degraded soils, particularly in Mediterranean regions. We will delve into the complexities involved in implementing carbon sequestration practices, the different pathways for sequestration, and the measurement methods used to assess carbon sequestration rates in the soil.

Carbon sequestration in poor and degraded soils is a multifaceted process influenced by a range of factors. These include past edaphoclimatic conditions, historical land use practices, political decisions, property structures, and land tenure systems. Additionally, the current state of the territory and future considerations further contribute to the complexity of implementing carbon sequestration practices. With their natural vulnerabilities and amplified climate change impacts, Mediterranean regions provide a unique context for analysing carbon sequestration strategies.

Implementing carbon sequestration practices in these regions is a multifaceted process influenced by various factors. Past edaphoclimatic conditions, historical land use practices, political decisions, land tenure systems, and the current state of the territory all contribute to its complexity. Furthermore, future considerations need to be accounted for to ensure long-term effectiveness.

In Mediterranean regions, carbon sequestration primarily relies on two pathways: agroforestry practices and land use management. Agroforestry practices entail direct soil interventions, such as crop rotations, afforestation, and the use of pastures. Conversely, land use management involves broader landscape changes impacting the carbon balance, such as the creation of protected areas or modification of agricultural practices.

Assessing the rate of carbon sequestration in the soil is achieved through two distinct methods. One quantifies the amount of carbon stored per hectare per year (tC/ha/year), providing a direct annual measurement. The other utilizes the "IPCC Change Factor" (IPCCf), a tool developed by the Intergovernmental Panel on Climate Change, which offers a relative measure of change in soil carbon content over time.

When pursuing these pathways, it is critical to account for secondary carbon costs, ensuring the net impact on the climate is positive. The practices chosen may have indirect emissions, which can potentially outweigh the carbon sequestration benefits. A comprehensive evaluation should consider both the direct carbon storage in biomass and soil and the indirect emissions associated with the chosen practices.

Sustainable soil management practices, which include crop rotation, cover cropping, reduced tillage, and biochar application, offer a portfolio of strategies that can enhance soil health, promote biodiversity, increase agricultural yield, and sequester carbon. Afforestation, the adoption of perennial crops, and agroforestry systems further augment the potential for carbon sequestration. The planning and management of land use, aligned with regenerative agriculture principles, fosters resilient landscapes with long-term carbon sequestration potential.

Carbon sequestration can prove vital for sustainable soil management, especially in areas like the Mediterranean, where climate change vulnerabilities are amplified. By understanding its complexities, exploring different sequestration pathways, and employing appropriate measurement methods, we can effectively incorporate carbon sequestration into agricultural systems. By integrating sustainable soil management practices, we can improve soil health, enhance agricultural productivity, and contribute to climate change mitigation."



# Management practices and carbon sequestration

Various soil management practices in farming can benefit both crop yield and the environment. These practices go beyond conventional methods and can potentially increase the carbon content in the soil. It is important to recognize that what is considered "conventional" can differ based on factors such as climate, soil type, traditional knowledge, property structure, and socio-economic conditions. Implementing multiple carbon-friendly practices often leads to even more positive outcomes (Aguilera et al., 2013).

There are two **Pathways to Increase Carbon Sequestration**:

- **Practices that enhance biomass production:** These practices introduce more carbon into the soil by promoting the growth of biomass. Examples include different types of crop tillage, surface cropping, waste management, and the use of natural or artificial fertilizers.
- **Practices that reduce soil erosion:** By implementing practices that decrease soil erosion, we can minimize the loss of carbon already present in the soil. Cover cropping, conservation tillage, and erosion control measures are some examples of practices that can help retain carbon in the soil.

## SUMMARY OF CARBON SEQUESTRATION RATES:

A comprehensive meta-analysis conducted in 2013 synthesized data from 174 datasets and 79 publications to assess the carbon sequestration potential of various soil management practices in Mediterranean agricultural systems. The analysis categorized the results into two groups: findings from actual agricultural fieldwork and results from experimental plot fieldwork. Additionally, it differentiated between "organic" treatments (including organic fertilization and cultivation methods other than zero-tillage with herbicides) and "conventional" treatments (no fertilization or only stubble, and traditional tillage) (Aguilera et al., 2013).

Here is a summary of carbon sequestration rates for various management practices:

- **No Till:** 0.44 tC/ha/year
- **Reduced Till:** 0.32 tC/ha/year
- **Surface Crops:** 0.27 tC/ha/year
- **Compost:** 1.32 tC/ha/year
- **Sideration:** 0.97 tC/ha/year
- **Manure + Surface Crops:** 0.97 tC/ha/year
- **Combination of practices:** 0.52 tC/ha/year
- **Organic farming compared to Conventional farming:** 0.97 tC/ha/year

To illustrate the potential impact, let us consider reduced tillage as an example for a 100-hectare piece of land. With a carbon sequestration rate of 0.32 tC/ha/year, this practice would result in the sequestration of 32 tonnes of carbon (tC) annually over 100 hectares. To convert this value to CO2, multiply the tC by 3.7 (as the molecular weight of CO2 is 3.7 times that of carbon), giving 118.4 tonnes of CO2 sequestered each year.

It is important to note that carbon sequestration rates can vary significantly based on local conditions. Factors such as soil type, topography, climate (including temperature and rainfall variability), crop selection, rotation, and fertilization techniques can influence the actual rates of carbon sequestration. Therefore, it is unrealistic to expect a universal or even a "Mediterranean" value for the carbon sequestration capacity of each practice.

The carbon sequestration rates provided serve as a starting point for farmers to understand the potential benefits of different soil management practices. However, these figures emphasize the need for further research and adjustments tailored to specific local conditions. By conducting site-specific studies and making adaptations, farmers can achieve higher carbon balances and capitalize on the benefits of carbon sequestration within the broader context of climate change mitigation strategies.

The following examples illustrate soil and land management elements that farmers and land managers can adopt to enhance carbon sequestration in agricultural systems. These practices are based on scientific literature and provide insights into potential gains in soil carbon. By emphasizing the importance of these practices, we highlight their role in mitigating climate change in poor and degraded soils within Mediterranean climates.

# Soil Mobilization

Tilling, or soil mobilization, is a significant factor contributing to soil loss and the subsequent loss of soil carbon. Research has shown that tilling can result in the erosion of soil carbon through mechanical and biochemical processes. Mechanical factors, such as the disruption of particulate organic matter, and biochemical factors, like increased oxidation rates due to exposure to air and sunlight, contribute to the loss of soil carbon (Roxo, 1994; Van Muysen et al., 1999; FAO, 2004; Bot & Benites, 2005).

To mitigate the loss of soil carbon and enhance carbon sequestration, different types of tillage practices have been studied in semi-arid conditions and Mediterranean agricultural systems. These practices include reduced tillage (RT), minimum tillage (MT), no-tillage (NT), subsoil tillage (ST), shallow tillage (ShT), and full inversion tillage (FiT). It's important to note that the precise definition of each practice varies due to local nuances and considers factors such as crop type, property structure, and land characteristics.

Studies have shown that after 20 years, a chrono sequence in Mediterranean conditions revealed a difference of 5.7 tonnes of carbon per hectare (t C/ha) between no-tillage and conventional tillage, corresponding to an annual sequestration rate of 0.285 t C/ha/year (Álvaro-Fuentes et al., 2014). The benefits of no-tillage become more pronounced over time. Initially, there is a significant increase in carbon in the surface layer (0-5cm), while some losses may occur in the deeper soil layers (up to 30cm). However, this trend reverses after approximately five years, resulting in a compensatory effect (Álvaro-Fuentes et al., 2014).

A review of 66 long-term experiments reported an average carbon sequestration rate of 0.3 t C/ha/year for no-tillage, compared to 0.17 t C/ha/year under conventional tillage, indicating a difference of 0.13 t C/ha/year. The study also highlighted that no-tillage benefits are greater when combined with diverse crop rotations. Additionally, lower values were observed under minimum tillage compared to conventional tillage, suggesting that the interpretation of results can be influenced by the local nuances of the "minimum" tillage concept (Francaviglia, Di Bene, et al., 2017).

Another long-term study comparing no-tillage with surface tillage and full inversion tillage found that carbon sequestration rates were initially intense during the first four years but started to stabilize at year 24 and decrease after year 28. However, this stagnation and decrease in carbon sequestration were associated with a particularly rainy period, highlighting the vulnerability of these practices to external factors such as climate and the duration of their application (Dimassi et al., 2014). Therefore, when implementing management practices for carbon sequestration, it is crucial to consider the long-term effects on carbon capture and storage and their susceptibility to exogenous factors like climate variability and unpredictability.

These findings emphasize the importance of adopting soil mobilization practices that reduce soil disturbance and promote carbon sequestration. Implementing no-tillage and other reduced or minimum tillage practices can contribute to the long-term sequestration of carbon in agricultural systems. However, it is essential to consider the local context, including soil characteristics, crop rotations, and climate conditions, to optimize the effectiveness of these practices for carbon sequestration.

# Waste Management

Effective waste management practices, particularly the reuse and recycling of agricultural residues, play a crucial role in carbon sequestration within agricultural systems. The approach to waste management is closely linked to soil mobilization practices and can significantly influence the decomposition rate, integration into soil organic matter, and subsequent carbon sequestration.

Traditionally, agricultural residues, such as those from olive groves, have been burned, resulting in the immediate release of carbon into the atmosphere. However, an alternative approach proposed by Nieto et al. (2011) involves spreading these residues directly onto the soil. This practice has been shown to enhance the soil's capacity to sequester carbon, leading to an increase in soil carbon content by approximately 0.5 to 0.6 tonnes of carbon per hectare per year (t C/ha/year).

The positive impact of waste management on carbon sequestration can be further amplified when combined with practices that promote the maintenance of spontaneous vegetation. Studies by Ruibérriz et al. (2012) suggest that the potential for carbon sequestration can increase to as much as 1.36 t C/ha/year in such scenarios. The presence of spontaneous vegetation contributes additional biomass, enriching the organic matter content of the soil and enhancing its carbon sequestration capacity. This highlights the importance of preserving and enhancing biodiversity in agroecosystems as a means of effective carbon management.

Another study conducted in an almond orchard, as reported by Garcia-Franco et al. (2015), examined two practices: green fertilization using vetch and oats and zero tillage. The results indicated that green fertilization led to a 14% increase in soil carbon content at the surface level compared to the initial period. The residues from vetch and oats played a significant role in the formation of new soil aggregates, thereby improving organic matter stabilization within the soil.

Stabilizing organic matter is critical for soil carbon dynamics as it helps retain carbon within the soil, reducing its vulnerability to decomposition and preventing its release as $CO_2$. By introducing fresh organic matter through practices like green fertilization, the soil's structure and ability to retain carbon are enhanced, making substantial contributions to carbon sequestration efforts.

# Surface Crops

In Mediterranean agricultural systems, poor and degraded soils present significant challenges to sustainable production. However, the use of surface crops, also known as cover crops, has proven to bring substantial benefits to such soils by promoting soil health and carbon sequestration.

A study conducted by Albaladejo et al. (1998) highlighted the crucial role of surface crops in maintaining soil carbon content and structure. The research found that four and a half years after the removal of surface crops from an experimental plot, the soil carbon content decreased by 35%. Additionally, soil aggregate stability decreased by 31%, leading to an 8% increase in gross density compared to control plots. These findings underscore the importance of cover crops in preserving soil structure and sequestering carbon.

Marquez-Garcia et al. (2013) investigated the effects of surface crops on erosion and carbon sequestration in dryland olive groves. Compared to the conventional practice of using glyphosate for herb removal, surface crops reduced soil erosion by 80.5% and soil carbon transport by 67.7%. The surface crops also sequestered 3.35 tonnes of carbon per hectare per year (t C/ha/year), demonstrating their effectiveness and cost-efficiency as a carbon sequestration method. However, the rate of carbon sequestration appeared to saturate or decrease over time.

The benefits of surface crops extend beyond dryland olive groves to irrigated systems as well. Preliminary data from an ongoing study by Ballesteros et al. (2020) suggest that surface crops in irrigated olive groves can potentially increase carbon content in the topsoil horizon, leading to improved water-use efficiency and offsetting evapotranspiration losses. This indicates that surface crops can contribute to maintaining soil health and productivity even in intensive, irrigated agricultural systems.

A comprehensive meta-analysis by Poeplau & Don (2015) incorporating 139 samples from 37 sites, primarily in temperate zones, over experiments lasting up to 54 years, reported an average increase in soil carbon content of $0.32 \pm 0.8$ tonnes of carbon per hectare per year (t C/ha/year). When these data were modelled using the RothC carbon cycling model, it predicted a carbon accumulation of 16.5 tonnes of carbon per hectare (t C/ha) after 155 years compared to conventional practices, averaging about 0.11 t C/ha/year.

It is important to note that the potential nitrous oxide ($N_2O$) emissions associated with the use of cover crops should be evaluated on a case-by-case basis. $N_2O$ is a potent greenhouse gas, and its emissions are highly influenced by local and cultural factors, making it challenging to generalize data on a global scale. Caution should be exercised to minimize $N_2O$ emissions while maximizing the benefits of surface crops for carbon sequestration.

# Natural and Artificial Fertilization

Natural and artificial fertilization practices are crucial to soil fertility and carbon sequestration in agricultural systems. The type of fertilization used, whether organic or inorganic, can significantly impact soil carbon content and overall carbon sequestration potential.

Organic fertilization, including materials such as manure, sludge, and compost, has been found to have substantial benefits for soil carbon sequestration. A global meta-analysis by Maillard & Angers (2014) demonstrated that manure fertilization accounted for at least 53% of the variation in soil carbon content compared to mineral fertilization or no fertilization. This resulted in a 12% increase in carbon assimilation and a soil carbon gain of 1.26±0.14 tonnes of carbon per hectare per year (t C/ha/year) in the top 30cm of soil. These findings highlight the significant potential of organic fertilization, particularly with manure, in enhancing soil carbon sequestration.

Inorganic fertilization, represented by mineral fertilizers, can also contribute to carbon sequestration through increased biomass production. The assumption is that greater biomass leads to more organic matter being returned to the soil, thereby increasing soil carbon content. However, it is crucial to consider the indirect emissions associated with inorganic fertilization, such as $CO_2$ emissions during production, transport, and application, as well as potential $N_2O$ emissions from denitrification. These emissions can offset the carbon sequestration benefits if not carefully managed (FAO, 2004).

A meta-analysis by Han et al. (2016) examined the rate of carbon sequestration associated with different types of chemical fertilization compared to a conventional base scenario. The results indicated increased rates of carbon sequestration across various categories: a 10% increase in simple chemical fertilization, a 15% increase in adjusted chemical fertilization, a 19.5% increase in chemical fertilization with straw integration, and a substantial 36.2% increase in chemical fertilization with manure introduction. This suggests that careful management and intensification of fertilization practices can be a powerful tool for carbon sequestration in agricultural systems.

To maximize the benefits of fertilization for carbon sequestration, it's essential to adopt an integrated approach that considers both organic and inorganic fertilizers. This approach should account for the potential environmental impacts and strive to minimize indirect emissions associated with fertilization practices. By carefully managing and optimizing fertilization techniques, farmers can enhance soil fertility, increase biomass production, and contribute to carbon sequestration efforts in agricultural systems, particularly in poor or degraded soils.

# Fallow Management

Fallow land management is crucial in soil carbon sequestration in agricultural systems. The type of land cover during fallow periods significantly influences the soil's ability to sequester carbon and prevent erosion.

Bare soil fallow, where the land is left unseeded without any vegetation cover, offers limited protection against erosion and minimal opportunities for carbon sequestration. While it allows for the natural restoration of soil nutrients, it does not contribute significantly to soil carbon storage.

Ploughed soil fallow, where the land is tilled during the fallow period, can help control weeds and pests. However, it can also accelerate the breakdown and loss of organic matter, decreasing soil carbon storage.

In contrast, fallow land with surface crops provides significant benefits for carbon sequestration and erosion control. Surface crops, whether spontaneous or intentionally sown, contribute to primary production through photosynthesis. Unlike regular farm crops that are harvested, surface crops on fallow land are typically left in the field, allowing their full integration into the soil. This process significantly increases the soil's organic matter content and enhances its carbon sequestration capacity.

Furthermore, surface crops provide mechanical protection against erosion. The presence of plant roots stabilizes the soil, reducing the risk of soil particles being washed away or blown off by wind. This is especially important in regions with heavy rainfall or strong winds, where soil erosion can have detrimental effects on soil fertility and carbon storage capacity.

Extending the duration of fallow periods, particularly incorporating surface crops, can further increase soil carbon sequestration. A study by Freibauer et al. (2004) suggests that increasing the duration of fallow pastures can result in an average gain in soil carbon ranging from 0.1 to 0.5 tonnes of carbon per hectare per year (t C/ha/year). This highlights the importance of strategic fallow land management for enhancing soil carbon sequestration in agricultural systems.

By implementing fallow land management practices that incorporate surface crops and extend fallow durations, farmers can promote soil health, increase carbon sequestration, and mitigate soil erosion, contributing to more sustainable and resilient agricultural systems.

# Integrated Systems: Agroforestry, Grazing, and Agrosilvopasture Practices

Integrated systems that combine agroforestry, grazing, and agrosilvopastoral practices offer sustainable farming approaches with significant potential for carbon sequestration and multiple ecosystem services. These practices integrate trees, crops, and livestock within the same land area, fostering resilience and environmental benefits.

Agroforestry practices, such as silvopastoral and silvoarable systems, can sequester carbon through the combined effects of trees and agricultural activities. Silvopastoral systems, which integrate trees, pasture, and livestock, have reported carbon sequestration rates ranging from 0.29 to 1.31 tonnes of carbon per hectare per year (tC/ha/yr) (Tsonkova et al., 2012). Silvoarable systems, which combine trees and crops, can sequester carbon at rates of 0.42 to 0.71 tC/ha/yr (Feliciano et al., 2018). Factors influencing carbon sequestration include tree species selection, tree density, and management practices like pruning and thinning.

Grazing and pasture management practices also play a role in carbon sequestration. Well-managed grazing systems, including rotational grazing, promote sustainable livestock farming while maintaining grassland productivity and carbon sequestration capacity. These practices enhance soil organic matter and soil structure, contributing to increased carbon storage.

Agrosilvopastoral systems, which integrate trees, crops, and livestock, provide combined benefits of carbon sequestration in biomass and soil, along with other ecosystem services. The specific tree species, arrangement, and management practices influence carbon sequestration potential.

Integrated systems like the Montado system in Portugal and the Dehesa system in Spain exemplify the successful implementation of agrosilvopastoral practices. These traditional systems incorporate tree species like cork oaks and holm oaks alongside pastures and livestock. They provide economic resources such as cork and high-quality meat products while contributing to carbon sequestration, biodiversity preservation, and landscape conservation.

**Figure 22.** Montado in Évora Alentejo. In this system, trees are explored for their cork and also provide pigs with food. The pigs, in turn, help fertilize the land to close the cycle.
Source: David Germano (2020).

In addition to carbon sequestration, integrated systems offer co-benefits such as enhanced soil fertility, increased biodiversity, improved microclimate, diversified farm income, and improved water quality. They also contribute to animal welfare and productivity, providing additional economic and social benefits.

To successfully implement integrated systems, careful management is required, considering the interactions between components. Selection of appropriate tree species, optimal grazing intensities, and effective management practices are essential for the long-term sustainability and productivity of these systems. Overall, integrated systems offer a holistic approach to sustainable agriculture, promoting carbon sequestration and environmental stewardship while supporting the livelihoods of farmers and rural communities.



# Tools for Implementation and Monitorization

Implementation and monitorization are crucial in ensuring the successful adoption and effectiveness of carbon sequestration practices in agricultural systems. Implementation refers to the actual application and integration of these practices on the farm or land, while monitorization involves ongoing assessment, measurement, and tracking of the outcomes and impacts of these practices. By implementing and monitoring carbon sequestration practices, farmers and land managers can evaluate the effectiveness of their efforts, identify areas for improvement, and make informed decisions to optimize carbon sequestration potential. This process allows for the identification of successful practices and the development of strategies to overcome challenges, ultimately contributing to the long-term sustainability and resilience of agricultural systems in mitigating climate change. It also provides valuable data and information for research, policy development, and promoting best practices, ensuring that efforts to enhance carbon sequestration in agriculture are targeted and impactful.

## REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS (GIS):

Remote sensing is a method of obtaining information about the earth's surface without physically being there. This technology has revolutionized how we perceive the earth's surface, including farmlands, and is instrumental in observing and interpreting changes.

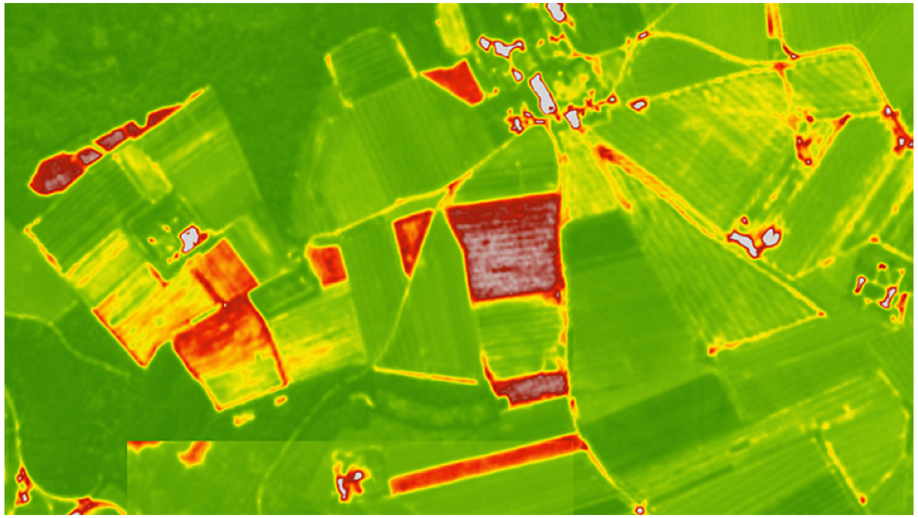

**Figure 23.** Normalized Difference Vegetation Index (NDVI) over an agricultural landscape. NDVI is a widely used index that makes use of the difference between the spectral response of RED and Near Infrared bands of the electromagnetic spectrum. Healthy plants have low spectral reflectance in the RED and Highest in the Near Infrared, thus allowing them to measure their health with relative ease. Image Source: Open Weather (2019).

Farmers can utilize remote sensing devices and GIS to monitor their land, keeping a keen eye on soil health, vegetation cover, and changes in land use. These tools can assist in identifying areas of soil degradation and mapping carbon stocks. For instance, multi-spectral satellites can identify areas of vegetation stress before they become apparent to the naked eye, enabling early intervention. Similarly, data from these tools can help farmers manage their land more effectively and make informed decisions on where to apply fertilizers, water, or other treatments.

- **Benefits:** Remote sensing and GIS technology allow farmers to monitor their land from a broader perspective. They can identify changes and potential problems, such as vegetation stress or soil degradation, early before these issues escalate. The ability to monitor these changes over time can help farmers make better-informed decisions about land management, such as when and where to irrigate, apply fertilizers, or implement other treatments. This can result in increased crop productivity and economic gain.
- **Challenges:** Despite its many benefits, implementing remote sensing and GIS technology can be challenging. Firstly, the equipment and software can be expensive, making it potentially out of reach for small-scale farmers. Furthermore, these technologies often require a certain level of technical expertise to use effectively, and interpreting the data collected can be complex.
- **Application:** While the full application of these technologies may seem daunting, farmers can start on a small scale. For instance, using free online satellite imagery to observe changes in land use over time or employing basic GIS software to map their farmland. Various online courses and local extension services can also provide necessary training.

## SOIL CARBON MEASUREMENT TECHNIQUES

Soil carbon content is a key indicator of soil health and its potential to sequester carbon. Measuring the carbon content of soil can be achieved via methods like dry combustion, wet oxidation, and infrared spectroscopy.

**Figure 24.** Soil samples in the oven. Loss on ignition is a technique where soil samples are weighted then heated to high temperatures and weighted again. The high temperature will oxidize any organic matter in the sample, and the difference in weight will be used to calculate the amount of organic matter. Source of the image USGS – NMWSC 2021.

Dry combustion or loss on ignition involves burning a dry soil sample in a furnace and measuring the CO2 produced. In contrast, wet oxidation involves treating a soil sample with a strong oxidizing agent. Infrared spectroscopy, on the other hand, involves the use of infrared radiation to determine the carbon content.



These techniques can provide farmers with detailed information about the carbon sequestration status of their soil, helping them to adopt the best management practices for enhancing soil carbon storage. However, it is important to note that while these techniques provide useful information, they may require specific equipment and technical expertise.

- **Benefits:** Understanding the carbon content of their soil allows farmers to monitor its health and adjust their practices accordingly. This knowledge can guide decisions on land management practices that enhance carbon sequestration and improve soil health, ultimately leading to better crop yields.
- **Challenges:** The techniques used to measure soil carbon content require specific equipment and technical knowledge. They may be time-consuming and could be expensive for individual farmers to implement on their own.
- **Application:** Some low-cost, easy-to-use soil testing kits are available on the market that can give farmers a basic understanding of their soil's health. For more detailed analysis, farmers might consider forming cooperative groups to share the cost and expertise required for more advanced soil testing.

## MODELLING TOOLS

Modelling tools are essentially computer programs that use data about current conditions and practices to predict future outcomes. In the context of agriculture and carbon sequestration, these tools can be very helpful. They consider various factors, such as current soil conditions, weather patterns, and farming techniques, and use this information to forecast how changes in these variables might affect the amount of carbon that can be stored in the soil.

These tools allow farmers to simulate different scenarios and see the potential impact of various management practices on their land. For example, a farmer could use a modelling tool to compare the potential outcomes of two different tilling methods or different crop rotations. The model would then provide estimates of how each scenario would impact carbon sequestration, allowing the farmer to make an informed decision about which method to use.

The use of modelling tools can save farmers time and resources as they provide the opportunity to test different strategies without having to implement and wait for observable results on the farm physically. This can allow for better planning and increased efficiency, potentially leading to practices that maximize carbon sequestration, improving soil health and productivity.

- **Benefits:** Modelling tools allow farmers to anticipate the impacts of different management practices on soil carbon sequestration. They offer a way to simulate various scenarios and make informed decisions about land management practices.
- **Challenges:** The main challenges with using these tools are their complexity and the requirement of detailed input data. Some farmers might find them too technical to use without appropriate training.
- **Application:** Some of these modelling tools are available online and come with user-friendly interfaces and guidance. Farmers can start using simpler models and gradually move to more complex ones as they gain confidence and understanding.

## COMMUNITY-BASED MONITORING

Engaging local communities in monitoring changes in land use and soil health can be an effective approach to gathering more accurate and locally relevant data. This is particularly relevant in regions with smallholder farming systems.

Farmers and other community members can be trained to recognize signs of soil health, changes in vegetation cover, or other indicators of carbon sequestration. They can also contribute to data collection efforts, for example, by maintaining soil health records or participating in soil sampling activities.

- **Benefits:** Community-based monitoring provides a low-cost and inclusive approach to gathering locally relevant data. It also promotes knowledge exchange and cooperation within the community, contributing to more sustainable farming practices.
- **Challenges:** It can be challenging to organize, train, and maintain active participation in community-based monitoring activities. The quality and consistency of the data collected can also be a concern.
- **Application:** Farmers can start by organizing small, informal groups to share observations and knowledge about their farmland. In cooperation with local agricultural extension services, they can also conduct basic soil health assessments or vegetation surveys.

# Ecosystem Services and Carbon Markets

Ecosystem services refer to humans' benefits from ecosystems, which are complex networks of organisms and their environment. These services are often grouped into four categories:

- **Provisioning services:** These are tangible goods that humans can extract from ecosystems, such as food, water, timber, and medicinal plants.
- **Regulating services:** These are the benefits obtained from an ecosystem's regulation of natural processes, such as climate regulation, natural hazard regulation, water purification, and disease regulation.
- **Cultural services:** These include the non-material benefits people gain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences.
- **Supporting services:** These services are necessary for the production of all other ecosystem services. They include processes such as nutrient cycling, soil formation, and the production of oxygen through photosynthesis.

Ecosystem services have been widely acknowledged by international bodies like the United Nations (UN), Food and Agriculture Organization (FAO), and Intergovernmental Panel on Climate Change (IPCC), and they have been integrated into numerous policies and management strategies.

The economic valuation of ecosystem services allows these benefits to be incorporated into market systems, leading us to the concept of carbon markets. A carbon market is a system that aims to reduce greenhouse gas (GHG) emissions by giving them an economic value.

Carbon markets operate on the principle of 'cap and trade'. A cap (or limit) is set on the total amount of certain greenhouse gases that factories, power plants, and other sources can emit. Companies or other groups are issued emission permits and are required to hold an equivalent number of allowances (or credits), representing the right to emit a specific amount. The total amount of allowances and credits cannot exceed the cap. This limit decreases over time to reduce the total emissions.

These allowances or credits can be traded in the carbon market, providing an economic incentive for emissions reductions. If a company reduces its emissions below its cap, it can sell its excess allowances to other companies or keep them for future use. Thus, companies have a financial incentive to reduce their emissions.

By assigning a monetary value to the carbon stored in forests (an important ecosystem service), carbon markets provide an economic incentive for forest conservation and the sustainable management of forests, contributing to climate change mitigation. This is called REDD+ (Reducing Emissions from Deforestation and Forest Degradation).

The voluntary carbon market is a sector of the overall carbon market where individuals, companies, or governments can purchase carbon offsets voluntarily. This is typically done to mitigate their greenhouse gas emissions. These offsets are quantified and sold per metric ton of carbon dioxide equivalent ($CO_2e$). They are generated from activities that prevent the release of $CO_2$ into the atmosphere or remove $CO_2$ already in the atmosphere.

Agriculture plays an important role in the voluntary carbon market, with farmers having the opportunity to generate and sell carbon credits by adopting practices that sequester carbon in their agricultural soils.

The process for farmers to certify their carbon sequestration generally follows these steps:

1. **Baseline Measurement:** This is the starting point for any carbon sequestration project. The farmer, in conjunction with a carbon project developer or an accredited organization, will measure the current level of carbon in their soils. This initial assessment creates a baseline against which future changes in soil carbon can be compared.
2. **Adoption of Carbon Sequestration Practices:** After measuring the baseline, farmers then need to adopt agricultural practices that are known to sequester carbon in the soil. These practices can include cover cropping, conservation tillage, crop rotation, improved grazing management, and agroforestry.
3. **Monitoring and Verification:** Over time, changes in soil carbon levels must be monitored and verified by a third party. These organizations use internationally recognized methodologies to ensure accuracy and integrity in the carbon measurement process. Verification must be conducted at regular intervals, typically every 5 years, to confirm that the adopted practices are indeed sequestering carbon and generating carbon credits.
4. **Carbon Credit Issuance:** Once the monitoring and verification process has confirmed that carbon has been sequestered, carbon credits can be issued. Each credit typically represents the sequestration of one metric ton of CO2e.
5. **Sale of Carbon Credits:** Farmers can then sell these carbon credits on the voluntary carbon market. Buyers could be individuals, corporations, or governments looking to offset their own emissions.
6. **Repeat:** This process is cyclical. After credits have been sold, farmers must continue to maintain or improve their carbon sequestration practices and undergo regular monitoring and verification to generate and sell more credits in the future.

However, it is important to note that entering the carbon market can be a complex process. For smaller farmers, the cost and complexity of monitoring and verification can be a barrier. However, various organizations and initiatives are working to reduce these barriers and make the carbon market more accessible to smallholder farmers.

The benefits of carbon sequestration practices extend beyond climate change mitigation. By storing carbon in the soil, these practices can help improve agricultural productivity and sustainability.

1. **Soil Health Improvement:** Carbon sequestration practices can significantly improve the health of the soil. Healthy soil contains more organic matter, which enhances its structure, fertility, and water-holding capacity. This means that it can support more robust plant growth, reducing the need for synthetic fertilizers. Soil rich in organic matter also helps to promote the growth and diversity of beneficial soil organisms, contributing to a more balanced and resilient soil ecosystem.
2. **Increased Crop Yields:** Improved soil health can lead to higher crop yields. Healthy soils that are rich in organic matter can better supply crops with water and nutrients. This, in turn, can lead to stronger plant growth and higher yields. Moreover, healthy soils can help to make crops more resilient to stresses like drought or pests, reducing the risk of crop failure.
3. **Water Management:** Practices that enhance carbon sequestration, such as conservation tillage or cover cropping, can help to improve water management on farms. These practices can increase the soil's water-holding capacity, reducing the risk of water stress during dry periods. They can also help to reduce runoff during heavy rains, minimizing soil erosion and the loss of nutrients.

4. **Biodiversity:** Carbon sequestration practices can also help to enhance biodiversity both above and below the ground. For example, cover cropping can provide habitat for beneficial insects and other wildlife. Below the ground, these practices can enhance the diversity of soil organisms, which play vital roles in nutrient cycling and disease suppression.
5. **Economic benefits:** While there are costs associated with implementing carbon sequestration practices, these can often be offset by the benefits. For example, increased crop yields can lead to higher income for farmers. Additionally, healthier soils can reduce the need for inputs like synthetic fertilizers or irrigation, potentially saving farmers money in the long term. And, as we have already discussed, there is the potential for additional income from selling carbon credits on the voluntary carbon market.

By integrating carbon sequestration practices into operations, farmers can not only contribute to climate change mitigation but also enhance the sustainability and resilience of their farms, improving their bottom line in the process.

# Conclusion

Agriculture plays a multifaceted role in the socio-economic fabric and environmental dynamics of our world. its pervasive impact, characterized by a range of trends and benefits, leaves a substantial footprint on the global climate. Exploring the interplay between agriculture and the environment is particularly relevant in regions like the Mediterranean, where diverse landscapes and intricate climate patterns create a crucible for the manifestations of climate change.

The threat of desertification in the Northern Mediterranean is a paramount concern, directly impacting the viability of agriculture in the region. This phenomenon, triggered by a combination of climatic variations and human activities, leads to soil degradation, reduced land fertility, and shifts in biodiversity. Desertification poses significant threats to local economies and food security.

However, the narrative of impending ecological disruption is not inevitable. Early recognition of desertification signs, combined with targeted interventions, can help slow down, halt, or even reverse this process. Monitoring changes in vegetation cover, soil properties, and erosion prevalence can serve as valuable indicators to detect desertification pre-emptively.

In response to desertification and climate change challenges, climate-smart agriculture (CSA) offers hope. This approach, focused on enhancing resilience, increasing agricultural productivity, and reducing greenhouse gas emissions, provides a roadmap towards sustainable agricultural transformation. However, transitioning from conventional farming methods to CSA is not without its difficulties. Farmers may encounter challenges related to the initial investment required, the necessity to acquire new knowledge and skills, and the uncertainty associated with shifting away from established, traditional farming practices.

The role of agriculture extends beyond food production—it plays an integral role in the global carbon cycle. Farmers can influence how much carbon is stored in their soils through management practices, offering an opportunity for climate change mitigation. Crop rotation, residue management, and other practices can enhance soil carbon sequestration capacity, thereby boosting productivity and climate resilience.

Policy frameworks such as the European Union's Common Agricultural Policy (CAP) support the efforts towards sustainable farming. CAP provides financial incentives and a unified policy directive to encourage farmers to adopt practices that promote environmental sustainability and economic viability.

Monitoring and implementing sustainable practices require the utilization of various tools and techniques. Remote sensing technologies and Geographic Information Systems offer unparalleled opportunities for land use mapping and monitoring changes over time. Soil carbon measurement techniques provide direct and detailed information about soil carbon content. Modelling tools offer predictive insights into the potential impacts of different management practices on soil carbon sequestration. Engaging local communities in the monitoring process provides more accurate and locally relevant data. Certification systems assure buyers and consumers of the sustainability of agricultural products.

However, these tools present challenges, particularly for smallholder farmers or those in resource-poor settings. Initial investment costs, technical know-how, and accessibility can be substantial barriers. Nevertheless, the manifold benefits these tools provide in terms of data accuracy, predictive power, and market assurance make them indispensable in the modern agricultural landscape.

This handbook is a valuable resource for farmers and land managers in the Mediterranean region. Its objective is to provide practical guidance and theoretical knowledge to facilitate the adoption of climate-smart agriculture practices. By equipping farmers with the necessary understanding of the systems at play, the importance of sustainable practices, and the technical know-how for implementation, this handbook aims to empower them to take the first steps towards a more sustainable agricultural future.

The handbook also sheds light on the Common Agricultural Policy of the European Union. This policy framework encourages the transition towards sustainable agricultural practices by providing financial support and incentives for farmers. By aligning with the CAP's objectives, farmers can contribute to the preservation of natural resources, the reduction of greenhouse gas emissions, and the maintenance of rural livelihoods.

Practical implementation of sustainable practices requires the utilization of various tools and techniques. Remote sensing technologies and Geographic Information Systems (GIS) enable farmers to map land use, monitor changes over time, and identify areas prone to soil degradation. Soil carbon measurement techniques provide valuable insights into soil health and carbon sequestration potential. Modelling tools help predict the impact of different farming approaches on soil carbon dynamics. Engaging local communities in community-based monitoring efforts fosters a participatory approach to sustainable agriculture. Certification and traceability systems assure buyers and consumers that agricultural products are produced using practices that enhance carbon sequestration.

While these tools offer tremendous benefits, challenges may arise in their implementation. Farmers may face barriers such as high initial costs, limited technical expertise, and the need for specialized training. Overcoming these challenges requires accessible training programs, capacity-building initiatives, and financial support to ensure farmers can adopt and utilize these tools effectively.

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