TRENDS IN THE DEVELOPMENT OF CONSERVATION / ECOLOGICAL AGRICULTURE IN THE CONTEXT OF CURRENT CLIMATE CHANGE – A REVIEW

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TENDINŢE ÎN DEZVOLTAREA AGRICULTURII CONSERVATIVE / ECOLOGICE ÎN CONTEXTUL SCHIMBĂRILOR CLIMATICE ACTUALE - O SINTEZĂ

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ABSTRACT

*In the context of severe climate change over the past 20 years, which has led to reduced rainfall and reduced crop yields, identifying solutions to meet these challenges has become a priority for agricultural researchers. Thus, conservation and ecological, organic farming practices have emerged, which can mitigate and even improve crop productivity, even in these harsh conditions for agriculture. This paper is a synthesis of **433** papers published worldwide (Europe, North America, South America, Africa, Asia and Australia) and analyzes how conservation and organic farming practices have influenced the increase in soil quality and health through: no-tillage, covering land with agricultural residues, crop rotation etc.*

REZUMAT

În condițiile schimbărilor climatice accentuate din ultimii 20 ani, care au condus la reducerea precipitațiilor şi scăderea randamentului culturilor, identificarea unor soluții care să răspundă acestor provocări a devenit o prioritate pentru cercetătorii din domeniul agricol. Astfel, au apărut practicile agriculturii conservative şi ecologice, organice, care pot atenua şi chiar îmbunătăți productivitatea culturilor, chiar în aceste condiții vitrege pentru agricultură. Această lucrare reprezintă o sinteză a 433 lucrări publicate în întreaga lume (Europa, America de Nord, America de Sud, Africa, Asia şi Australia) şi analizează modul în care practicile agriculturii conservative şi ecologice au influențat creșterea calității şi sănătății solului prin: lucrări no-tillage, acoperirea terenurilor cu reziduuri din agricultură, rotația culturilor etc.

INTRODUCTION

Agriculture plays a crucial role in sustaining life on Earth, being the foundation of global food security and local economies. By providing the resources needed for human and animal nutrition, agriculture supports not only daily life but also economic development, accounting for a significant share of the GDP of many countries, especially in rural regions. In addition, the agricultural sector supports social cohesion and the sustainable development of communities, being of vital importance for our collective future.

On the other hand, agriculture has a direct impact on the environment, being responsible for the use of natural resources such as water, soil and energy. In addition, agriculture contributes significantly to global greenhouse gas emissions (GES), not only through methane and nitrous oxide, but also through land use and emissions from industry and transport.

Estimates of agriculture's contribution to global emissions may vary depending on the methodologies used and data sources. According to data provided by the United States Environmental Protection Agency (EPA), the "Agriculture, Forestry, and Other Land Use" sector was responsible for approximately 22% of global GES in 2019, from agricultural activities, such as crop cultivation and animal husbandry, as well as from deforestation and other land use changes (*US EPA, 2019*). According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, in 2022, agriculture was responsible for 10.8% of GES in the European Union (*IPCC, 2023*).

The Intergovernmental Panel on Climate Change has highlighted the importance of farmers implementing climate change mitigation measures to help reduce GES (*Van Wyngaarden et al., 2024*).

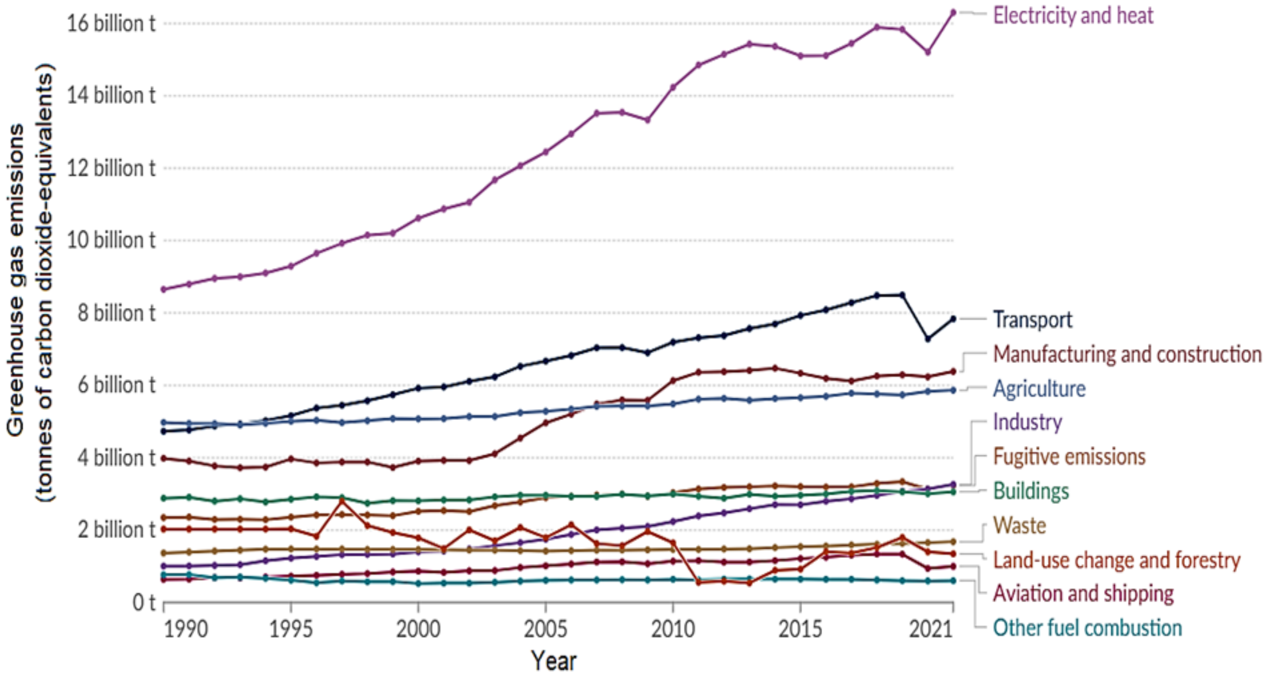


Fig. 1 – Greenhouse gas emissions by sector, worldwide (*Our World in Data, 2024a*)

- ✓ **The impact of climate change on water availability and quality**

Agriculture is the largest consumer of water globally. The irrigation sector is responsible for more than 70% of global water withdrawals from surface and groundwater sources (*Ungureanu et al., 2020b*), but this percentage can vary by region and season. Irrigation plays a critical role in increasing crop yields, particularly in arid and semi-arid regions of Asia, but also in developed countries (*Serra et al., 2023*). Traditional pollutants that could exceed irrigation water quality criteria include particulate matter, certain toxic metals (such as Cd, Cu, and Zn), synthetic organic chemicals (such as agrochemicals and polycyclic aromatic hydrocarbons), and waterborne pathogens (*Deng et al., 2021*).

Drought is one of the most severe types of natural disasters and one of the most significant consequences of climate change on ecosystems and human populations (*Zeng et al., 2022*). In recent years, concerns about the risks of hydrological drought and the reliability of irrigation water supplies have increased, especially in regions with Mediterranean climates (*Gómez-Limón et al., 2023*). Annual global economic losses caused by drought are estimated at over $6 trillion, which represents about one-third of the total impact of natural disasters.

In many regions of the world, including the southern hemisphere, climate change is causing changes in precipitation, leading to a decrease in the total amount of water available and a change in the timing of its occurrence (*Norwood, 1994; Nielsen et al., 2005; Torres et al., 2019*). Global warming is also affecting Arctic regions through accelerated melting of glaciers and sea ice, which contributes to global sea level rise. These changes have major implications for local ecosystems and can influence global ocean and atmospheric circulations (*Yamanouchi et al., 2019*). In mountain regions, cryosphere water resources, originating from melting glaciers and snow, are threatened, which represent an important source of freshwater for downstream regions, especially in arid and semi-arid areas. This water contributes to maintaining river flows during dry periods, thus supporting agriculture, drinking water supply and hydropower production. Rapid glacier retreat, attributed to human-induced climate change, is a global phenomenon observed, and projections indicate a significant loss of glacial mass by the end of the 21st century, affecting mountain regions such as Central Europe, the Caucasus, Mountain Asia and the Southern Andes (*Jones et al., 2019*).

Climate change may also threaten the viability of fisheries, with significant changes in ocean conditions predicted, including increases in sea surface temperatures, water acidification, changes in ocean currents, weather patterns and ecosystems (*Fatima et al., 2023*). Microplastic pollution poses a significant threat to aquatic and terrestrial ecosystems, affecting the health of organisms and the entire food chain. Even if microplastics are effectively removed in sewage treatment plants, most of them end up in the generated sludge, which is then used as fertilizer on agricultural land, leading to soil contamination (*Lofty et al., 2022).*

Research suggests that in areas where lupins are grown there is an increased risk of contamination of drainage water and soil with indole and quinolizidine alkaloids, chemical compounds produced by this plant (*Hama et al., 2023*).

✓Degradation of agricultural land

Physical processes of soil degradation include deterioration of soil structure, crusting, compaction, erosion and desertification. Chemical processes include leaching, acidification, salinization and pollution. Biological processes of soil degradation include carbon reduction and decline in soil biodiversity.

Ongoing land degradation directly affects approximately 25% of the Earth's surface. Recent research suggests that approximately 2 billion hectares of land are severely degraded (some of them irreversibly), leading to serious damage to local ecologies and contributing significantly to climate change in recent years. Globally, at least one in three people is affected by land degradation in one way or another, and approximately 75 billion tons of soil material are lost each year as a result of this degradation. The European Commission's Soil and Food Mission Committee recently launched the report "Caring for Soil is Caring for Life", which highlighted that 60–70% of soils in the European Union are currently in an unhealthy state (*Ungureanu et al., 2024*).

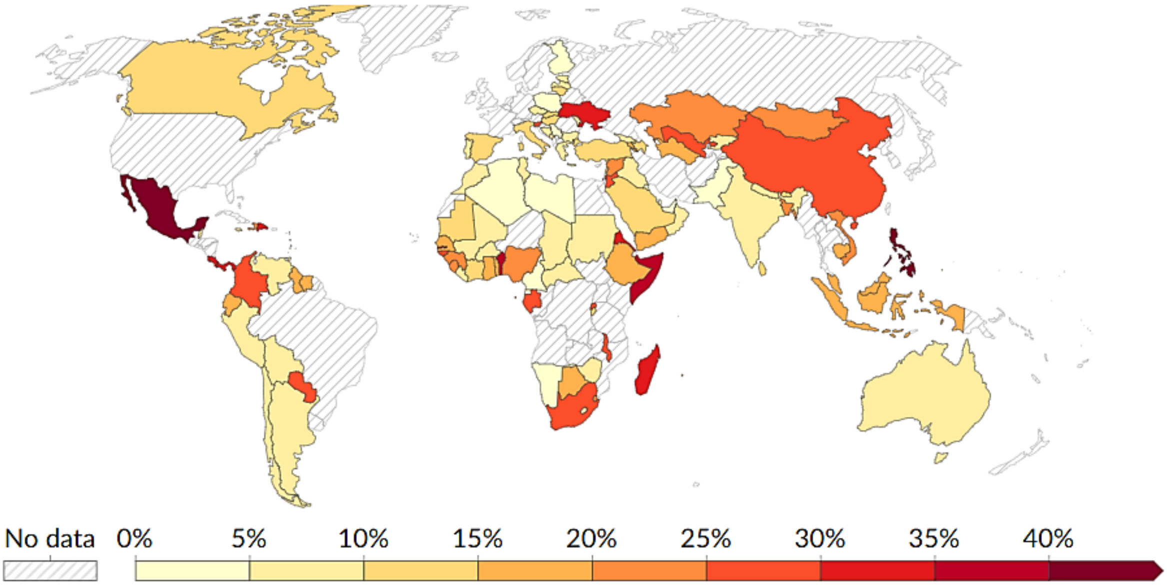


Fig. 2 – Proportion of land that is degraded over total land area (%), worldwide
(*Our World in Data, 2024b*)

Drought can affect the structural stability of the soil, destroying macroaggregates and reducing the protection of organic matter. This effect is evident in Mediterranean grasslands, especially in winter, when agricultural activities are stopped, and the soil is exposed to extreme dryness. The decomposition of aggregates allows microorganisms to access organic carbon, a process that increases CO_2 emissions and leads to the loss of organic matter, affecting the carbon cycle and reducing the soil's capacity to sequester carbon (*Quintana et al., 2023*).

Erosion of fertile soil has a negative impact on land productivity and the environment, affecting soil structure and vegetation, through the loss of essential nutrients, such as carbon, nitrogen and phosphorus. Soil erosion also influences the global carbon cycle and can cause climate change (*Feeney et al., 2022*).

Grasslands cover approximately 40% of the Earth's land surface and 70% of agricultural land, playing an important role in storing soil organic carbon. Intensive grazing practices, which lead to overexploitation of vegetation and soil compaction, can prevent carbon sequestration and increase emissions of the greenhouse gases methane and nitrous oxide. In addition, high grazing intensity can reduce plant productivity, favoring fewer valuable species and affecting soil fauna (*Abdalla et al., 2018*). For example, intensively managed grasslands in the Netherlands are affected by high nitrogen emissions from intensive agriculture, which harms biodiversity and water quality. This has led to a "nitrogen crisis", which requires a political response in the context of farmer protests. Changing agricultural practices to restore biodiversity is complex, involving economic and governmental factors. In this sense, a better understanding of farmers' behavior could improve the efficiency of agri-environmental governance (*Westerink et al., 2024*).

✓Pollution with chemical fertilizers and chemical phytosanitary products

The intensive use of chemical fertilizers in agriculture has become a widespread practice, with the aim of increasing crop productivity. However, the environmental side effects are significant and complex. In the soil, excessive accumulation of nitrogen and phosphorus from fertilizers can lead to nutritional imbalances, acidification and structural degradation. These factors affect the soil's ability to support microbial life essential for natural fertility. Over time, soils become less productive and more vulnerable to erosion.

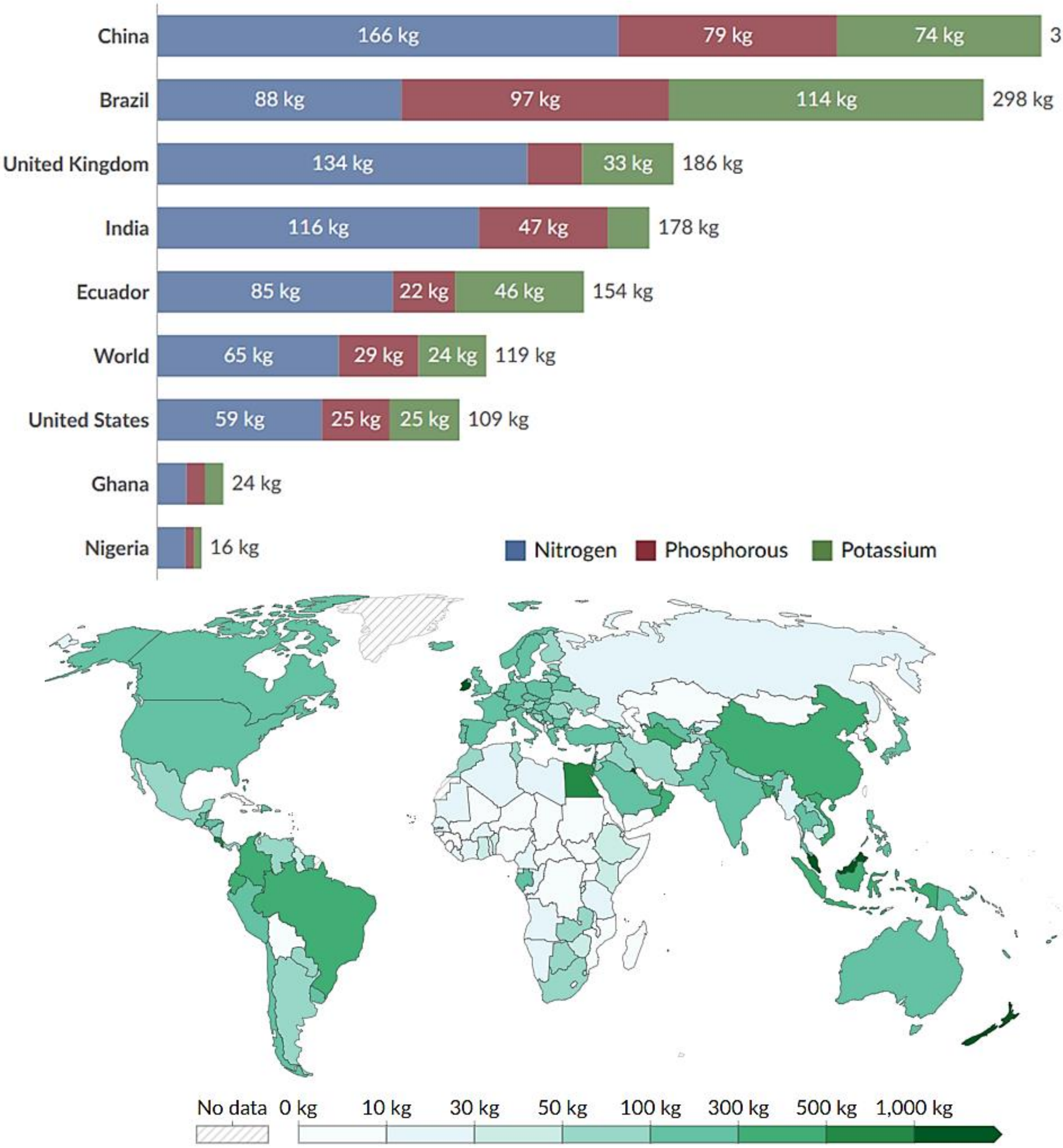


Fig. 3 – Fertilizers use per hectare of arable land in 2022, worldwide (*Our World in Data, 2024c*)
(Fertilizer products cover nitrogenous, potash, and phosphate fertilizers, including ground rock phosphate. Animal and plant manures are not included. Application rates are measured in kilograms per hectare)

In addition to the impact on the soil, agricultural activities influence the quality of surface water and groundwater through sources of NO_3 pollution originating from synthetic NH_4^+ fertilizers together with organic nitrogen in the soil (*Li et al., 2022*). NO_3 contamination can lead to risks of acidification and eutrophication, with negative impacts on the aquatic environment and toxic effects on animals, and in humans it can cause conditions such as methemoglobinemia and cancer (*Kruisdijk, 2022*).

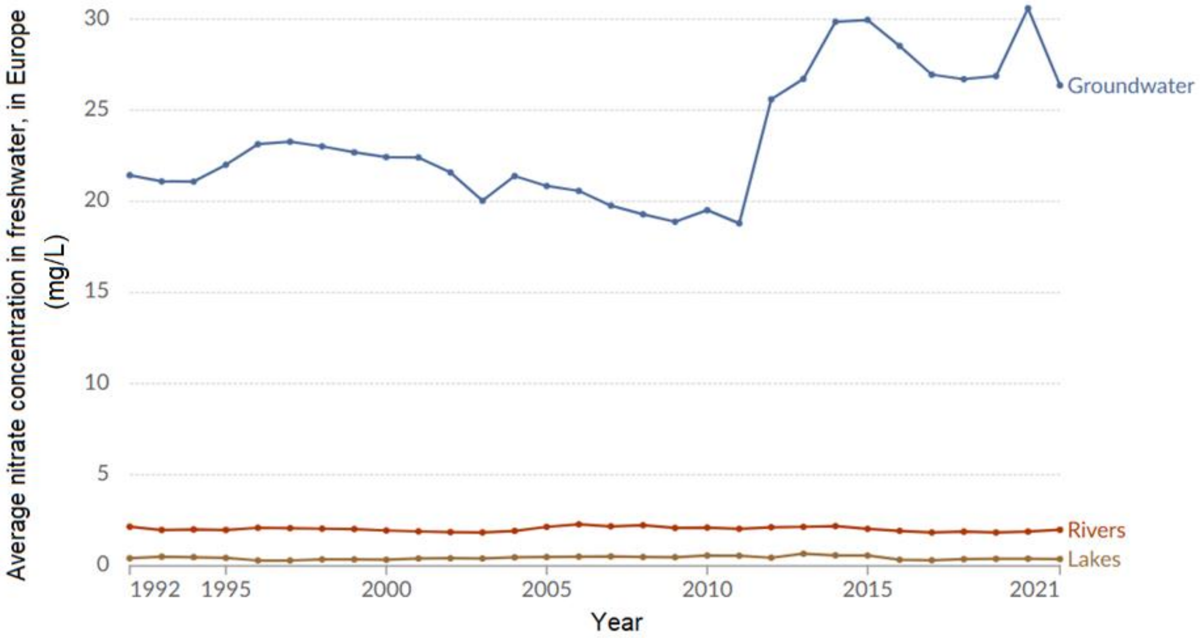


Fig. 4 – Average nitrate concentration in European freshwaters (*Our World in Data, 2024c*)

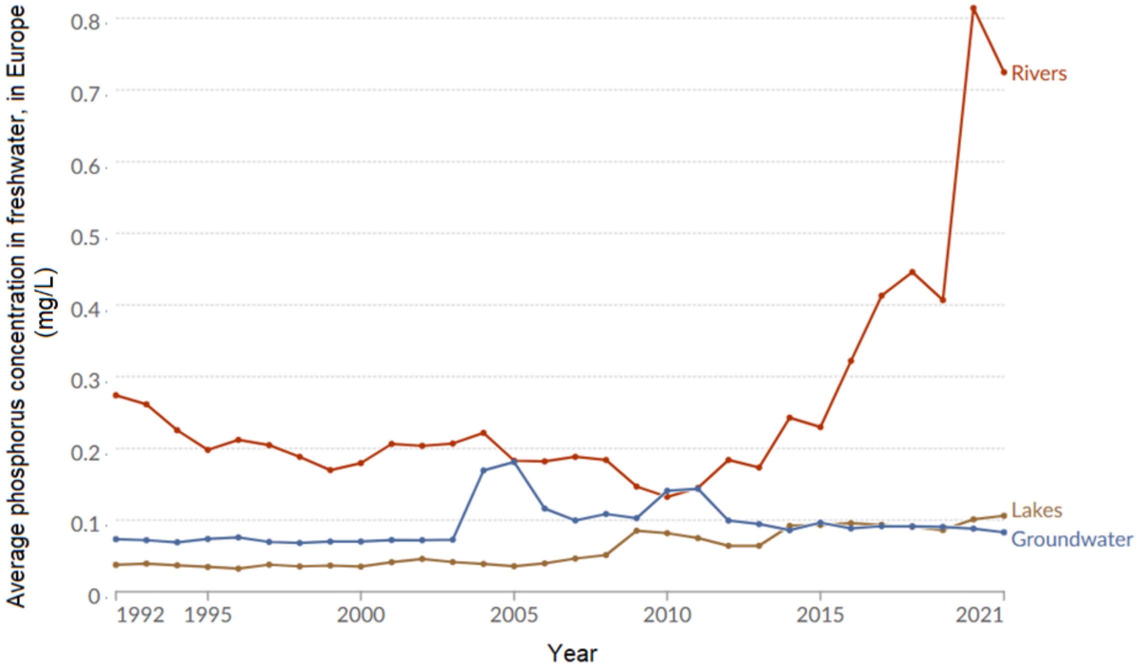


Fig. 5 – Average phosphorus concentration in European freshwaters (*Our World in Data, 2024c*)

In the air, the use of nitrogen-based fertilizers contributes to greenhouse gas emissions, such as nitrous oxide, which is about 300 times more potent than carbon dioxide. These emissions amplify climate change, and volatile particles also affect air quality, with a direct impact on human health. Chemical fertilizers reduce the diversity of wild plants and affect the natural habitat of pollinating insects. These changes disrupt food chains and the balance of ecosystems, reducing their ability to self-regulate

An extensive analysis of the impact of fertilizers on the environment, crops and human health was recently presented by *Ungureanu et. al. (2024)*, concluding that a more sustainable approach, such as the use of biofertilizers and organic farming practices, could help reduce these harmful effects and protect the environment for future generations.

Herbicides, pesticides and fungicides are essential in protecting crops from pests and diseases, contributing significantly to increasing agricultural production and ensuring food security. These chemicals help to quickly and effectively control problems that can affect crops, thereby increasing yields and reducing losses. However, the long-term use of these products can have negative effects on the environment and human health, such as soil and water contamination, the development of pest resistance and the reduction of biodiversity.

Therefore, it is crucial to implement sustainable management strategies and use these substances responsibly to minimize their negative impacts.

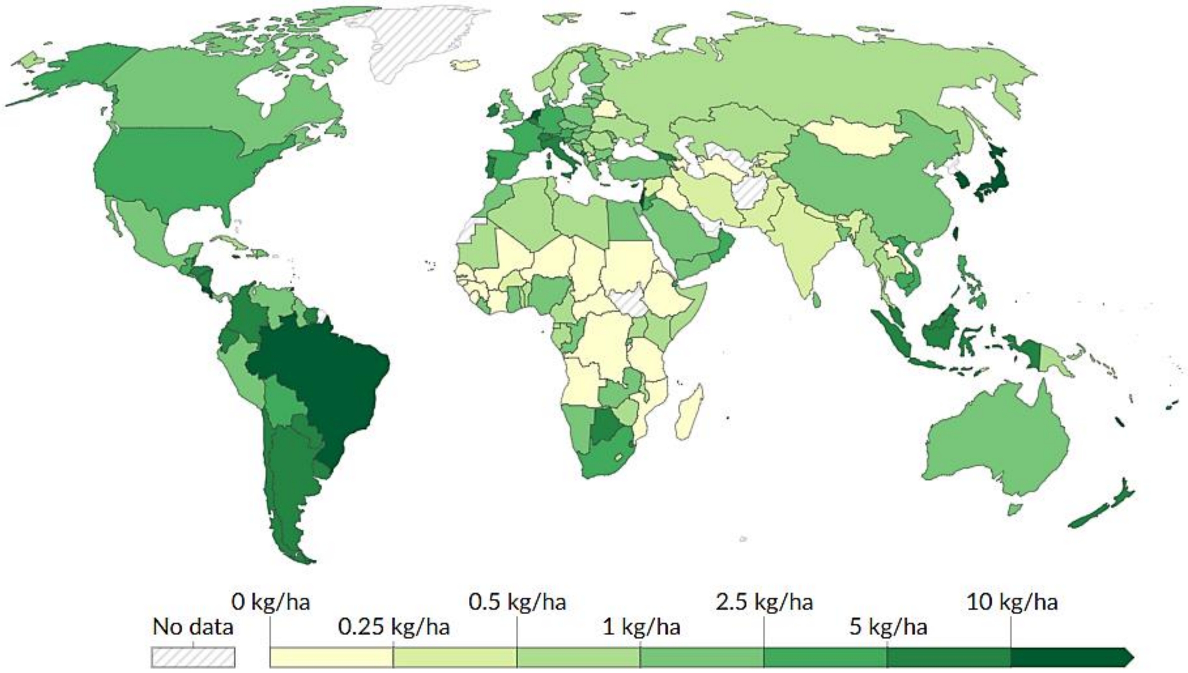


Fig. 6 – Pesticides use per hectare of cropland arable land in 2021, worldwide (*Our World in Data, 2024d*)

A major problem for farmers in any crop production system is weeds, which ultimately lead to reduced productivity and profitability. After the 1950s, most weed management strategies in developed countries were based on chemical (classical) weed control because it is the simplest and most effective method. Herbicides have been, along with mechanization and plant breeding, one of the cornerstones of modern high-yield agriculture (*Liebman et al., 2003*). However, over time, weed resistance to herbicide chemicals has increased significantly, leading to an increase in the number of treatments and, implicitly, to excessive dependence on them. On the other hand, major problems have begun to arise on soil quality and health as a result of the excessive use of these substances over a long period of time (decades), which also affects human health (*Sharma et al., 2021*).

Some studies have revealed that chemical compounds used to prevent crop diseases, such as fungicides, can negatively influence the health of bees by contaminating pollen and nectar, their essential food resources, causing physiological and behavioral problems. The degree of exposure varies depending on the species and biological characteristics of the bees (*Zioga et al., 2023*).

The application of insecticides such as chlorpyrifos and carbaryl near homes can contribute to their presence in dust, with higher concentrations at distances of 2-4 km, and other chemicals such as cyfluthrin and phosmet have been detected more frequently in dust inside homes located up to 4 km from agricultural areas (*Madrigal et al., 2023*). In addition, herbicide residues (such as triasulfuron, chlorsulfuron, clopyralid and pyroxasulfone) significantly reduce nodulation and nitrogen fixation, affecting root and stem growth. Even at very low concentrations, triasulfuron can have negative effects on several legume crops (*Yates et al., 2024*).

In view of the above, but also in the global context marked by climate change, pollution, rapid population growth, technological innovations and societal transformations, the adaptation of agriculture in the coming decades to new challenges and the implementation of innovative technologies are crucial for maintaining a balance between human needs and environmental protection (*Soane et al., 2012; Debonne et al., 2022*). The doubling of global food demand by 2050 brings huge challenges for the sustainability of food production, but especially of terrestrial and aquatic ecosystems and the services they provide to society (*Tilman et al., 2002*).

For these reasons, farmers are looking for new, more efficient and productive methods, practicing intensive agriculture to meet the growing demand for products, which may lead to irreversible changes on the Earth's surface in the coming decades. To combat climate change and ensure environmental protection while improving crop yields, food security and human health, incentives and policies must be sought that ensure the sustainability of agriculture and ecosystem services (*Palm et al., 2014; Gonzalez-Sanchez et al., 2016*).

Given these pressing environmental challenges, it becomes increasingly clear that conventional agricultural practices must evolve toward more sustainable alternatives. In this context, conservation and ecological agriculture emerge as viable solutions, offering methods that not only mitigate the negative impact of farming but also promote long-term soil health, biodiversity, and climate resilience. The following sections explore the principles, benefits, and challenges of these approaches, highlighting their potential to transform modern agriculture.

CONSERVATION AGRICULTURE

Conservation agriculture began as a response to the Dust Bowl crisis of the 1930s and 1940s in the United States, which was marked by extensive soil erosion and agricultural destruction throughout the American Great Plains. This led to a paradigm shift toward farming methods that put an emphasis on soil health, reduce soil disturbance, and improve long-term ecological resilience (*Román-Vázquez et al., 2025*).

In the last 20–30 years, climate change has been increasingly acute, and its effects on agriculture have had a significant impact from year to year, especially due to prolonged droughts, culminating in disastrous effects in recent years, which led to the partial or almost total collapse of agricultural production (*Popescu et al., 2022*). Conservation agriculture has gained momentum especially in the last 20 years, with the area cultivated in the conservation system increasing from year to year, largely due to the decrease in annual rainfall (*Kassam et al., 2009*), and there is also a fundamental change in the thinking of the production system.

Conservation agriculture is a way to increase the competitiveness of an agricultural farm by reducing production costs, while adapting the work carried out to climate change, sustainable soil and water management (*Stagnari et al., 2009; Verhulst et al., 2010*).

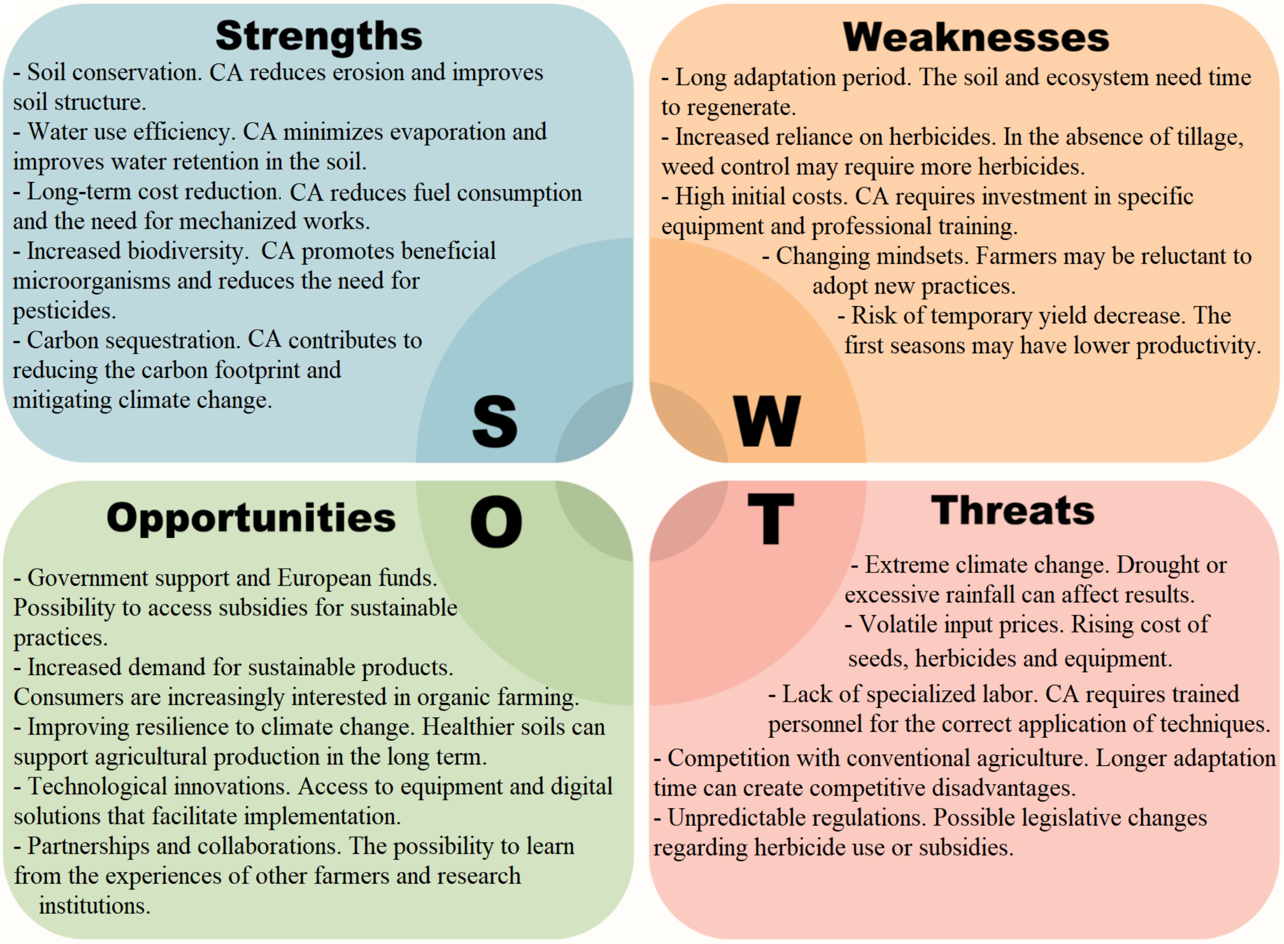
Conservation agriculture is a more sustainable and environmentally friendly management system for growing various crops (*Hobbs et al., 2007; Thomas et al., 1990*). Through conservation agriculture, "sustainable agricultural systems" are used, which, when implemented, lead (over time) to the restoration of soil fertility (*Aguilera et al., 2021*). By permanently covering the soil surface with a layer of plants and practicing a rotation with a wide diversity of the basic crops grown, one can contribute to the conservation of soil and natural resources in a few years (*Gabriel et al., 2013*).

One of the measures with a long-term effect in mitigating climate change may be the application of conservation agriculture in areas strongly affected by successive droughts (and not only), because this type of agriculture has numerous advantages, including:

- it increases soil permeability for water and improves overall soil drainage;
- it reduces soil erosion; plant residues remaining on the soil surface contribute to moisture conservation, the growth of soil fauna and flora and improved productivity (*Fageria et al., 2005*);
- soil structure is restored, and surface and deep compaction are reduced (*Vlăduţ et al., 2017; Ungureanu et al., 2017*);
- it increases the organic matter content of the soil, and in the long term, increases fertility (*Robert and Chan, 1990; Popescu et al., 2022*);
- the quality of groundwater and surface water is maintained (*Cârdei et al., 2021*);
- air quality is maintained by reducing fossil fuel emissions (diesel) used for classic energy-intensive works and by reducing carbon released into the atmosphere (being fixed by increasing organic matter in the soil);
- soil work time is reduced by 2-4 times;
- fuel consumption per unit area is reduced by 30–50%;
- the need for agricultural machinery per unit area is reduced (*Ungureanu et al., 2016*).

Given that agriculture will need to produce a greater quantity of food in the coming years, sustainably, using less agricultural land, by making natural resources more efficient, with low environmental impact, to meet the ever-increasing demands of the ever-growing population, the promotion and adoption of management systems of conservation agriculture can help achieve this objective (*Braim et al., 1992*). However, financial institutions are often reluctant to promote agricultural projects that use this conservation system (*Dauphin, 2003*). The promotion of conservation agriculture focuses on the development of alternative crops, crop rotation and residue management (*Paulitz et al., 2010*). Conservation agriculture plays an important role in sustainable agriculture, aiming to achieve minimal soil disturbance (no-till), to achieve continuous soil coverage (with mulch) combined with crop rotation, so as to function as a more sustainable cultivation system for the future.

Climatic conditions, the date of crop establishment, plant density per hectare and agronomic management practices affect the yields obtained, research carried out on different tillage techniques using conservation soil cultivation methods has highlighted that the yield varies depending on the type of plant cultivated before the crop to be established in a conservation system (*Di Ciocco et al., 2008*) and in addition, when residues from previous crops are used as mulch, higher yields are obtained (*Nematzadeh et al., 2022*), these can influence both the fungal communities in conventionally cultivated soils and those in the no-tillage system (*Beare et al., 1993*), including carbon sequestration (*Duiker and Lal, 2002; Franzluebbers, 2010; Gonzalez-Sanchez et al., 2012*). At the same time, the implementation of integrated and sustainable livestock systems is a priority, considering the adaptation of agricultural practices to climate change. Particular attention is recently paid to the potential of dry biomass crops in areas where there is demand for the biofuel industry, thus contributing to an economic and ecological balance.



Strengths

- Soil conservation. CA reduces erosion and improves soil structure.
- Water use efficiency. CA minimizes evaporation and improves water retention in the soil.
- Long-term cost reduction. CA reduces fuel consumption and the need for mechanized works.
- Increased biodiversity. CA promotes beneficial microorganisms and reduces the need for pesticides.
- Carbon sequestration. CA contributes to reducing the carbon footprint and mitigating climate change.

Weaknesses

- Long adaptation period. The soil and ecosystem need time to regenerate.
- Increased reliance on herbicides. In the absence of tillage, weed control may require more herbicides.
- High initial costs. CA requires investment in specific equipment and professional training.
- Changing mindsets. Farmers may be reluctant to adopt new practices.
- Risk of temporary yield decrease. The first seasons may have lower productivity.

Opportunities

- Government support and European funds. Possibility to access subsidies for sustainable practices.
- Increased demand for sustainable products. Consumers are increasingly interested in organic farming.
- Improving resilience to climate change. Healthier soils can support agricultural production in the long term.
- Technological innovations. Access to equipment and digital solutions that facilitate implementation.
- Partnerships and collaborations. The possibility to learn from the experiences of other farmers and research institutions.

Threats

- Extreme climate change. Drought or excessive rainfall can affect results.
- Volatile input prices. Rising cost of seeds, herbicides and equipment.
- Lack of specialized labor. CA requires trained personnel for the correct application of techniques.
- Competition with conventional agriculture. Longer adaptation time can create competitive disadvantages.
- Unpredictable regulations. Possible legislative changes regarding herbicide use or subsidies.

Fig. 7 – SWOT analysis of implementing conservation agriculture

PRINCIPLES OF CONSERVATION AGRICULTURE

Conservation agriculture is based on a series of practices designed to protect and improve soil health while reducing negative environmental impacts. This approach aims to maintain natural fertility, increase crop resilience to climate change, and optimize the resources used in agricultural production. By applying specific principles, conservation agriculture contributes to a more sustainable and efficient agriculture in the long term. There are three core principles in conservation agriculture (*Ruiz-Espinosa et al., 2024*): conservation tillage by minimum soil disturbance (soil disturbed area < 15 cm wide or 24% of the cropping area); permanent soil organic cover (>30% soil cover with cover crops, crop residues or mulch); crop diversification (includes a lot of break crops or non-cereal crops, particularly legumes).

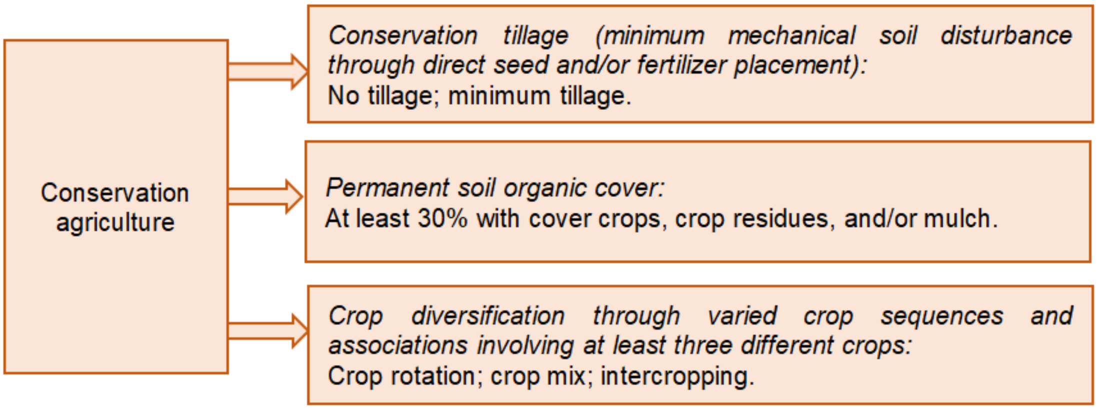


Fig. 8 – Three core principles of conservation agriculture

The following are the main principles underlying conservation agriculture.

✓**Storage of organic carbon in the soil**

Given the continuous population growth and the events caused by climate change in recent years, more and more studies are focusing on increasing the capacity of agriculture to store (sequester) organic carbon in the soil, carbon having a major impact on the physical and chemical properties of the soil, respectively its yield (*Page et al., 2020*).

Carbon storage in agricultural soil is essential for climate change mitigation, contributing to reducing the concentration of carbon dioxide in the atmosphere. At the same time, it improves soil fertility, water retention capacity and the resilience of agricultural ecosystems, supporting long-term sustainable production.

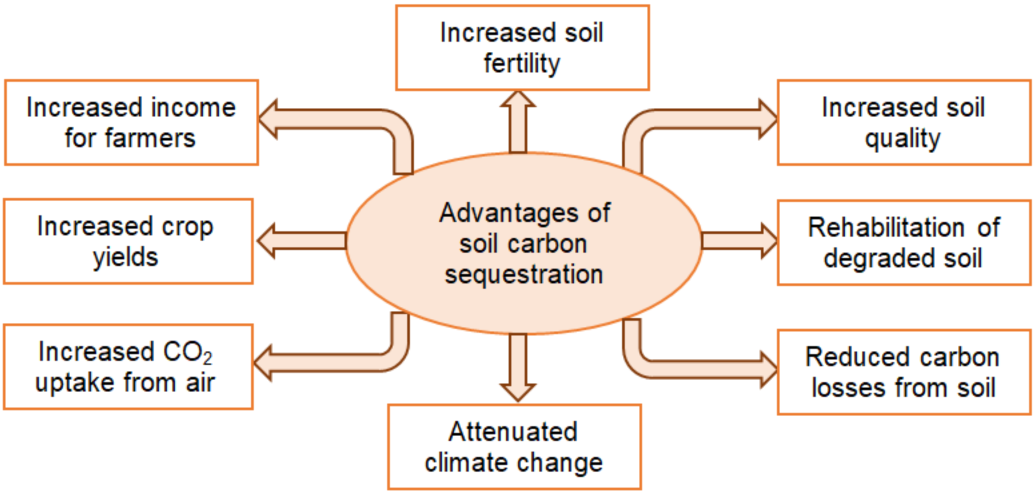


Fig. 9 – The advantages of carbon sequestration practices

Since Mediterranean lands are seasonally dry agroecosystems with low soil organic carbon content and high risk of land degradation and desertification, urgent measures are required to manage soil carbon, thus mitigating climate change and adapting Mediterranean cropping systems to practices that support these measures (*Steinbach and Alvarez, 2006; Aguilera et al., 2013; Garcia-Palacios et al., 2019*), of which conservation tillage practices (no-tillage and minimum till) did not have high effects on degradation but carbon sequestration was good and on the other hand the use of practices that combine the use of organic amendments with cover crops or conservation tillage had very good performances in carbon fixation (*Luo et al., 2010*).

A solution for storing soil organic carbon using nitrogen fertilizers and conservation tillage was studied by *Alvarez (2006)*, field trials conducted worldwide (137 locations and 161 sites) tracking the impact of management practices on carbon sequestration. The model used considered the following independent variables: cumulative nitrogen fertilizer rate; rainfall, temperature, soil texture and crop intensity index and found that carbon sequestration increased as more nitrogen was applied to the system and as rainfall or crop intensity increased, and in areas with higher average temperatures and fine-textured soils, carbon sequestration decreased. Carbon sequestration when conservation tillage practices were applied was independent of climate, soil texture or crop rotation (*Angers et al., 1995; Bayer et al., 2006b*).

Agricultural management also impacts soil organic carbon storage, and in wet and dry climates of temperate and tropical regions (USA), estimates of its impact have been obtained through a centralized carbon approach that tracks the impact of long-term cultivation, the removal of a portion of land from crop production, modification of tillage management, and soil carbon input through modification of harvesting practices (*Ogle et al., 2004; Tarkalson et al., 2006*).

The impact of tillage practices on organic carbon and nitrogen sequestration was studied on cold and wet soils in eastern Canada (*Angers et al., 1997*) and the results highlighted the fact that the storage capacity of soil organic matter depends on (*Bayer et al., 2006a*): soil type, climate and agricultural management practices (*Teliban et al., 2022*), while also determining the effects of different tillage systems on the storage of organic C and N, on different soils, for corn and cereal crops. It was thus found that under the conditions of the studied area, crop production and agricultural waste residues were not affected by tillage, with reduced tillage systems not having a significant impact on the storage of soil organic matter in the first years of the study.

✓ Conserving water in the soil

Soil water conservation is a key principle of conservation agriculture, with a direct impact on the efficiency of natural resource use and the long-term sustainability of agricultural systems. Through practices such as reduced tillage and maintaining a layer of crop residues, conservation agriculture helps improve soil structure, preventing excessive evaporation and facilitating water retention in the soil. These measures not only reduce the need for supplemental irrigation, but also help protect the soil from erosion, thus ensuring more efficient and sustainable management of water resources in agriculture.

Understanding the role of soil management practices in increasing water use efficiency has been studied very often in recent years, as there is a high concern about the availability of water resources in irrigated agriculture and beyond (*Ungureanu et. al., 2020b*), and there is increased interest in understanding how to improve water use efficiency, namely how agricultural systems can be modified to be more efficient (*Hatfield et al., 2001*). Thus, soil management practices can influence evapotranspiration by modifying the energy and water available in the soil profile or the exchange rate between the soil and the atmosphere.

In humid and semi-arid temperate regions, there has been a need to conserve soil moisture and reduce soil erosion through conservation tillage practices that are mainly based on covering the soil surface with residues (*Carter, 1994; Montgomery, 2007; Verhulst et al., 2011*), respectively evaluating the potential for managing soil aggregation for storing and sequestering organic matter (*Angers and Carter, 1995; Du et al., 2017*). The most important advantages of conservation tillage practices in humid climates are their continuity of living soil cover (especially during non-crop periods), the use of mulches, the incorporation of residues, and the speed and efficiency of crop establishment. In addition to their ability to conserve soil, conservation practices in humid regions must also consider the sustainability of the agricultural system in terms of energy conservation and nutrient management.

✓ Crop rotation

Although crop rotation has been used since ancient times, in the 1950–1960's it was found that chemical fertilizers and pesticides could largely replace this crop rotation without major yield losses, but later, based on more in-depth studies, it was found that crop rotation still has its role, because in the long term it increases yield and profit and allows for sustained production (*Bullock, 1992; Karlen et al., 1994; Waldhoff et al., 2017; Chamberlain et al., 2020*).

Crop rotation is an essential practice in conservation and organic agriculture, helping to improve soil health, reduce erosion and limit the proliferation of weeds and pests. Diversified crop rotation helps maintain soil fertility and optimize nutrient cycles, thus reducing dependence on chemical inputs and promoting long-term sustainability.

The impact of tillage combined with crop rotation on soil carbon dynamics and storage has been a longstanding research focus for agricultural specialists (*Huggins et al., 2007*), as soil organic carbon levels are closely linked to both cropping systems and the intensity of soil disturbance. Reduced tillage and diversified crop rotations have been shown to enhance carbon sequestration by minimizing organic matter decomposition and promoting microbial activity. Understanding these interactions is essential for developing sustainable agricultural practices that improve soil health and mitigate climate change.

✓Use of cover crops and crop residue management

The use of cover crops has grown rapidly in the last 20 years, and is closely linked to climate change (*Kaye et al., 2017*), as they have the potential to reduce erosion, fix atmospheric nitrogen, reduce nitrogen runoff and improve soil health. Soil health measures, such as increasing soil cover, reducing tillage and soil conservation practices (especially no-till or strip-till) (*van Bruggen et al., 2006*), used in combination with soil conservation practices (crop rotations for soil conservation and cover crops), can lead to a number of benefits such as: increased agricultural productivity, increased drought resistance and a better environmental impact (*Panigrahy and Sharma, 1997; Moraru et al., 2013; Claassen et al., 2018*).

Using field-level data, new tillage practices could be adopted without disturbing the soil, partially or completely eliminating tillage operations. This allowed an assessment of tillage intensity (STIR, for mulching) as well as adoption rates for practices that affect soil cover – including cover crops, soil conservation crop rotations, double cropping, fencing and residue harvesting, or grazing (*Sun et al., 2019*).

Crop residues have several important functions in conservation agriculture, the most important of which are: preserving soil moisture, restoring soil organic carbon and preventing erosion, and the degree of residue coverage on the soil surface highlights the result of the intensity of soil work and crop management practices (*Hively et al., 2018*). Management of crop residues is an integral part of many soil conservation systems and at the same time, one of the solutions for reducing soil erosion and increasing the percentage of organic carbon in the soil. Through appropriate management of crop residues, positive effects on agricultural production can be achieved, since they (mulch, etc.) have positive effects on plant growth, weed reduction, soil conservation and the environment (*Mesgaran et al., 2017*). Maintaining straw on the soil is a widespread solution because it is an environmentally friendly practice for managing carbon sequestration in agricultural ecosystems (*Liu et al., 2014*), with straw return being an effective way to increase soil organic carbon accumulation, soil quality and crop yield (*Radford and Thornton, 2011*).

Although methods have been sought and various methodologies have been developed to allow a rapid, accurate and inexpensive assessment of the degree of soil cover with plant residues, this has not yet been fully achieved. Due to the fact that classical methods for quantifying crop residue cover are only partially adequate for characterizing the spatial variability of residue cover in fields and over large areas, *Daughtry et al. (2005*) evaluated several spectral indices for measuring crop residue cover using remote sensing (hyperspectral ground and aerial data), aiming to classify the intensity of soil work in agricultural lands based on crop residue cover. Authors *Uri (2001)* and *Daughtry and Hunt (2008)* conducted research to determine the effects of water content on remote estimates of crop residue cover, proposing a method to mitigate the effects of water content on remote estimates of crop residue cover, using advanced multispectral or hyperspectral imaging systems.

Satellite imagery is increasingly being used to estimate crop residue coverage using Landsat residue indices. A new normalized difference residue index (NDRI) was evaluated using multiple image data from 2005–2006 on soils in the state of Iowa (USA), which were processed using an automated method for field boundary delineation (*Gelder et al., 2009*). Another method for modeling and mapping crop residue was based on the use of Landsat, ALI, Hyperion (*Galloza et al., 2013*).

Gao et al. (2020) developed a novel Within-Season Termination (WIST) algorithm to map cover crop termination dates using imagery from the Vegetation and Environment Monitoring New Micro-Satellite (VENµS). Another method for mapping crop residue and tillage intensity is the use of shortwave infrared residue indices using the WorldView-3 satellite, which is a space-based platform for collecting narrowband SWIR reflectance images capable of measuring the absorption characteristics of cellulose and lignin. Images acquired with the WorldView-3 satellite allow for SWIR reflectance measurements that demonstrate the utility of clearly mapping crop residue cover after harvest *(Hively et al., 2018).*

The use of cover crops and living mulches is one of the basic works in conservation agriculture, as they can bring many benefits, which is why there is an increased interest in annual winter cover crops (e.g. winter rye and fescue), for soil cover and soil erosion control (*Hartwig and Ammon, 2017*), because the integration of these cover crops in a relay cropping / over-seeding / inter-seeding / double cropping system can provide and conserve nitrogen (*Zhou et al., 2018*) for subsequent cereal crops, respectively reduce soil erosion, weed pressure and increase the organic matter content in the soil (Hartwig and Hoffman, 1975), knowing that no-tillage cultivation practices can result in better soil aggregation (higher levels of organic matter), compared to conventional practices (*Beare et al., 1994*).

Fescue has an increased availability of nitrogen for subsequent crops and increases soil organic matter, improving soil structure and water infiltration capacity, reducing surface runoff (*Tisdall and Oades, 1982*), while lowering soil surface temperature and water evaporation, improving weed control and increasing soil productivity (*Frye et al., 1988*). Research on the use of living perennial mulches, such as crownvetch (Hartwig, 1983) but also birdsfoot trefoil, flatpea and white clover (*Ammon et al., 1995*) has highlighted the advantages of using ground covers that eliminate the need for annual reseeding.

Legume cover crops are suitable as precursors for crops that consume a large amount of nitrogen – maize because they have the potential to fix nitrogen. Even if the crop is established after these cover crops, this excess nitrogen is not lost and is preserved for the following year's crop that can use it (Hooda et al. 1998) and the long-term influence of soil conservation on the chemical properties of the surface horizon and the yield of legume crops in a Vertisol in southern Spain was studied by *Bravo et al. (2007)* and *Nyagumbo et al. (2017)*.

- ✓ **No-till agriculture**

No-till, or no-tillage agriculture, or farming without soil processing, is a key practice in conservation agriculture, which involves direct seeding crops without turning the soil over through plowing. This method helps reduce soil erosion, increase water retention capacity, and maintain microbial biodiversity. By reducing energy inputs and soil disturbance, no-till farming promotes long-term soil sustainability and health.

Over time, numerous studies have been conducted on the implications of no-tillage soil management on carbon sequestration, soil fertility and crop yields, but a synthesis on the impact of no-tillage systems on soil physical properties, based on a comprehensive analysis of published studies worldwide, is not yet available. The analysis of changes in soil physical properties after the adoption of no-tillage technology is important for managing soils, agricultural production and environmental quality; by comparing soil physical property data between no-tillage, minimum tillage and conventional systems, the factors influencing the effects of the soil tillage system were tracked and research needs were highlighted (*Blanco-Canqui and Ruis, 2018*). It was thus found that no-tillage management generally improves soil physical properties and the benefits for improving soil properties increase over time and accompanying practices (e.g. cover crops) can enhance no-tillage performance and in general, the single tillage of the soil in a no-tillage system does not negatively affect soil properties.

No-tillage systems represent a solution to restore the structure and health of agricultural soils, by identifying how chemical gradients and topsoil acidification can determine how the chemical properties of a clay soil can be affected by the no-tillage system (*Limousin et al., 2007*). It was found that yields were not negatively affected by the no-tillage system in the long term and the organic carbon content increased, therefore this system can be an economic choice for wheat and corn crops in temperate environmental conditions.

In order to determine the efficiency of soil nitrogen use in the long-term use of no-tillage systems, soil nitrogen changes and its use efficiency were studied in an experimental plot over a period of over 40 years (1968–2013), using completely randomized tillage practices (conventional mechanical tillage and no-till), crop residue management (burned residues and retained residue), and nitrogen fertilization (0, 30 and 90 kg N/ha) on a Vertisol (Ustic Pellusert) (*Dalal, et al., 2011*).

The fact that farmers have started to leave more crop residues on the soil surface helps to reduce soil erosion, conserve energy, retain soil moisture and increase crop yields, but on the other hand, many plant pathogens in the soil survive in these residues, so diseases are more problematic under reduced tillage conditions (*Bockus and Shroyer, 1998*). Thus, reduced tillage can favor pathogens by: protecting the pathogen refuge in the residue from microbial degradation (*Angers et al., 1993*), lowering soil temperature, increasing soil moisture and leaving the soil undisturbed. However, it is recommended that crop rotation be coupled with reduced tillage, through this practice controlling many diseases, and also allowing as much of the crop residues as possible to be retained on the soil surface.

Conservation tillage technologies can be an effective tool to increase the yield of certain agricultural crops, under conditions of stress caused by prolonged drought. Thus, studies have been conducted on the effect of applying tillage strategies on soybean production (*Hosseini at al., 2016; Huang et al., 2021*).

Tillage is also important for a good understanding of field conditions in terms of drainage and soil pathogens and determining the need for tillage in cropping systems (*Rajana et al., 2022*). It has been shown that even by improving plant genetics, there are practically no consistent changes in the response to tillage compared to no-tillage systems (*Arora et al., 2011*). Currently, technologies exist that allow planting and weed control without tillage practices, and selective fungicidal seed treatment can further increase the profitability of no-tillage systems (*Wu and Babcock, 1998; Liebhard et al., 2022*), but there are also certain constraints in adopting these systems in developing countries (*Lal, 2007*).

To investigate the long-term (20-year) effects of no-tillage on soil properties and productivity in maize compared to conventional tillage, *Ismail et al. (1994)* studied how the lack of soil disturbance in no-tillage systems changes some of the most important basic soil properties. The comparative analysis showed that soil organic carbon was restored to the soil level after a decline of almost 20%, whereas grain yields, which had declined with organic carbon, did not recover.

In comparative studies on conventional tillage for 13 years versus no-tillage, the impact of crop residue retention versus burning, as well as nitrogen fertilizer application (23-69 kg N/ha/year) versus no-tillage, on organic carbon content, total nitrogen, mineralizable nitrogen, pH, electrical conductivity, and other chemical properties in a fine-textured Vertisol was analyzed. It was found that tillage and residue management significantly influence soil organic matter, microbial activity, and water relations, even in a fine-textured Vertisol (*Dalal, 1989; Dou et al., 2008; Mangalassery et al., 2015; Mbuthia et al., 2015*).

In conservation agriculture, sowing is done with minimal or no tillage. In study a by *Baker et al. (2007*), the authors made an analysis of no-tillage technologies, emphasizing no-tillage seed drilling, but also address the issue of soil carbon and how its fixation/sequestration interacts with soil tillage and no-tillage, how traffic control on agricultural lands can help no-tillage, the role of band fertilization on no-tillage, but also the economics of no-tillage, forage cropping by no-tillage and a method for risk assessment of different levels of machine sophistication (*Triplett and Dick, 2008*).

Although it is recognized that conservation agriculture has beneficial effects on soil health in the medium and long term, the combined effects of no-tillage practices and residue management on soil properties remain a subject of research.

MECHANIZATION OF SOIL WORKS IN CONSERVATON AGRICULTURE

An essential component of agricultural development is mechanization, which plays a primary role in responding to the needs of farmers. Due to the fact that a large part of agricultural land is subject to erosion, salinization, etc., increasing yield per hectare is crucial for increasing agricultural productivity (*Emadodin et al., 2012*).

Carter (1991) conducted research to evaluate shallow tillage of spring cereal crops over a 4-year period in the Canadian province of Prince Edward Island on a fine sandy loam soil (orthic podzol), which is not very suitable for direct seeding. Tillage was performed with a furrow plough and shallower tillage with a disc harrow (to a depth of 10 cm) followed by direct seeding. Compared to conventional ploughing (furrow ploughing), shallow tillage reduced machinery and energy costs by 25-48% for seeding, with the advantage of increasing the potential area that can be prepared for seeding in the short early spring period, eliminating some of the constraints associated with direct establishment and providing an alternative to conventional ploughing.

Soil tillage equipment has a high influence on soil compaction (*Ungureanu et al., 2015*), sowing precision (*Cujbescu et al., 2021*) and therefore the technologies developed within conservation agriculture must respond and solve these challenges through specific characteristics and design (*Croitoru et al., 2015; Croitoru et al., 2016*), reduce resistance to advancement (*Duiker and Beegle, 2006; Vlăduţoiu et al., 2016; Vlăduţoiu et al., 2023)* using active vibrating parts (*Cârdei et al., 2023a*) and in conjunction with the introduction of new plant varieties that are more drought-resistant and have high productivity (*Matei et al., 2020*), which also have an impact on ecosystem conservation (*Nenciu and Vlăduţ, 2021b*), from whose residues other products with high added value can be obtained (*Nenciu et al., 2021a*).

The use of deep soil loosening equipment (*Matache et al., 2015; Croitoru et al., 2017*) can partially solve the problem of deep decompaction, so that water can also reach the lower layers of the soil. At the same time, the use of soil cover residues (including algae), resulting from the production of the main products (e.g. biogas, bioethanol), can be a solution for maintaining water in the soil and increasing soil fertility over time (*Rhoton, 2000; Ungureanu et al., 2020a*).

In many cases, the use of plant residues in conservation agriculture represents a challenge for farmers because the so-called clogging with crop residues occurs, which leads to low soil cultivation due to the stalk residues used as mulch (*Li et al., 2022*); thus, it was necessary to design a combined towed machine for subsoiling and land preparation by crushing the stalk residues, simultaneously incorporating them into the soil, using grooved coulters and a crushing roller, a solution for soil cultivation in a conservation system.

Another solution for conservation soil cultivation in hilly and mountainous areas in China consisted in the development of a mini-tiller that performs soil cutting with rotary blades (*Xiao et al., 2024*), based on the analysis and simulation of soil cutting optimization with such equipment, using the ANSYS/LS-DYNA program. Solutions were sought to reduce the cutting resistance and energy consumption of the rotary blade of the mini-tiller, the cutting process of the rotary blade being analyzed through numerical simulation, taking into account parameters such as: tangential bending radius, bending angle and thickness of the rotary blade edge, in order to optimize it.

The development of a precision, strip-type, no-till soybean planting equipment that performs seed metering for the Huang-Huai-Hai region of China was analyzed by *Ma et al. (2024)*, who performed parameter optimization through simulation and functionality was verified through bench testing.

In general, large agricultural equipment manufacturers have developed solutions and equipment for soil cultivation in a conservation system, but less often such equipment for medium and small farms. Especially in small farms in hilly and mountainous areas, the implementation of conservation practices is lower due to the lack of specific equipment for the application of such practices. In this regard, *Li et al. (2023)* developed and tested a furrow opening device for a two-row seeder, analyzing the general structure and operating principle while optimizing the soil structural parameters

For sowing small vegetables in greenhouses, a single disc multi-row seeder was developed in which the airway disc structure was redesigned so that the negative pressure air chamber was divided into three separate air chambers. This solved the problem of the high pressure requirements of the traditional single air chamber seed metering device, adapting the solution with several smaller separate chambers for low-power machines (*Zhang et al., 2023*).

For no-till seeders, a problem is the adhesion of wet and sticky soil to the working parts entering the soil, the soil sticking practically blocking these parts and affecting the quality of sowing (*Fu et al., 2023*). Research aimed to improve the anti-adhesion properties of the seeding monomer, so that it can also work in wet soils, using the "Theory of Inventive Problem Solving", based on the systemic-functional analysis of the seeding depth limitation device and the analysis of the force of the measuring wheel during operation, a new type of depth measuring wheel with a large hole was designed.

Cârdei et al. (2023b) analyzed the intensity of traction forces in the supports of the working parts of a cultivator taking into account the fact that the distribution of traction resistance forces on the working parts of a complex cultivator is unpredictable, using the validation of the random nature of the force loading the active parts to indicate the mathematical model to be followed for the research of the soil cultivation system.

Conservation agriculture aims, among other things, to reduce soil compaction, which is the result of successive passes with the tractor - agricultural machine aggregate during agricultural work, harvesting etc., especially since in recent decades equipment has been developed that works on increasingly larger and therefore much heavier surfaces.

Cujbescu et al. (2019) investigated the influence of specific compaction factors: tire pressure, wheel load and contact pressure on the tire-soil contact area, as well as obtaining 2D and 3D maps of the pressure distribution in the contact patch of a Romanian agricultural tractor - U445, at five tire pressures: 100, 150, 200, 250 kPa. The study was later extended to other types of agricultural machinery.

Bularda et al. (2020) carried out an in-depth analysis of the effects of the conservation mechanized work system, minimum-till (heavy and scarified disc) and no-till (direct sowing), compared to the conventional system (plowing), highlighting their influences on the soil and plants, ways to reduce technological costs, improve soil quality indices by accumulating organic matter and increasing the supply of humus, the need to reduce mechanical equipment traffic and the possibilities of reducing fuel consumption, improving the conditions for retaining water reserves in the soil, reducing working times and the need for labor.

REMOTE SENSING IN MODERN AGRICULTURE: TECHNOLOGY FOR SUSTAINABILITY

Quantifying crop residue coverage, identifying tillage intensity, and assessing the effectiveness of conservation management practices are essential aspects of modern agriculture. Traditional methods for assessing these parameters are often costly, time-consuming, and require skilled labor.

Studies and research on the impact of conservation agriculture on reducing environmental degradation through sustainable management of agricultural lands show that since the 1990s, agricultural research has focused on remote sensing technologies, but less on the use of conservation management practices (*Roper and Gupta, 1995; Ge et al., 2011; Sonmez and Slater, 2016; Ahmed et al., 2024*).

Remote sensing is a technology that involves the collection and analysis of data about the Earth's surface without direct contact, using sensors mounted on satellites, aircraft, or drones, to monitor and assess various environmental characteristics.

The use of remote sensing and advanced visual technologies in agriculture allows for rapid and accurate monitoring of crops and soil conditions (*Zheng et al., 2014*). The data obtained, including information on soil carbon, water retention capacity and evapotranspiration, are essential for optimizing the use of resources such as water, fertilizers and pesticides. These modern methods support the early detection of plant stress and diseases, contributing to increasing the productivity and sustainability of agricultural systems.

Satellite remote sensing has been found to be very useful for spatially interpolating and estimating cover crop biomass and nitrogen uptake in a small watershed (*Xu et al., 2018*). Authors *Beeson et al. (2016*) monitored and evaluated crop residue coverage and tillage intensity in a watershed in central Iowa (USA) for three years (2009-2011), using multispectral satellite imagery. The determination of crop residues using remote sensing was studied by *Beeson et al. (2020)*, who used Landsat Thematic Mapper Series platforms to track global temporal and spatial coverage starting in the mid-1980s, for 10 years, in the states of South Dakota, North Dakota and Minnesota, using the Normalized Difference Tillage Index (NDTI) and then validating the results against field-level survey data (*Zheng et al., 2013*).

In a study by *Gowda et al. (2008)*, a set of linear logistic models based on Landsat Thematic Mapper (TM) were presented, which had been previously used for mapping tillage practices and verified with an independent dataset (*South et al., 2004*). Another approach for mapping conservation tillage practices was through the use of artificial neural networks (*Sudheer et al., 2010*).

Conservation agriculture is closely related to precision agriculture because the use of field data such as: vegetation index (VI), normalized difference vegetation index (NDVI), green normalized difference vegetation index (GNDVI) and soil adjusted vegetation index (SAVI), to examine the vegetation vigor for each crop, helps farmers make quick and efficient decisions, which are vital for obtaining high yields for each crop. To determine these indices, *Candiago et al. (2015*) used an unmanned aerial vehicle - hexacopter (UAV) on which a Tetracam camera was mounted that allowed obtaining multispectral data, after processing obtaining triband orthoimages of the scanned areas, subsequently extracting the previously mentioned indices.

The influence of soil properties on soil tillage, and on soil quality parameters in a tallgrass prairie area, was addressed in studies by *Van Deventer et al. (1997)* and by *Brye and Pirani (2005)*, the authors analyzing the physical, chemical and biological properties of the soil at depths of up to 10 cm, in the Grand Prairie region of east-central Arkansas, on six native pastures, these being then compared with the data obtained in the adjacent cultivated agricultural lands (11 combinations of land use from prairie-agriculture). Thus, it was found that the soil organic matter and total N and C concentrations were much lower, and the soil pH, electrical conductivity and extractable soil (K, P, Fe, Mg and Ca) were higher in the cultivated agricultural lands than in the native prairie lands, but the mechanization of intensive agriculture and its associated practices negatively affected the quality of the native soil in this region.

Chen and Wang (2010) used satellite sensing to observe land cover changes in a mountainous area of China near the Three Gorges Dam (TGA) over a 10-year period (1987-2006), developing a specific procedure that uses a decision rule-based classification method and post-classification change detection techniques, combining spectral and spatial knowledge in multi-temporal image classification. The responses of soil chemical and microbial indicators to conservation tillage were also monitored compared to conventional tillage in the North China Plain, with the results showing that after a 6-year period, conservation tillage improved soil quality (by improving its chemical and microbial properties), as well as the geometric mean of the tested enzymes, microbial biomass C, microbial biomass N and β-glucosidase (*Qin et al. 2010*).

In the case of winter cover crops also, one of the monitoring methods is satellite remote sensing to approximate the efficiency of nutrient uptake from them (*Hively et al., 2009*), and to estimate the effect of these cover crops on nitrogen fixation in the soil, using in addition cost recording data and Soil and Water Assessment Tool modeling (*Hively et al., 2020*) or by using Landsat and SPOT satellite images in conjunction with USDA cropland data (*Hively et al., 2015*), so that the extent and quantity of winter green vegetation can be assessed on agricultural fields in four counties in Pennsylvania / USA, over a 4-year period (2010-2013). Analysis of winter satellite imagery revealed significant increases in vegetative ground cover over the study period, indicating that farmers have increasingly adopted practices such as cover crops that promote winter vegetation.

Remote sensing is a valuable tool for assessing and mapping the level of soil cover with post-harvest agricultural residues and cover crops, including during non-growing periods, based on multitemporal satellite imagery and spectral detuning techniques (*Laamrani et al., 2020; Prabhakara et al., 2015*). Given that understanding spatial variability in the adoption of cover crop practices, and their impact on soil, water and soil nutrients, is an important step in determining and prioritizing areas within a watershed to effectively utilize this practice, and that data are often lacking, the development of a method for assessing cover crops, using remote sensing based on spatial assessment models, was studied by *Kc et al. (2021)*, who used images collected by Landsat 5, 7 and 8 satellites, during the period 2008-2019 in the Google Earth Engine platform.

By monitoring tillage practices, soil quality and production trends can be tracked, respectively their impact on environmental quality, but this depends largely on the existence of accurate maps of agricultural residues, one solution being the mapping of soil cultivation technologies using spatial information techniques. In this regard, in a study by *Paul Obade and Gaya (2020)* an empirical model for mapping surface agricultural residue cover was created by integrating line-transect % residue cover field measurements with information obtained from soil spectroradiometers and Advanced Wide-Field Sensor satellite images, the map being then validated using the fractional component of non-photosynthetic vegetation extracted through spectral mixture analysis.

ADOPTION OF CONSERVATION AGRICULTURE AT THE GLOBAL LEVEL: PROGRESS AND CHALLENGES

Although soil health practices such as cover crops, crop rotation, and conservation tillage certainly provide economic and ecological benefits on farms where they are implemented and indirectly on the environment, the implementation of these practices is still not widespread enough, and researchers are analyzing what may be the causes that lead to this situation (*Carlisle, 2016*).

From the analysis of recommendations for increasing the adoption of soil health practices, it was found that a complementary approach that combines education, policy, research, equipment adaptation measures, and efforts to address the farm and food system context may be the key to wider adoption of these practices among farmers. Soil conservation practices play an important role in restoring soil quality (organic carbon, microorganisms, etc.) but there is still reluctance among farmers regarding how these practices will influence production. The results of a study by *Anderson et al. (2020)* highlighted that both no-tillage and cover crops can help reduce production risk for farmers, while reducing soil and nutrient losses.

However, applying the principles of conservation agriculture does not automatically lead to better results in every situation, because under certain conditions (e.g. cold, wet environments, poorly drained soils) or if the practices have not been well adapted to the specific conditions of the area, the conservation management system may not be successful. Farmers need to have access to tools and resources that allow them to identify those principles of conservation agriculture that are appropriate for their situation and to well-established, locally adapted systems to successfully overcome the agronomic, social and economic challenges that may arise at a given time.

At European Union level, sustainable land management practices, which balance competitive agricultural production and environmental protection, have been supported in recent years through policies and subsidies, but the adoption of these practices that regulate biogeochemical cycles requires further studies, especially due to the effects of local pedo-climatic variability. A research study by *Camarotto et al. (2018)* aimed to analyze the influence of conservation agriculture and practices using cover crops to regulate water, carbon and nitrogen cycles in the Venetian lowland.

In Turkey, in the last two decades, agricultural land degradation due to intensive farming has increased greatly and therefore it has become necessary to apply conservation practices that protect both land and production, by establishing urgent measures and a national strategy to promote conservation agriculture throughout the country (*Altikat et al., 2018*), while also pursuing the various economic aspects of the conservation agriculture system (no tillage - direct seeding) that may influence farmers' decisions (*Kan et al., 2018*).

In Serbia, government authorities have also begun to align with European Union policies on stimulating and promoting the adoption of conservation soil cultivation practices, because although these practices (no-tillage, minimum tillage) have been available for many years, their adoption in Europe has not had the desired expansion (*Harper et al., 2018*), so the promotion of new technologies and the dissemination of agricultural innovations has required a commitment and close collaboration between all the factors involved: government, farmers, agricultural enterprises, advisory services and research.

Quantification of soil water storage and crop yield using different tillage systems was analyzed in dry semi-arid Mediterranean conditions in Spain during 1987–1992 (*Lampurlanés et al., 2016*). Their study highlighted that in semi-arid pluvial conditions, soil water storage increases with the use of conservation systems, being amplified with the degree of aridity of the site.

Studies on tillage systems in Mediterranean crops (Greece, Italy, Spain and Morocco) and soil organic carbon sequestration were carried out in 15 locations, aiming to identify biophysical and agronomic variables associated with the rate of carbon sequestration and it was found that tillage, crop rotation and fertilization were the most important factors affecting the sequestration rate (*Francaviglia et al., 2017*).

A comparative multidimensional evaluation study of conservation agricultural systems, carried out for an area in southern Italy, highlighted the fact that conservation agriculture can be a viable alternative to conventional systems, and in the Mediterranean area it has the advantage of good yields even in dry years (conservation practices preserve water in the soil for crops). In addition, European public authorities (including policymakers) need to recognize the positive benefits of conservation agriculture and support them as ecosystem services within good agri-environmental practices and current CAP subsidies (*Vastola et al., 2017*).

In the USA, the adoption of conservation agriculture practices began about 40 years ago (*Nowak, 1987*), with research highlighting the fact that the variables positively associated with the adoption of these practices by farmers were those related to: financial non-involvement, attitude towards the environment, previous adoption of other conservation practices, etc. (*Prokopy et al., 2019*). Of course, the adoption of cover crops (*Arbuckle and Roesch-McNally, 2015*), the use of conservation practices (*Barbercheck et al., 2014*), best management practices (*Baumgart-Getz et al., 2012*) and the adoption of no-plow tillage (*Belknap and Saupe, 1988*), supported by voluntary agricultural policies to protect water quality (*Bosch et al., 1995*) although supported by the government, has always encountered resistance from farmers to the adoption of best management practices in certain regions (*Burnett, 2014*), because the transition to sustainability implies a change in thinking about changing food systems (Hinrichs, 2014), the modern world with current agri-food systems not always supporting sustainability (*Buttel, 2006; Gillespie et al., 2007*).

The continued decline in soil productivity in certain areas of the USA has been one of the main factors influencing the adoption of soil health practices by farmers (*Knowler and Bradshaw, 2007; Kara et al., 2008; McCann et al., 2015; Carlisle, 2016; Liu et al., 2018*), along with the adoption of agricultural production practices in pilot farms (lessons learned), supported by the Department of Agriculture (*Caswell et al., 2001; Singh et al., 2018*) or through incentive payments to encourage farmers to adopt water quality protection practices (*Cooper and Keim, 1996*). As a result, the conservation behavior of farmers following participation in these voluntary incentive programs has changed (*Kraft et al., 1996; Napier et al., 2000; Lichtenberg, 2004; Fishbein and Ajzen, 2010; Mase et al., 2016; Stallman and James, 2017; Dayer et al., 2018*), and a modeling of multiple adoption decisions within a common framework has been achieved (*Dorfman, 1996*), inevitably emerging new trends regarding the attitude towards the environment (*Dunlap et al., 2000; Gifford and Sussman, 2012*), including that of cattle breeders (*Kim et al., 2005; Lambert et al., 2014; Medwid, 2016*), and the perception regarding the use of cover crops among farmers has also changed (*Gottlieb et al., 2015; Dun et al., 2016*).

The USA is currently one of the largest and most powerful countries with a highly developed agriculture. In order to have a sustainable agriculture, a balance must be achieved between productivity, profitability and environmental health. *Davis et al. (2012)* have shown that by increasing the diversity of cropping systems, a balance can be achieved between these three important indices, taking into account that in the USA the vast majority of crop production systems are characterized by low species diversity and management, the large-scale use of fossil energy and chemicals having a major negative impact on the environment. Starting from the hypothesis that the diversification of crop systems can promote ecosystem services, as they can supplement and subsequently replace external synthetic inputs used to increase crop productivity, a field study was conducted during 2003–2011 (in the state of Iowa, USA), including three contrasting systems, where the length of the crop sequence and inputs varied and in the end it was found that grain yields, the mass of harvested products and implicitly the profit in diversified systems were similar or higher than those in the conventional system, even though chemical inputs were reduced, even weeds being effectively eliminated in all systems, but the toxicity of water in the soil on the lands where diversified systems were used was lower than in the conventional system by two orders of magnitude. Basically, the study highlighted the fact that more diversified cropping systems, although using reduced amounts of synthetic agrochemical inputs, can become powerful tools that allow regulating, rather than boosting, the performance of agroecosystems, while outperforming less diverse systems.

Given that the USA is one of the largest and most powerful countries with a highly developed agriculture, in recent years it has become a priority to identify and quantify the adoption of conservation practices on agricultural lands, by precisely monitoring soil health trends at the regional and national levels, in efforts to mitigate climate change (*Hagen et al., 2020*). In this regard, a mapping of conservation management practices for corn crops was carried out, using an operational soil cultivation information system (OpTIS) and a denitrification-decomposition model (DNDC). The USA has vast agricultural lands, characterized by large monocultures where intensive agriculture is practiced, supported by chemical fertilizers and pesticides, so as to maintain high productivity (*Schipanski et al., 2016*), but over time, with all the inputs, productivity has decreased and farmers have adopted a regenerative model of agricultural production that promotes soil health and biodiversity, while producing nutrient-rich but profitable agricultural products (*LaCanne and Lungren, 2018*).

No-tillage agriculture is promoted as one of the management practices that maintains the amount of and water, respectively the increase of organic carbon in the soil, compared to conventional tillage practices. Considering that the Great Plains region of the USA is an area with low rainfall, the crop that is best suited is wheat but even in these conditions satisfactory yields cannot be obtained without irrigation, so the adoption of no-tillage cultivation practices has become a necessity because it has led to more efficient storage and use of precipitation and implicitly to improvements in soil properties and increased productivity, in conjunction with a more diverse crop rotation (*Hansen et al., 2012*).

For carbon sequestration in the soil, no-tillage agriculture represents a solution. *Christopher et al. (2009)* conducted a study on the effects of no-tillage on carbon sequestration in the Midwestern United States, and the results highlighted that most information on carbon sequestration in no-tillage systems was based on measurements in the surface layer of the soil (<30 cm) and the level of carbon sequestration at greater depths (up to 60 cm) is unknown. An analysis of the soil profile distribution of carbon and associated properties in no-till along a precipitation gradient in the semi-arid Central Great Plains of the USA and Canada was conducted in many studies (*Tessier et al., 1990; Puget and Lal, 2005; Blanco-Canqui et al., 2011*). Soil carbon storage and soil structural properties (aggregate stability and soil strength at 1 m depth) were evaluated in three long-term experiments (over 20 years) using no-tillage and conventional systems. It was found that no-tillage does not increase soil organic carbon stock, but increases wet aggregate stability and reduces aggregate tensile strength at the soil surface, and the impact of no-till management on soil carbon storage varies depending on soil structural properties, precipitation, equipment used, and cropping system (*Olson, 2013*).

In general, dryland crops do not produce large amounts of residues, and in this case the effects of no-tillage technology on infiltration, runoff and water conservation on land are generally small. In order to have the most accurate results, these effects were compared over a period of 12 years with those resulting from stubble mulch tillage in the state of Texas, USA (*Jones et al., 1994*), with terminal infiltration rates being similar for both tillage systems. Despite the higher surface runoff from the no-tillage system compared to the conventional one, soil management in the no-tillage system led to improved water conservation due to reduced evaporation.

Given that the central US has some of the most productive agricultural land in the world and relatively large areas, and the stored carbon and greenhouse gas emissions due to agriculture represent a significant percentage of the entire country (*Johnson et al., 2005*), the assessment of the greenhouse gas contribution and mitigation potential of agriculture in this region was studied, by converting agricultural land to grass, increasing the percentage of soil organic carbon sequestration. The assessment of the potential for reducing greenhouse gases: carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) through the application of sustainable management practices in eastern Canada and the northeastern US was studied by *Gregorich et al. (2005)*, who synthesized the most recent information on the contribution of agricultural soils to atmospheric levels of these gases.

Most of Australia is affected by drought and cultivated agricultural areas are highly subject to erosion, and Australian farmers were among the first to implement conservation agriculture practices and even came up with innovations to increase yields with these systems (*Belloti and Rochecouste, 2014*). The first experiments by farmers with conservation agriculture began as early as the 1960s and have continued to the present day, when about 80-90% of Australia's winter crops are grown using conservation agriculture principles. This is also due to continuous investments in agricultural research and development, but especially to the innovation of farmers who adopted conservation agriculture (through waste management practices) because it satisfied their needs, maintaining productivity and profitability, having a positive impact on the chemical and microbiological properties of the soil (*Pankhurst et al., 2002; Thomas et al., 2007*) and sustainably increasing production with better environmental outcomes (*O'Leary and Connor, 1997*).

In Australia, no-tillage has been widely used in regions suitable for cereal cultivation over several decades (*Llewellyn et al., 2012*), this paper analyzing the factors favoring the adoption of no-tillage systems, demand-driven innovation by farmers and agricultural researchers, which led to the development of high-performance agronomic technologies (herbicide and crop disease resistance, extension processes and economic influences); the impact of conservation tillage on soil quality and health (*Pankhurst et al., 1995*), including soil-borne crop diseases (*Rahman et al., 2007*), in semi-arid cereal cropping systems was also studied (*Page et al., 2013*). At the same time, changes in soil water storage in the no-tillage system and the maintenance of agricultural waste on a Vertisol were monitored, respectively their impact on productivity and profitability, over a period of 50 years (*Page et al., 2019*).

Analysis of differences in soil organic carbon levels following different tillage and stubble management practices in a continuous cropping system on a red soil in the New South Wales (Wagga Wagga) region, Australia, was studied in a wheat/lupine rotation experiment over a 10-year period (*Chan et al., 1992*). During this period, stubble burning and tillage had the same impact on reducing the total amount of organic carbon in the upper soil (0-2 m horizon), with no significant differences between conventional (3-crop) and reduced-tillage (1-crop) systems (*Loch et al., 1984*).

Although conservation farming practices are largely implemented by farmers in northeastern Australia, they often resort to an occasional tillage operation - strategic tillage - to combat the constraints of no-tillage systems (*Dang et al., 2015; Dang et al., 2018*), suggesting that there must be a tillage strategy in conservation farming systems. In order to validate this strategy, 14 experiments were established over a 4-year period (2012-2015), in farms that had implemented no-tillage systems for several years, so that there would be unity in: quantifying the associated risks and benefits on crop productivity, soil health and the environment, respectively exploring the key factors that must be taken into account to implement this strategy in a no-tillage system, the results highlighting the fact that the introduction of the strategy reduced weeds and improved crop productivity and profitability in the first year after soil cultivation, with no impact in the following 4 years, this strategy being viable for managing the constraints of no-tillage systems, with reduced short-term costs for the soil and the environment and some benefits (short-term farm productivity and profitability and reduced dependence on herbicides).

Farmers in developed countries in North and South America and Australia have implemented conservation agriculture on a large scale, achieving high profitability through a combination of increased agronomic productivity and reduced input costs (*Thomas et al., 1995*). Building on these results, smallholder farmers in sub-Saharan Africa and South Asia have also adopted conservation agriculture practices for a wide range of crops and farming systems, even though there are major differences between the biophysical and socio-economic environments in these regions (*Brouder and Gomez-Macpherson, 2014; Pannel et al., 2014; Pheap et al., 2019*). Based on the data evaluated from the reviewed studies, a minimum set of generic, relatively inexpensive and easy-to-implement data was proposed, which would allow quantifying and explaining crop and crop system performance.

In Portugal, the main constraints of agricultural production in the Mediterranean region were analyzed and the importance of conservation agriculture to mitigate them, having an even more important role, taking into account long-term studies carried out with these practices, studies that highlighted an increase in soil organic matter, improved aggregate stability and continuity of biological porosity along the soil profile (*Carvalho and Lourenço, 2014*). It was found that changes in soil properties help overcome edaphic and climatic constraints in Mediterranean conditions, improve saturated hydraulic conductivity which allows for better drainage during wet winters and better soil traversability, and highlight the fact that conservation agriculture can be economically and environmentally advantageous, contributing to the sustainability of rainfed agriculture.

In Brazil, conservation agricultural practices based on no-tillage systems were introduced over 35 years ago, initially in the southern state of Paraná, as a means of reducing erosion, and subsequently, research was conducted to study crop residue management and its effects on soil fertility, phosphorus management as a means of controlling soil acidity, and establishing how manure can be applied in a more localized manner (*Bernoux et al., 2006*). The spread of conservation agriculture in Brazil has involved major expansion works, with the area worked in no-tillage systems increasing, especially in the center and north of the country, occupying over 20 million hectares, covering a diversity of environmental conditions, cropping systems and management practices that track the interactions of conservation systems on soil organic carbon and soil fertility (*Sa et al., 2009*).

The soil conservation movement in Brazil has been the main driver for the continuous identification of new agricultural systems that are more sustainable than existing ones, especially in tropical and subtropical areas, and the development and adoption of Zero Tillage Conservation Agriculture has been key to the success of this movement, generating numerous agricultural, environmental and societal benefits (*Freitas and Landers, 2014*). This led to a major transformation of agriculture in Brazil through the development and adoption of conservation no-till agriculture, which now accounts for over 50% of the total cultivated area. This was due to the work and innovation of all those involved: farmers, agronomists, researchers, consultants, etc., as farmers realized that erosion control required continuous soil cover, protecting it from torrential storms common to these regions. *Zero Tillage Conservation Agriculture* has stopped land and soil structure degradation by eliminating conventional tillage, thus improving its physical and chemical characteristics, this being achieved by promoting cover crops and permanent soil coverage with crop residues (*Raphael et al., 2016*), crop rotations and complementary technologies, appropriate for soil management.

By increasing soil carbon supply and stabilizing it, soils can become reservoirs of atmospheric CO_2-C, thus helping to mitigate global warming, in which case the combined role of no-tillage systems in storing and stabilizing soil carbon is essential (*Conceição et al., 2013*). A study conducted by *Veloso et al. (2018)* aimed to evaluate the sequestration and stabilization of carbon in a subtropical Acrisol from the Eldorado do Sul region, Brazil, which was conventionally worked for 18 years and subsequently with the no-tillage system, with two cropping systems: black oats (*Avena strigosa* Schreb) - winter cover crop and corn (*Zea mays* L.) - summer cereal crop, respectively black oats + vetch (*Vicia villosa* Roth) - winter cover crops and summer corn interspersed with cowpea (*Vigna unguiculata* (L.) Walp) - cover crop. Their results demonstrated that the no-tillage system is recommended for sustainable soil management and to increase soil carbon accumulation, the potential of cropping systems based on legume cover crops being used concurrently.

In tropical and subtropical mountainous areas there are many problems related to the sustainability of agriculture due to erosion and reduction of soil fertility, a long-term solution to these problems being the tillage in a conservation system, residue management and crop rotation (*Govaerts et al., 2007; Steward et al., 2018*). Both environmental conditions and microflora played an important role in the biology and expression of soil pathogens in the subtropical semi-arid and pluvial mountainous areas of central Mexico, along with the positive effects of no-tillage, crop rotation, and crop residue retention compared to conventional agricultural practices (*Govaerts et al., 2008*).

The implementation of conservation agricultural practices in the mountainous areas of central Mexico, especially through the use of crop residues, has been stimulated by the authorities through social and income crop compensations (*Beuchelt et al., 2015*). Due to the fact that a large part of farmers have low incomes, they use crop residues not only for soil cover but also as fodder or as an additional source of income, which largely explains the low adoption of conservation agriculture in some regions due to crop residue management in mixed crop-animal systems.

Climate change affects the livelihoods of people dependent on agriculture, causing migration, political instability and economic losses (*Linke et al., 2021*). In areas such as South Africa and Kenya, the tendency of residents is to use traditional knowledge to predict the weather, determine wind speed and preserve seeds, having a significant impact in reducing climate change affecting agricultural activities (*Apraku et al., 2021*). The need to identify appropriate weather conditions that directly influence soil cultivation processes led to the development of an automated climate prediction system for smart agriculture that uses a hybrid Deep Belief Network based on the Pelican Optimization algorithm, which has a maximum accuracy of 95.03% (*Punitha and Geetha, 2023*).

Although conservation agriculture has been heavily promoted in Africa as an alternative to the need for high food production based on more sustainable agricultural practices, its success in adopting it on farms is still limited, even though investments in research and development have been made over the last three decades (*Corbeels et al., 2014*). Smallholder farmers in Africa have not widely adopted conservation agriculture (*Brown et al., 2017; Thierfelder et al., 2018*), the main factor in the negative assessment of these conservation agriculture practices being the feasibility of implementation, primarily due to the fact that the resources required for their implementation (financial, physical, human and informational) are limited by community and institutional constraints and cannot be overcome by interventions aimed at addressing household resources.

To understand the impact and adoption of conservation agriculture in Africa, a multi-scale analysis must be carried out that takes into account the results obtained in previous and ongoing experiences, in a set of case studies, so that ultimately the reasons for the limited adoption of conservation agriculture practices on this continent can be better understood. Potential causes include: the lack of immediate income growth for farms that apply conservation practices, with small farmers often having short-term time horizons because future benefits do not adequately exceed their immediate needs, and conservation agriculture does not bring immediate benefits; in mixed livestock systems, crop residues are often used as animal feed and can no longer be used for soil cover; lack of good markets for purchasing inputs and selling products.

A large part of African countries are affected by drought (*Tekle, 2016*) and therefore the adoption of conservation tillage technologies may represent a solution (*Mrabet et al., 2012; Abdulai, 2016*). Some research has sought to highlight the impact of conservation technologies on the well-being of farmers in Zambia and southern Africa, tracking the main factors that can determine the improvement of the situation of these farmers (*Rusinamhodzi et al., 2011; Sithole and Magwaza, 2019*). Thus, an endogenous switching regression model was used to estimate the impact of technology on outcomes (agricultural production, transfer accounting ratio, poverty gap, poverty severity, etc.) and in addition farmers were educated, taught to access social networks, how to access credit, benefited from extension services and equipment to see how soil quality is positively influenced by the adoption of conservation technologies.

Also, in Malawi, on-farm evaluations were carried out on the yield and economic benefits of short-term legume intercropping systems in conservation agriculture (*Ngwira et al., 2012; TerAvest et al., 2019*). In other countries in southern Africa, such as Malawi and Zimbabwe, farmers began to adopt soil and water conservation measures starting in the 1990s, and then promoted them on a large scale (*Andersson and D'Souza, 2014*), but they did not expand as desired, with the use of these practices still being quite limited.

Given that much of Ethiopia is mountainous, extremely high volumes of runoff occur on cultivated land when it rains, and in this case the research aimed to see the medium-term effects (2005–2010) of applying cropping systems based on conservation agriculture on sustainable soil, water and crop productivity management in the highlands (*Araya et al., 2012*). No-tillage systems, crop rotation and post-harvest residues in combination with conventional systems were tested in Ethiopia, for several types of crops and in the end it was found that runoff was reduced simultaneously with an increase in crop yield (higher in recent years).

In recent years, conservation agriculture has also been promoted in subhumid and semi-arid areas of Zimbabwe, from the point of view of increasing water use efficiency for crops and stabilizing yields (*Baudon et al., 2012; Nyamangara et al., 2014*), over three consecutive seasons, tracking the comparative short-term performance of conservation agriculture and current agricultural practices on small farms, in addition to biophysical measurements, farmers' perceptions of the technology were also assessed. Given that most soils in the study area fall into the dry and highly compacted category, farmers perceived conventional tillage as necessary in drier years (to maximize water infiltration) and conservation tillage systems as more beneficial in wetter years, which is incorrect because by applying conservation practices, crust formation and soil compaction can be avoided. This can be achieved through better crop management (adequate fertilization, timely planting, crop protection) in combination with intercropping.

A global perspective on the application of conservation agriculture in smallholder farming in southern Africa and Southeast Asia was presented by *Ares et al., (2015)*, who examined the potential benefits as well as the biophysical and socio-economic constraints that the expansion of conservation agriculture could bring to farmers in these areas. Although conservation agriculture systems around the world share many common principles, there are important differences depending on geographical location, climatic conditions, soil, and type of farming systems, crop-animal interactions, and farmers' access to resources, highlighting the effects of such differential conditions on the development of conservation systems.

Recent research in sub-Saharan Africa and South Asia, in dryland areas with smallholder farms, has sought to highlight the limits of productivity and the potential of conservation agriculture principles in these areas (*Vanlauwe et al., 2014; Pittelkow et al., 2015*; *Pittelkow et al., 2020; Rosenstock et al., 2024*). This is due to the fact that the population in these areas has grown rapidly in the last 20 years, but the conditions are not exactly conducive to developed agriculture, making these principles all the more suitable, with reduced external input and minimal impact on the environment, in variable and extreme climatic conditions (*Tittonell et al., 2012*). Conservation agriculture in these areas aims not to reduce production, but under certain conditions, this no-tillage system can produce equivalent or higher yields than conventional agriculture because when the no-tillage system is applied combined with the other two principles of conservation agriculture: maintaining agricultural residues and crop rotation, its negative impact is minimized and at the same time increases the productivity of rainfed crops in dry climate areas, which leads us to the idea that this can be an important future strategy for adapting agriculture to climate change in countries located in dry areas (*Seufert et al., 2012*).

In Central Asia, the use of cover crops as a conservation agriculture practice for climate change mitigation and adaptation has gained momentum over the last 50 years, with concerns for increasing sustainability and efficient use of land and resources over a longer period of time (*Kienzler et al., 2012*), however, given the diversity of institutional, socio-economic and agro-ecological contexts, a geographically differentiated approach to the dissemination of conservation agriculture practices must be taken, also considering a change in research paradigms (more participatory approaches with farmers). In Nepal, the introduction of sustainable crop establishment practices has increased profitability and yields in rice and wheat crops (*Devkota et al., 2019*).

To understand the long-term impact of conservation tillage on soil structure and productivity, the effects of no-tillage practices and residue mulching compared to conventional tillage were analyzed over a 15-year period in northern China (*Li et al., 2007*), finding that crop yield and water use efficiency tended to be higher when using the no-tillage system combined with agricultural waste mulching compared to the conventional tillage system, especially during periods of low rainfall, highlighting that the modification of soil structure provided a better environment for crop development. Thus, the data obtained over this 15-year period highlight the fact that no-tillage is a more sustainable agricultural system, which over time can improve soil structure and increase crop yield, with positive environmental impacts in dryland agricultural areas. Also, maintaining residues on the soil and minimally cultivating it improves the physical soil environment in cultivated lands (*Li et al., 2019*), tracking the effects of soil conservation practices on soil physical properties, including soil bulk density, aggregate size and stability, hydraulic properties, and soil pH.

One way to conserve soil water is to till the soil as little as possible (in a single pass, if possible), without turning the furrow. To this end, researchers in Indonesia have developed a soil tillage and seedbed preparation equipment for small farms in mountainous areas (*Mustaqimah et al., 2021*), so that farmers can benefit from a mechanized solution that retains water in the soil.

The assessment of the problems and prospects of adopting conservation agriculture in Bangladesh (Jamalpur and Bogra districts) was studied by *Dhar et al. (2018)*, the research being conducted on a group of 120 farmers (20 from the focus group and 100 from the control group), surveyed to collect the necessary data and information and a combination of descriptive statistics and mathematical techniques was used for data analysis. The farmers in the target group followed the basic principles of conservation agriculture, and the farmers in the control group continued conventional crop cultivation practices, it was found that the focused farmers were more profitable compared to the farmers in the control group in terms of wheat and bean production.

In India, considerable efforts have been made in the last 30 years to develop and promote agricultural technologies based on conservation tillage systems and although significant progress has been made, there are still many constraints affecting the adoption of conservation agriculture, even though in principle it involves minimal soil disturbance, permanent coverage of the soil with crop residues or cover crops, and crop rotations to achieve higher productivity (*Bhan and Behera, 2014*). It was found that there are more benefits than trade-offs for adopting conservation technologies, offering opportunities to reduce production costs, save water and nutrients, increase yields, increase crop diversification, improve resource efficiency and benefit the environment. Obviously, there are also constraints to promoting conservation technologies, especially due to the lack of adequate equipment (seeders) for small and medium-sized farmers (*Pradhan et al., 2018*). In the semi-arid regions of India, the effects of conservation agriculture on soil properties and crop productivity were studied simultaneously with the maintenance of residues on the soil, under different heating systems, and it was observed that the average moisture content improved, the degree of compaction was reduced, and the organic carbon content in the soil increased (*Somasundaram et al., 2019*).

Given that intensive tillage combined with crop residue burning in the rice-wheat system is widely used in northwestern India, representing a serious problem that causes soil degradation and environmental pollution, losing large amounts of organic carbon, the no-tillage system has been recommended on a large scale as an alternative to improve soil carbon sequestration, biological properties and crop productivity (*Vandenbygaart et al., 2003; Jat et al., 2019*). It has been found that adopting climate-smart agricultural practices involving no-tillage, crop establishment, residue management and crop diversification in the rice-wheat system can significantly improve the productivity of the systems by increasing the percentage of soil organic carbon and soil health (*Jat et al., 2014*).

In Azerbaijan and Iran, the effects of tillage systems on productivity (dryland winter wheat–chickpea rotation) were also studied, as data on the success of intensive cropping systems in relation to conservation tillage management were insufficient (*Hemmat and Eskandari, 2004*), and tests were carried out to determine the effect of five tillage systems on crop yield in a winter wheat–chickpea rotation, over a 3-year period on a loamy-clayey soil.

From the analysis of these studies, it can be concluded that the adoption of conservation agricultural practices is influenced by a combination of environmental, economic, social, and institutional factors. Soil characteristics, climate variability, and water availability play a crucial role in determining the feasibility and effectiveness of these practices in different regions. Economic considerations, such as initial investment costs, long-term financial benefits, and access to subsidies or financial incentives, significantly impact farmers' willingness to transition.

Social and cultural factors, including traditional farming practices, peer influence, and knowledge transfer through extension services, also shape adoption rates. Additionally, institutional support, including government policies, availability of technical assistance, and access to appropriate machinery, can either facilitate or hinder implementation. Understanding these key factors is essential for designing targeted interventions that promote the widespread adoption of conservation agriculture.

ECOLOGICAL AGRICULTURE

Ecological agriculture is a sustainable production system aimed at maintaining and improving the health of soils, ecosystems and human communities. This model of agriculture is based on the use of ecological processes, biodiversity and natural cycles adapted to local specificities, instead of resorting to inputs with potential negative impacts. By integrating tradition, innovation and scientific knowledge, ecological agriculture aims to protect the environment, promote social equity and ensure a higher quality of life for all stakeholders.

Ecological or organic agriculture contributes to increasing the resilience of agroecosystems to climate change by creating sustainable agricultural systems that protect the soil and adapt to temperature fluctuations and drought. It also promotes ecological conservation and restoration practices, being a less expensive method compared to conventional agriculture (*Gamage et al., 2023*).

According to the most recent data, globally, at least 4.5 million farmers manage more than 96 million hectares of agricultural land (mainly due to growth in Australia) in 188 countries that practice organic agriculture (*Trávníček et al., 2024*).

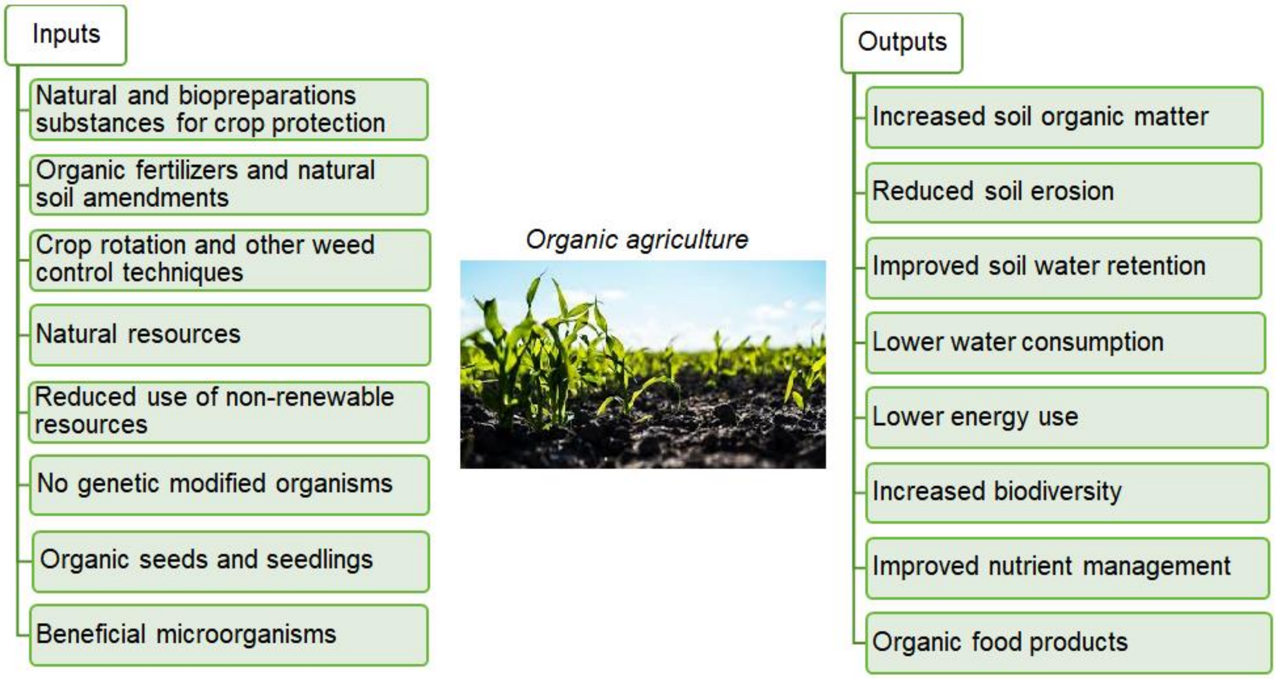


Fig. 10 – Inputs and outputs of organic agriculture

Although it promotes biodiversity and is generally more sustainable, organic farming has a significantly lower temporal stability of yield (-15%) per production unit compared to conventional farming (*Knapp and van der Heijden, 2018*).

In addition, ecological farming faces significant challenges, including limited access to resources, technical knowledge and markets for organic products. It is essential that government policies support the transition to more sustainable agricultural practices through financial incentives, education and research (*FAO, 2018; Ding, 2018*).

Diversifying cropping systems in conservation and organic agriculture is essential for improving biodiversity, preventing soil erosion and managing nutrients efficiently. It also contributes to the stability of agricultural ecosystems, reducing risks associated with pests and diseases, while supporting natural resource conservation practices.

An essential aspect of sustainable agriculture in dryland farming systems is the integration of well-nodulated legumes, which can provide nitrogen through a symbiotic process with root nodule bacteria (*Lupwayi et al., 2001*). Incorporating legumes into crop rotations helps reduce agricultural risks, lowering nitrogen fertilizer costs and allowing for better management of herbicides, pests and diseases (*Yates et al., 2024*).

Agroecology is one of the most used terms lately when farmers want to obtain organic production using ecological systems, being a system of practices that allow food production in a sustainable way without the use of agrochemicals. So ecological / organic farming also translates into a more ecologically sustainable and socially equitable agriculture.

Agroecology can also be defined as the application of ecological concepts and principles to the design and management of sustainable agroecosystems, with conversion to sustainable agriculture involving three levels of investigation: improving the efficiency of conventional agricultural inputs and practices in ways that reduce their quantities and the environmental impact of their use; replacing conventional inputs and practices with alternatives that meet broader environmental standards, i.e. the agroecosystem is redesigned to operate on a new set of ecological processes (*Gliessman, 2004*). Agroecology can be considered as the solution to the many challenges of the agricultural and food system, and can become a model for transforming agriculture towards more sustainable and resilient agri-food systems, with an important role played by new and emerging technologies related to digitalization and reproduction (*Ewert et al., 2023*).

Organic and regenerative agriculture is gaining ground in response to the negative environmental impacts of commercial agriculture, focusing on sustainable practices that improve biodiversity, water efficiency, and climate resilience. Global organic agriculture has grown significantly and its market has reached high values, with the US having the largest market share (*Boris and Lal, 2015; Mpanga et al., 2021*).

The Water-Energy-Food Framework (WEF) is a system developed to guide cross-sectoral policymaking, maximizing synergies and minimizing conflicts between water, energy and food systems (*Almulla et al. 2021*). In recent decades, European cities have even begun to reintegrate urban farms and gardens into their plans, promoting policies that support urban agriculture to meet the demands for local food, biodiversity and sustainable development (*Fox-Kämper et al., 2023*).

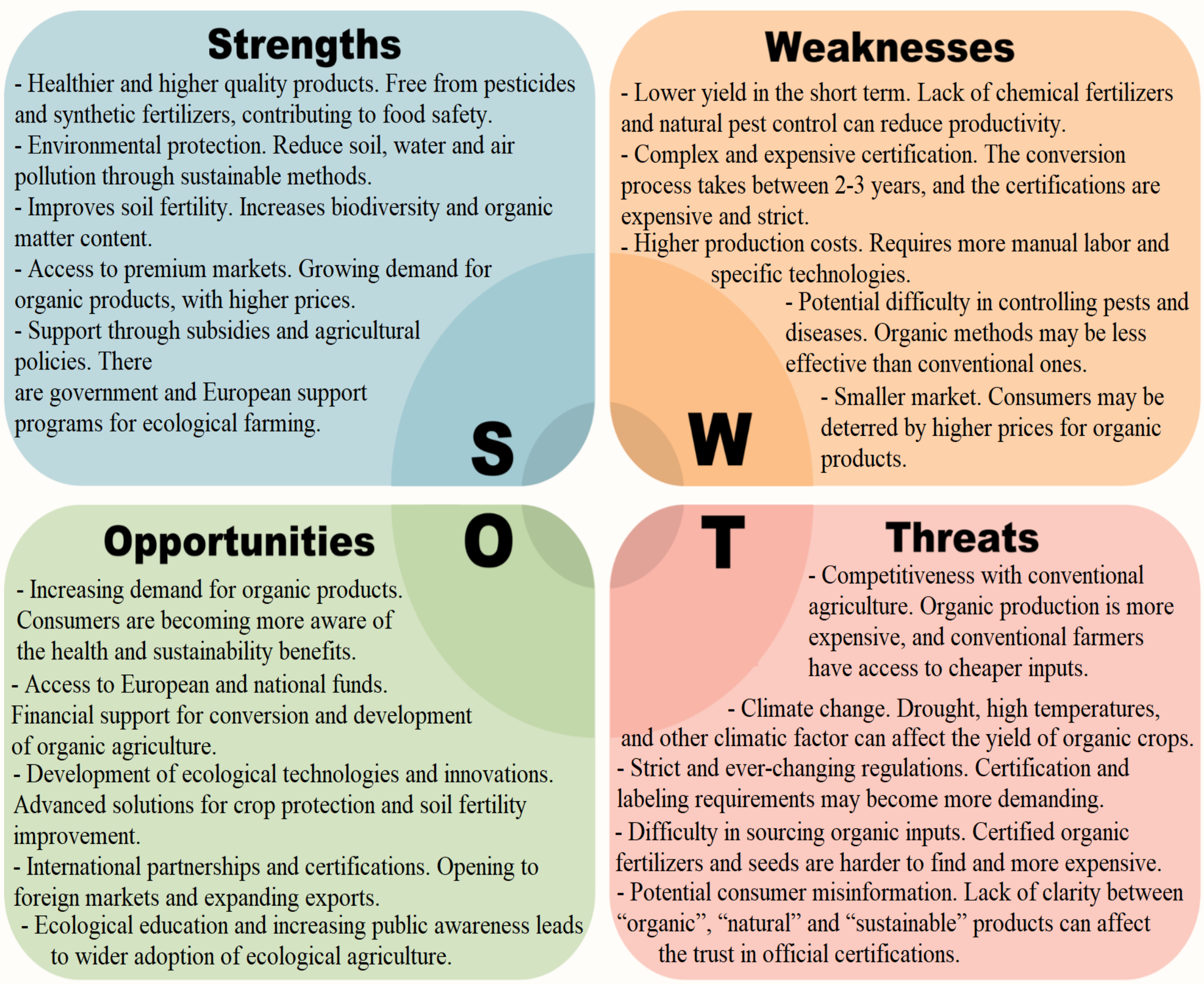
Adoption of sustainable agricultural practices depends on factors such as household wealth, age of household head, education and size (*Okello et al., 2021*). Studies suggest that authorities and agricultural development agencies should focus on increasing household assets and promoting training programs to support the adoption of these new practices (*Oyetunde-Usman et al., 2021*). Because the adoption of agri-environmental management mechanisms is somewhat of a voluntary process, it presents implementation difficulties for individual producers (*Van Wyngaarden et al., 2024*).

Ecological farming has gained considerable attention in recent decades, especially in the context of global climate change. It not only promotes sustainable practices, but also contributes to the reduction of greenhouse gas emissions (*Smith et al., 2014; Sun et al., 2020; Alhassan et al., 2021*). Studies show that organic farming can significantly reduce the carbon footprint of the agricultural sector (*Garnett et al., 2015*).

Another essential aspect of organic farming is crop diversification, which helps increase the resilience of agricultural systems to climate change (*Altieri and Nicholls, 2017*). By using crop rotation and perennials, farmers can improve soil health and reduce erosion, critical issues in the context of extreme weather events (*Kremen and Miles, 2012*). Ecological farming also promotes the use of renewable resources and water management techniques, which is crucial in the face of increasingly frequent droughts (*Lal, 2015*). Agroecological practices, such as agroforestry, contribute to carbon sequestration and improve biodiversity (*Milder et al., 2016*). Another important benefit of ecological / organic farming is its ability to support local communities and promote food security. By reducing dependence on chemical inputs and promoting local products, organic farming can contribute to circular economies and sustainable development (*Gliessman, 2015*).

A study by *Seitz et al. (2019)* evaluated the effect of different agricultural practices on soil erosion, comparing ecological farming, conventional farming, and no-tillage farming. The results indicated that ecological farming reduces sediment delivery by 30% compared to conventional farming, and the use of reduced tillage in ecological farming decreases sediment loss by 61% compared to intensive tillage.

According to *FAO (2018*), organic agriculture plays a vital role in adapting to and mitigating the effects of climate change. By promoting sustainable practices, it not only helps protect the environment, but also contributes to the well-being of rural communities and global food security. It is essential that agricultural policies integrate the principles of organic agriculture to respond to the challenges posed by climate change and ensure a sustainable future for future generations.



Strengths

- Healthier and higher quality products. Free from pesticides and synthetic fertilizers, contributing to food safety.
- Environmental protection. Reduce soil, water and air pollution through sustainable methods.
- Improves soil fertility. Increases biodiversity and organic matter content.
- Access to premium markets. Growing demand for organic products, with higher prices.
- Support through subsidies and agricultural policies. There are government and European support programs for ecological farming.

Weaknesses

- Lower yield in the short term. Lack of chemical fertilizers and natural pest control can reduce productivity.
- Complex and expensive certification. The conversion process takes between 2-3 years, and the certifications are expensive and strict.
- Higher production costs. Requires more manual labor and specific technologies.
- Potential difficulty in controlling pests and diseases. Organic methods may be less effective than conventional ones.
- Smaller market. Consumers may be deterred by higher prices for organic products.

Opportunities

- Increasing demand for organic products. Consumers are becoming more aware of the health and sustainability benefits.
- Access to European and national funds. Financial support for conversion and development of organic agriculture.
- Development of ecological technologies and innovations. Advanced solutions for crop protection and soil fertility improvement.
- International partnerships and certifications. Opening to foreign markets and expanding exports.
- Ecological education and increasing public awareness leads to wider adoption of ecological agriculture.

Threats

- Competitiveness with conventional agriculture. Organic production is more expensive, and conventional farmers have access to cheaper inputs.
- Climate change. Drought, high temperatures, and other climatic factor can affect the yield of organic crops.
- Strict and ever-changing regulations. Certification and labeling requirements may become more demanding.
- Difficulty in sourcing organic inputs. Certified organic fertilizers and seeds are harder to find and more expensive.
- Potential consumer misinformation. Lack of clarity between "organic", "natural" and "sustainable" products can affect the trust in official certifications.

Fig. 11 – SWOT analysis of implementing ecological agriculture

ECOLOGICAL SOLUTIONS FOR SOIL FERTILIZATION AND CROP PROTECTION

Biofertilizers used in organic farming have numerous benefits (they eliminate chemical fertilizers) but also limitations (they do not have the same effect on weeds and pests as chemicals) (*Ritika and Utpal, 2014*), so that always, a correct analysis must be made regarding the final impact on agricultural production, regardless of how much is used (*Carvajal-Muñoz and Carmona-Garcia, 2012; Nabti et al., 2016*).

Biofertilizers can also be obtained from the algae used in the treatment of dairy wastewater and pig manure (*Mulbury et al., 2008*). To increase soil fertility using organic fertilizers, soil health boosters (Kaur, 2020) based on micro and macro algae (*Chapman, 2013; Silva and Bahcevandziev, 2019; Chittora et al., 2020; Ammar et al., 2022*) can be used, proposing an effective approach, replacing inorganic and organic fertilizers that have a polluting impact on the soil (*Gonçalves, 2021*). The use of microalgae has also been extended to the cultivation of tomatoes in hydroponic cultures (*Zhang et al., 2017; Barone et al., 2019*) or in greenhouses (*Coppenes et al., 2016; Alobwede et al., 2019; Suleiman at al., 2020*) and not only that, they can have multiple applications as biofertilizers (*Chatterjee et al., 2017; Guo et al., 2020*) and even improve the productivity and salt stress tolerance of plants (*Hashem et al., 2019*), sandy and clay soil fertility (*Izzati et al., 2019*), they can have a biostimulatory role but also be a biofertilizer in vegetable crops (*Ronga et al., 2019*).

Another potential approach for sustainable crop production was studied by *Nosheen et al. (2021*), who pursued the use of microbes as biofertilizers in agriculture, respectively for wastewater remediation using algae, simultaneously with the production of biofertilizers (*Zou et al., 2021*).

Ecological farming uses a variety of plant protection products approved by different countries, depending on local crops, pests and specific regulations. These products include biorational, inorganic, botanical, microbial, oil-based and soap-based pesticides, and some natural substances, such as nettle decoction, are used for pest control. In addition, EU regulation 1107/2009 introduced the concept of "basic substances", which are not primarily intended for plant protection but can be legally used in organic farming, such as food products as vinegar or sunflower oil, with the exception of herbicides. (*El-Shafie, 2019*).

There is also a growing concern among agricultural scientists and the general public about the many problems associated with the use/reliance on herbicides, with direct threats to human health. Based on this concern, ecological management of agricultural weeds proposes alternative approaches, less dependent on herbicides and more on the understanding and manipulation of resources, allelopathy, disease, seed and seedling responses to soil cultivation and succession. Crop diversification can sustainably manage weeds in crop production systems, combined with the use of technological innovations that use non-chemical methods (*Teasdale, 1996*). As a result of crop diversification, weed density can be reduced by negatively impacting weed germination and subsequent growth. At the same time, diversified agricultural systems will be more resilient to climate change than monoculture systems and will provide better crop yields.

Combating trends in the use of synthetic fertilizers, pesticides and other plant protection substances is addressed within the framework of the European Union's Common Agricultural Policy, which aims for a 20% reduction in fertilizer use and a 50% reduction in pesticide use (*Slijper et al., 2023*).

WATER CONSERVATION THROUGH ECOLOGICAL AND SUSTAINABLE AGRICULTURAL PRACTICES

Water conservation is essential to protect water resources and ensure a sustainable future. Techniques such as efficient irrigation, mulching, crop rotation, and the use of cover crops reduce water loss and maintain soil moisture, preventing drought and land degradation. Ecological practices minimize water pollution from pesticides and chemical fertilizers, protecting aquatic ecosystems and drinking water quality. Adopting these methods not only supports agricultural production, but also the ecological balance, contributing to the resilience of communities in the face of climate change.

The creation and management of riparian buffer zones is considered an essential practice globally for improving the health of watercourses. In agricultural areas, they are often used as productive pastures, which can lead to increased levels of nutrients and sediment in the water, as well as reducing the capacity to sequester carbon and protect natural biodiversity (*Cambardella and Elliott, 1992*). An innovative approach to applying multisystem ecological and economic models, facilitating quantification at the property level, with reduced costs and greater speed, has been proposed by researchers *Malcher et al. (2023*).

In the Northern Ireland region, short rotation coppice (SRC), grown as a riparian buffer in intensive agriculture, has been proposed as a solution to improve agricultural sustainability, contributing both to reducing greenhouse gas emissions and preventing water quality degradation, while the impact on food production remains minimal (*Livingstone et al., 2023*). In the coastal regions of the San Quintín Bay, salt marshes and seagrass have the ability to filter trace amounts of toxic elements from the environment. These plant ecosystems thus function as natural biofilters, protecting the environment from contaminants and helping to maintain the health of adjacent ecosystems (*Cuellar-Martinez et al., 2021*).

Retention lakes represent an innovative and sustainable solution for water management in agriculture, addressing the critical challenge of water availability during dry seasons (*Staccione et al., 2021*). These artificial or natural reservoirs are designed to capture and store excess water during periods of heavy rainfall, such as in the winter, and release it gradually for use in agricultural irrigation during droughts or dry seasons. This approach not only ensures a consistent water supply for crops but also helps mitigate the risks associated with water scarcity, which is becoming more frequent due to climate change. In addition to supporting irrigation, retention lakes play a crucial role in maintaining a minimum ecological flow in rivers, ensuring that aquatic ecosystems remain healthy even during periods of reduced rainfall. This is particularly important for preserving biodiversity and preventing the complete drying of riverbeds, which can have severe consequences for local wildlife and communities that depend on these water sources. Moreover, retention lakes can reduce the risk of flooding in agricultural areas by capturing excess runoff, protecting both crops and infrastructure. When integrated with other sustainable practices, such as efficient irrigation systems (e.g., drip irrigation) and crop rotation, retention lakes become a cornerstone of resilient water management strategies in agriculture. They not only improve water security but also contribute to the overall sustainability of farming systems, helping farmers adapt to the challenges posed by climate variability.

Micro-dams are used to reduce runoff, soil erosion and transport of crop protection products (CPPs) in agricultural fields. Research has shown that micro-dams can reduce runoff by an average of 62% (for corn and potatoes, the reduction was 62% and 81%, respectively), and soil erosion by an average of 73% (75% for corn and 89% for potatoes). PPP transport was also reduced by an average of 67%, with a significant reduction for potatoes (91%). These results suggest that micro-dams can be integrated into environmental exposure assessments, by reducing the percentage of runoff, erosion and transport of CPPs or by decreasing the runoff curve number in numerical models (*Sittig and Sur, 2023*).

SOIL CONSERVATION THROUGH ECOLOGICAL AND SUSTAINABLE AGRICULTURAL PRACTICES

The European Commission, in the European Union Thematic Strategy for Soil, identified the following 7 soil functions that must be protected: biomass production, including in agriculture and forestry; storage, filtration and transformation of nutrients, substances and water; reservoir of biodiversity, such as habitats, species and genes; physical and cultural environment for people and human activities; source of raw materials; carbon sink; archive of geological and archaeological heritage.

Soil conservation and security gain global prominence as they are linked to crop production and global climate, soil contamination and human health, agriculture and ecosystem services, and the Millennium Sustainable Development Goals. Sustainable Development Indicator 15.3.1. assesses the degree of degradation by measuring soil carbon, land cover and productivity (*Thomas et al., 2023*).

Given that a large part of the population of developing and underdeveloped countries is dependent to a large extent on agriculture, animal husbandry and fishing, and modern and mechanized technologies are almost non-existent, their existence is directly linked to the quality of the land and its resources, and the role of sustainable management of agricultural land is of vital importance for the inhabitants of these states (*FAO, 2000; Alemu, 2016; Tey et al., 2017; Xiao et al., 2021*).

Ecological soil management is an alternative for healthy soils, based on the concept of “building soils as a solution for better crops” (*Magdof and Van Es, 2009*). Organic matter is the key to healthy soils and depending on the percentage of organic matter in the soil, we will benefit from a healthier soil. This is influenced by the physical properties of the soil, the degree of its degradation, but also by the cycles and flows of carbon and nutrients in the soil. Ecological soil management is influenced by factors such as: soil health, plant health and pests, and to obtain high-quality soils, organic matter management, diversification of crop systems, integration of crops and animals, use of composts, reduction of runoff and erosion, reduction of compaction, minimization of soil cultivation, water management: irrigation and drainage, and nutrient management must be taken into account.

Conservation tillage in ecological farming has several advantages, such as reducing soil erosion, improving macroporosity, carbon storage, increasing microbial activity, reducing nutrient runoff and fuel consumption, allowing for faster tillage. Disadvantages include increased pressure from perennial grasses, incompatibility with poorly drained or unstable soils, and limited crop options due to reduced nitrogen availability. The success of this method depends on the correct choice of crop rotation, management of weed and disease control, and adaptation to local soil and terrain conditions (*Peigné et al., 2007*)

Applying best management practices is a long-term conservation effort and can be achieved by adopting structural conservation practices to reduce soil erosion and surface water runoff (*Prokopy et al., 2008; Gedikoglu et al., 2011; Martins et al., 2021*). However, the geographical distribution of these practices is not very widespread, and for their digital mapping, timely and spatially explicit inventories of the areas to be mapped must be carried out. The development of such mapping is of real use for conservation programs, the geospatial inventory being easily accessible information for the evaluation of large-scale conservation practices on cultivated lands in a region / country.

Adopting regenerative agriculture practices on temperate arable lands can increase soil organic carbon concentrations without reducing yields, and can be considered a climate change mitigation strategy. Some studies in the UK show that the use of cover crops can increase stocks by an average of 10 $t \cdot ha^{-1}$ within 30 years of adoption, sequestering approximately 6.5 megatons of carbon dioxide per year ($Mt\ CO_2 \cdot y^{-1}$) (*Powlson et al., 2016; Jordon et al., 2022*).

The application of biochar obtained by pyrolysis of corn straw instead of lime is a solution that has been shown to improve the physicochemical properties of the soil and its resistance to reacidification. The results showed that the application of biochar can significantly reduce soil acidity, from 8.2 ± 0.8 meq 100 g^{-1} to 1.9 ± 0.3 meq 100 g^{-1}, considerably decreasing the bioavailability of nickel. (*Becerra-Agudelo et al., 2022*).

Within negative emission technologies, biochar obtained from forest residues represents a mature option for capturing and storing carbon in soils (*Ogle et al., 2019*). Studies show that biochar can generate negative CO_2 emissions, with additional benefits for agricultural yields and reduced air and marine pollution, but also some trade-offs regarding tropospheric ozone formation, land acidification and ecological toxicity. In

Norway, at the national level, biochar could offset between 13-40% of greenhouse gas emissions from the agricultural sector (*Tisserant et al., 2022*).

The aim of a research study by *Devine et al. (2022)* was to develop a guide for estimating the “time to trafficability” of soil (the period during which the soil is suitable for agricultural work and traffic), using data from soil surveys and hydroclimatological models. The study showed that fine and loamy soils have a longer time to trafficability in the cold months, and seasonal effects were more pronounced in loamy soils. The models developed allow mapping of typical time to trafficability and can help in decision-making regarding the management of aquifer recharge and soil compaction risks.

Cruz-Ramírez et al. (2012) studied the role of conservation agriculture in reducing soil erosion in olive groves and soil protection with cover crops between rows. Given the high erosion of olive soils in Spain and especially in the Andalusian area, the authorities have taken subsidy measures and developed regulations to stimulate the establishment of cover crops between rows in olive groves, using a method based on multi-objective neural networks to classify olive trees, bare soil and different cover crops, respectively, using remote sensing data recorded in spring and summer.

THE IMPACT OF CONSERVATION AND ECOLOGICAL AGRICULTURE ON BIODIVERSITY

Although biodiversity is a key factor for sustainable agriculture, measures to protect it are rarely put into practice by farmers, the main causes being different perceptions between scientists and farmers regarding the importance and implementation of these measures (*Maas et al., 2021*).

A key aspect of ecological / organic farming is its beneficial impact on biodiversity. Organic practices, such as crop rotation, the use of perennials, and the avoidance of chemical pesticides, play a crucial role in creating and maintaining a diverse habitat for numerous plant and animal species (*Kremen and Miles, 2012*). This biological diversity contributes not only to the health and resilience of ecosystems, but also to the improvement of ecosystem services, such as natural pest control and soil fertility, and to a stable food supply.

Organic farms have between 46-72% more semi-natural habitats, 30% more species, and 50% more individuals than non-organic farms, depending on altitude (*Pfiffner and Balmer, 2011*).

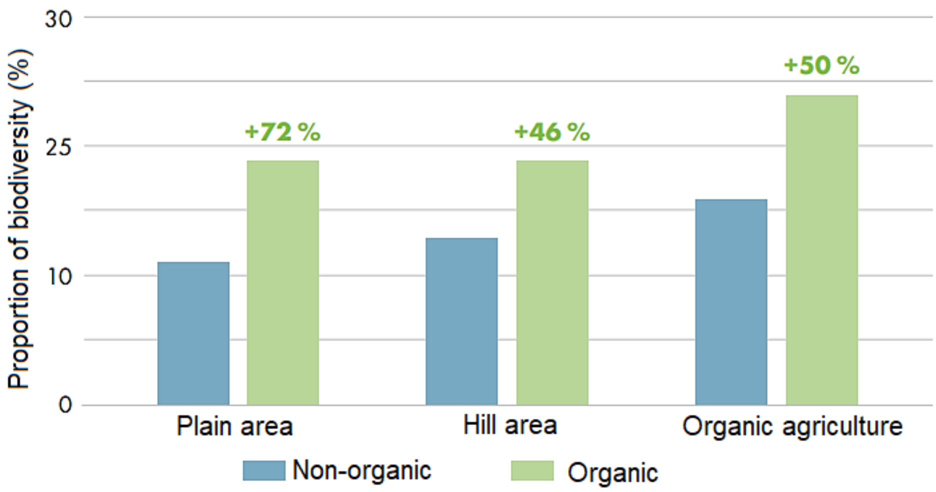


Fig. 12 – Proportion of biodiversity by altitude, in non-organic vs. organic farms (*Pfiffner and Balmer, 2011*)

A notable example is the support provided by biological diversity to the pollination process, an indispensable element for global food production. Increased biodiversity ensures the presence of a diverse range of pollinators, such as bees, butterflies and other beneficial insects, which, in turn, directly influence the quality and quantity of agricultural crops (*Potts et al., 2016*). In addition, organic systems reduce the risk of ecological imbalances caused by the intensive use of chemicals, thus protecting vulnerable species and contributing to the long-term regeneration of agricultural ecosystems.

Understanding how soil biology can influence soil health, soil properties and biological processes contributes to the sustainability of agriculture and ecosystem services. Through appropriate soil management (no-tillage) it is possible to influence (increase) microbial biomass and modify community profiles in soil aggregates (*Helgason et al., 2010*), this aggregation being important for soil functioning, as it provides physical protection of organic matter and microbial inhabitants and tillage disturbs aggregates, increases soil erosion (wind and water) and exposes previously protected organic matter to decomposition and loss.

Lehman et al. (2015) have analyzed how soil biology can be manipulated to increase nutrient availability for high-yield, high-quality crops, protect crops from pests, pathogens, weeds, and manage other factors that can limit production, the provision of ecosystem services, and stress resistance. Such an understanding and improvement of soil biological health may be the solution to reversing soil degradation (*Lal, 1994; Eswaran et al., 2001*).

The effects of tillage practices on the populations, functions and interactions of soil organisms depend on tillage systems that can affect the physical and chemical soil environment in which soil organisms live, directly affecting them (*Kladivko, 2001*). These practices alter soil water content, temperature, aeration and the degree of mixing of crop residues in the soil matrix (*Rochette, 2008*), affecting soil organisms, and understanding the impact of management on the complex interactions of all organisms at the soil level is a challenge for soil ecology research. Through the implemented practices, conservation agriculture can contribute to improving the ecology of aquatic ecosystems and increasing biodiversity (*Voicea et al., 2024*). It is true that soil conservation agricultural practices have been promoted and used mainly to improve soil health and mitigate soil loss, but an additional benefit of these practices has been to reduce the negative impact of agricultural runoff on aquatic ecosystems (*Lizotte et al., 2021*).

Analyzing ecological responses to conservation agriculture practices, it emerged that in about 40% of the studies there was a positive response to these practices – increased biodiversity (*Zedler, 2003; Moore and Palmer, 2005; Cullum et al., 2006; Moore et al., 2007a; Moore et al., 2007b; Schäfer et al., 2007; Smith et al., 2007a; Smith et al., 2007b; Maret et al., 2008; Smiley et al., 2008; Ellison et al., 2009; Knight et al., 2010; Lizotte et al., 2010a; Lizotte et al., 2010b; James et al., 2011; Christensen et al., 2012; McKinney, 2012; Sarkar et al., 2012; Seger et al., 2012; Knight et al., 2013; Withers et al., 2014; Smiley and Rumora, 2015; Ullah et al., 2015; Bullerjahn et al., 2016; Gbaguidi et al., 2016; Hall et al., 2017; Hunt et al., 2017; Kovalenko et al., 2019; Larned and Schallenberg, 2019; Moran et al., 2019; Goeller et al., 2020; Smith et al., 2020; Sander, 2021;* and in almost 41% of the studies it had no visible ecological impact (*Boesch et al., 2001; Zablotowicz et al., 2001; Knight and Welch, 2002; Paerl et al., 2003; Knight and Welch, 2004; Carey et al., 2005; Carey et al., 2007; Moore et al., 2007c; Knight et al., 2008; Stephens et al., 2008; Utley et al., 2008; Todd et al., 2009; Smiley and Gillespie, 2010; Todd et al., 2010; Zablotowicz et al., 2010; Brooks et al., 2011; Smiley et al., 2011; Lizotte et al., 2012a; Lizotte et al., 2012b; Lizotte et al., 2012c; Lizotte et al., 2012d; Smiley et al., 2012; Knight and Cullum, 2014; Knight et al., 2015; Pearce and Yates, 2015; Porter et al., 2015; Whittaker et al., 2015; Wronski et al., 2015; Holmes et al., 2016; Álvarez et al., 2017; Wainger et al., 2017; Tsaboula et al., 2019; Lürling and Mucci, 2020*) and in two out of two studies the influences were negative (*Chapmen et al., 2008; Sarkar et al., 2020*).

In almost all developed countries (USA, European Union, Japan, Canada, etc.) there are agricultural agencies that support farmers with programs to implement a variety of practices for agricultural conservation and in recent years their actions have also been directed to counteract the loss of habitat, biodiversity and ecosystem services, correlated with increased eutrophication and harmful algal blooms that are directly influenced by global population growth and climate change.

Therefore, conservation and ecological / organic agriculture not only supports sustainable food production, but also actively contributes to protecting biodiversity and maintaining the health of ecosystems, offering a viable solution to the challenges generated by climate change and the loss of natural habitats. However, it should be noted that activities aimed at expanding conservation agriculture and implementing these types of agriculture, although contributing considerably to solving ecological problems and preserving soil fertility, are also linked to the creation of favorable conditions for the development of harmful organisms.

THE IMPACT OF CONSERVATION AND ECOLOGICAL AGRICULTURE ON FOOD SECURITY AND LOCAL ECONOMIES

Conservation and ecological agriculture is increasingly recognized as a cornerstone of sustainable development, particularly in the face of climate change and economic instability. By prioritizing soil health, water conservation, and biodiversity, this model ensures that farming systems remain productive and adaptable over time. Practices such as crop rotation, cover cropping, and reduced tillage not only improve soil fertility but also enhance the capacity of the land to withstand extreme weather events like droughts or floods. For vulnerable communities, where access to resources is limited, ecological agriculture offers a cost-effective alternative to conventional methods reliant on expensive synthetic inputs. Farmers can cultivate healthy and diverse crops (*Gliessman, 2015*) using locally available organic fertilizers, pest management techniques, and traditional knowledge, reducing dependency on external inputs and market fluctuations.

A significant benefit of ecological / organic farming is its positive impact on local economies. By promoting local products and reducing dependence on external inputs, organic farmers contribute to circular economies and sustainable development. This not only supports the local economy, but also reduces the carbon footprint associated with transporting food. For example, recent studies highlight that organic farming can generate higher incomes for small farmers, due to the increased demand for organic products and the premium prices they attract (*FAO, 2020*). At the same time, by stimulating local markets and short supply chains, organic farming reduces the vulnerability of rural communities to global food price fluctuations (*IPES-Food, 2021*).

Thus, conservation and ecological farming represents not only a solution for sustainable food production, but also an opportunity to strengthen local economies, reduce inequalities and protect natural resources for future generations. Through its integrated approach, this agricultural model can respond to both economic and environmental challenges.

CONCLUSIONS

Conservation and organic agriculture plays a fundamental role in shaping the future of sustainable agriculture, having a significant impact on soil health, agricultural productivity and ecosystems.

By implementing practices such as crop rotation, the use of cover crops, and reduced tillage, these methods contribute to the conservation of natural resources while promoting biodiversity, reducing greenhouse gas emissions, and combating climate change. At the same time, organic agriculture supports food security and local economic development by reducing dependence on chemical inputs and stimulating circular economies. However, the success of these practices depends on close collaboration between farmers, researchers, authorities and civil society. Only through a collective effort to integrate these methods into a sustainable and accessible framework will the people be able to ensure a healthier, more equitable and more resilient agricultural future for future generations.

However, for effective large-scale implementation, further research is needed to address the technical, economic and social challenges associated with these systems. A key area of research is the optimization of crop rotations and permanent soil cover for different climatic conditions and soil types. Future studies should assess how specific combinations of cover crops and nitrogen-fixing plants influence soil fertility and agricultural productivity in the long term. Further investigation is also needed into the mechanisms by which conservation and organic agriculture can contribute to increased soil carbon sequestration. Research should determine the long-term impact of these practices on greenhouse gas emission reduction and climate change adaptation.

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