UNIVERSITÀ DEGLI STUDI DI PADOVA
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Second Cycle Degree (MSc)
in Sustainable Agriculture

TRANSITION TO CONSERVATION AGRICULTURE: EVALUATING THE SOIL QUALITY DURING TILLAGE SHIFT FOR ENHANCED ADOPTION

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1. ABSTRACT

This study delves into the pivotal role of conservational agriculture in addressing the global challenges of food production, economic sustainability, and environmental conservation. CA is an agroecosystem management emphasizing minimal soil tillage, permanent soil cover, and diversified crop rotation. The research explores the adoption challenges of CA in Europe, highlighting the influence of agricultural policies and the cognitive shift required by farmers.

A field experiment was carried out at the Lucio Toniolo Experimental Farm in Italy, studying the transition from conventional to conservational agriculture. The experiment encompasses three tillage systems: Conventional tillage (CT), minimum tillage (MT), and no-tillage (NT). Various soil parameters were monitored during the 3 years of the experiment, such as bulk density, hydraulic conductivity, earthworm presence, pH, nutrient analysis. During this experimental period the wheat crop (Triticum aestivum L.) was cultivated.

After 5 years after the conversion from conventional tillage to conservation tillage, in this field, the MT and NT soils present, as expected, a higher bulk density. Despite this, the hydraulic permeability appears to be almost unaffected while a tendency of a higher plant available water is evident. Furthermore, the increase of earthworm abundance in MT and NT indicates a better biological functioning of the soils. Looking at chemical soil parameters, total N content and Soil organic carbon showed an increase in NT and MT over CT.

Conservation agriculture is a competent practice in this study area, clearly, further research is needed to get more long-term answers from the implementation of conservation agriculture.

2. INTRODUCTION

Today's world demands that we take our thinking towards a more holistic mentality, towards the total and global integration of food, economy, culture, the planet, etc. We need to recognize the strengths and weaknesses of current food production systems, which require urgent modification to achieve efficiency and address the crises we face (Kassam and Kassam, 2021). This is where conservation agriculture (CA) plays a key role, enabling sustainability in human food production.

CA is an approach to managing agroecosystems for improved and sustained productivity, increased priors, and food security while preserving and enhancing the resource base and the environment. Conservation Agriculture, as a concept for natural resource-saving, strives to achieve acceptable profits with high and sustained production levels while concurrently conserving the environment (Friedrich *et al.,* 2012).

The agronomic practices applied in CA are based on three interrelated principles: minimal or no soil tillage in all farming operations, establishment of permanent vegetation cover, and diversification of the cropping system (Kassam *et al.*, 2019).

2.1 Principles of Conservation Agriculture

Three main principles guide Conservational Agriculture:

2.1.1. Minimum soil tillage/ Minimum soil disturbance

Reduced tillage and minimum tillage, (Figure 1) both under the concept of minimal soil disruption, help maintain healthy soil (Nunes *et al.*, 2020). By minimizing soil disturbance, the habitats of arthropods are less disturbed, creating favorable conditions for their growth and survival. This process, often termed "biological tillage," creates different-sized pores in the soil, allowing better air and water penetration and making it easier for soil-dwelling pests to grow (Rabary *et al.*, 2008). According to Jasrotia *et al.* (2023), no-till systems not only increase the density of white grubs but also enhance their natural control by conserving their natural enemies. Soil biological activity leads to stable soil aggregates and diverse pore sizes, aiding air and water movement, organic matter balance, and weed seed control (Sofo *et al.,* 2020).

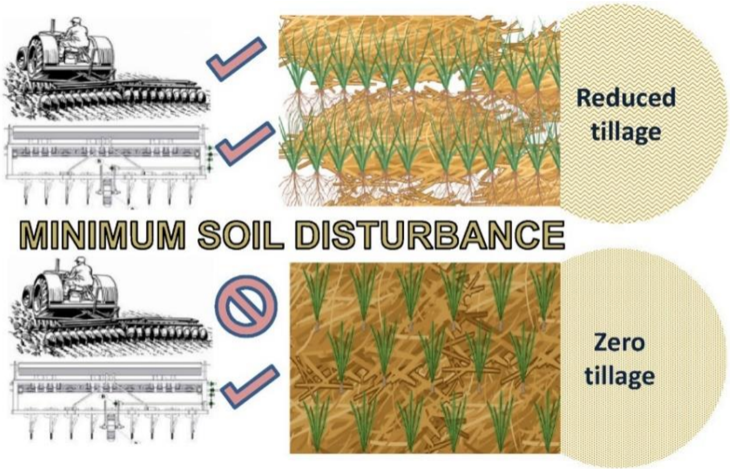

Figure 1: Practices followed under the minimum-soil-disturbance principle of

Conservation agriculture (Jasrotia *et al*., 2023)

2.1.2. Permanent soil cover

The main practices that follow this principle include using organic amendments, mulching, and cover crops (Figure 2). Keeping the soil covered all the time is crucial to shield it from harsh weather like heavy rain and direct sunlight. This practice also changes the soil's microclimate, creating a haven for various organisms, which in turn enhances soil biodiversity and boost the number of predators and parasitoids that attack different insect pest, thereby improving biological activity and carbon storage (Bhan & Behera, 2014).

Cover crops are crucial for maintaining a stable conservation agriculture system, directly impacting soil quality. Unlike regular crops grown for their market value, cover crops primarily enhance soil fertility and serve as animal feed (Snyder, 2019). In areas with limited biomass, like in dry and eroded soils, cover crops play a key role by:

- Protecting the soil during fallow periods
- Activating and reusing nutrients
- Improving soil structure and breaking tough layers
- Allowing rotation in monoculture systems
- Managing weeds, pests, and reducing soil compaction

These crops are typically planted during fallow periods, utilizing the remaining soil moisture.

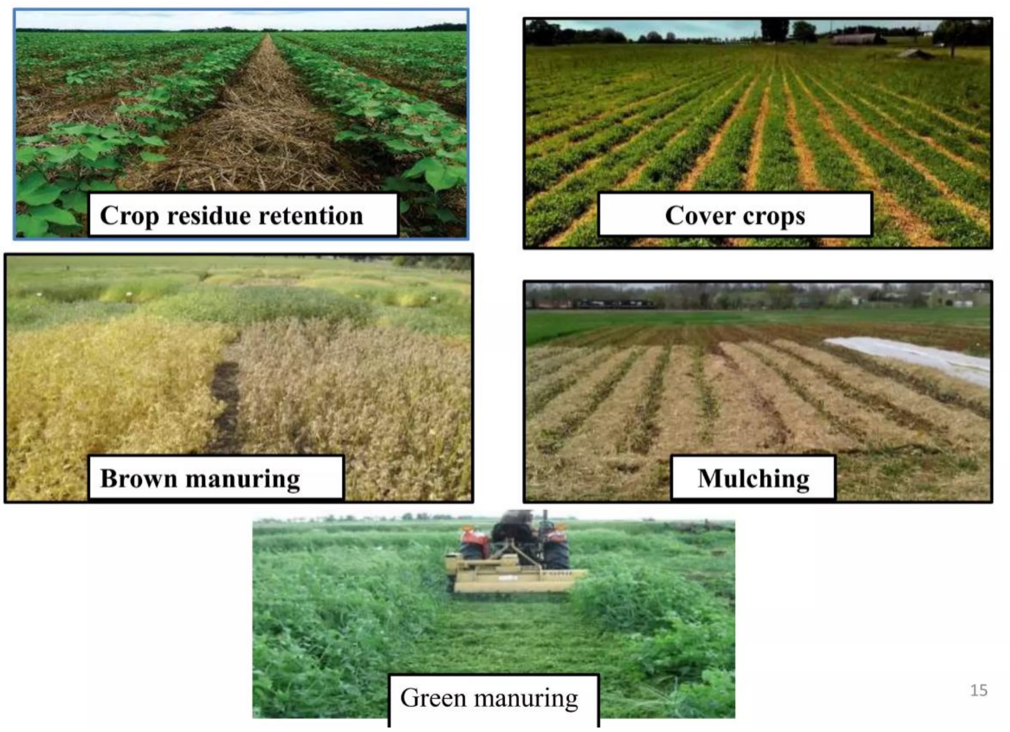

Figure 2 – Permanent organic soil cover (Chethan Babu, 2021)

2.1.3. Diversified Crop rotation

Diversifying crop rotation, intercropping, and using cover crops are key practices under this principle (Figure 3). This approach involves rotating between three or more crops to reduce farming risks and enhance soil health, creating a balanced environment for both beneficial and pest insects. By improving the soil's condition, it enhances the system's productivity and resilience to challenging growing conditions, such as drought (Volsi *et al.,* 2022). Diversified crop rotations not only help farmers diversify their income sources but also contribute to sustainable farming by reducing pests, diseases, and weeds, and improving soil fertility, soil microbial activity, water holding capacity, and conservation. This popular approach fosters long-term soil health and sustainable crop production (Shah *et al.,* 2021).

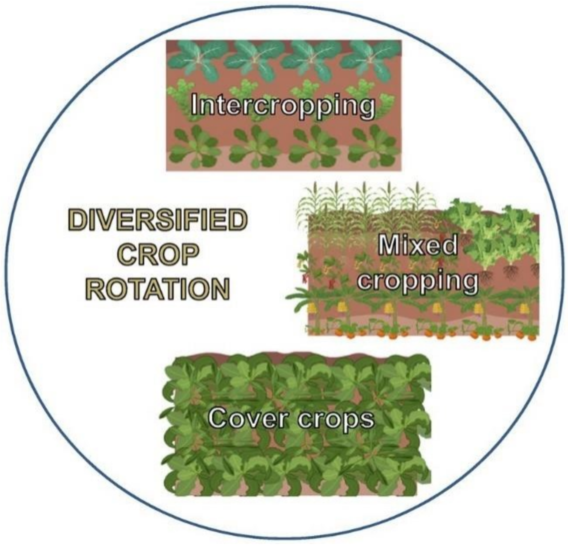

Figure 3 - Practices involved under the diversified-crop rotation principle. ((Jasrotia *et al.,* 2023)

2.2. The Situation of Conservational agriculture in global uptake:

The historical chart of CA uptake at the global level is shown in Figure 4. The transformation of conventional tillage-based agriculture began in the 1930s after the ‘Dust Bowl’ that shook the farming communities in the midwestern US, causing the scientific community to rethink what was not going right with farming, particularly with regards to soil conservation (Smith, 2021). Minimization of soil disturbance with stubble mulching was a breakthrough in the understanding of how the objective of crop production intensification could be combined with the objective of soil and water conservation at the practical level by farmers (Kassam *et al.,* 2021).

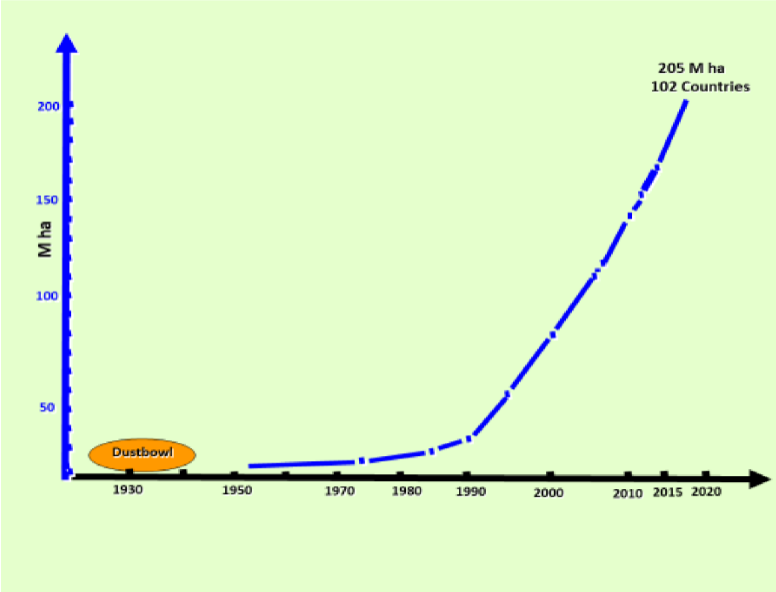

Figure 4 – Historical chart of CA uptake at the global level (Kassam *et al.,* 2022)

At first, the goal was to stop the erosion caused by tilling the soil, so they started using "conservation tillage," where they only left enough crop leftovers to protect the soil from erosion. It wasn't until a few years later that people began questioning the whole idea of tilling the soil. They realized it wasn't just causing erosion but also making other soil problems worse. In the late 1960s, some innovative farmers demonstrated that seeding without tilling, using the remains of the previous crop, was a way to prevent or even fix soil degradation and erosion (Kassam *et al.,* 2021).

In 2018/2019, the total area of Conservation Agriculture (CA) farmland worldwide was around 205.4 million hectares, which makes up about 14.7% of all global cropland (Table 1). This is a significant increase from 106.5 million hectares in 2008/2009, with almost half of the increase happening in both the Global South and the Global North. Since 2013/2014, the global CA farmland has gone up by about 48.6 million hectares, and since 2015/2016, it has increased by 25 million hectares. The yearly growth rate of CA farmland has been approximately 10 million hectares from 2008/2009 to 2018/2019, whereas it was about 5 million hectares annually from 1990 to 2008/2009 (Figure 5). (Kassam *et al*., 2021)

Table 1: Global spread of CA cropland area ('000 ha) in different regions for 2008/2009, 2014/2015, and 2018/2019, and corresponding percent change. (Kassam *et al.,* 2022)

Region	CA Cropland Area 2008/2009	CA Cropland Area 2013/2014	CA Cropland Area 2015/2016	CA Cropland Area 2018/2019	Percent Change in CA Area Since 2015/2016	Percent Change in CA Area Since 2013/2014	Percent Change in CA Area Since 2008/2009	Percent CA Cropland Area in the Region 2018/2019
S and C America	49,564.10	66,377.00	69,895.00	82,996.18	18.7	25.0	67.5	68.7
North America	40,003.80	53,967.00	63,181.00	65,937.22	4.4	22.2	64.8	33.6
Australia and New Zealand	12,162.00	17,857.00	22,665.00	23,293.00	2.8	30.4	91.5	74.0
Russia and Ukraine	100.00	5200.00	5700.00	6900.00	21.1	32.7	6800.0	4.5
Europe	1560.10	2075.97	3558.20	5601.53	57.4	169.8	259.0	5.2
Asia	2630.00	10,288.65	13,930.20	17,529.02	25.8	70.4	566.5	3.6
Africa	485.23	993.44	1509.24	3143.09	108.3	216.4	547.8	1.1
Total	106,505.23	156,759.06	180,438.64	205,400.04	13.8	31.0	92.9	14.7

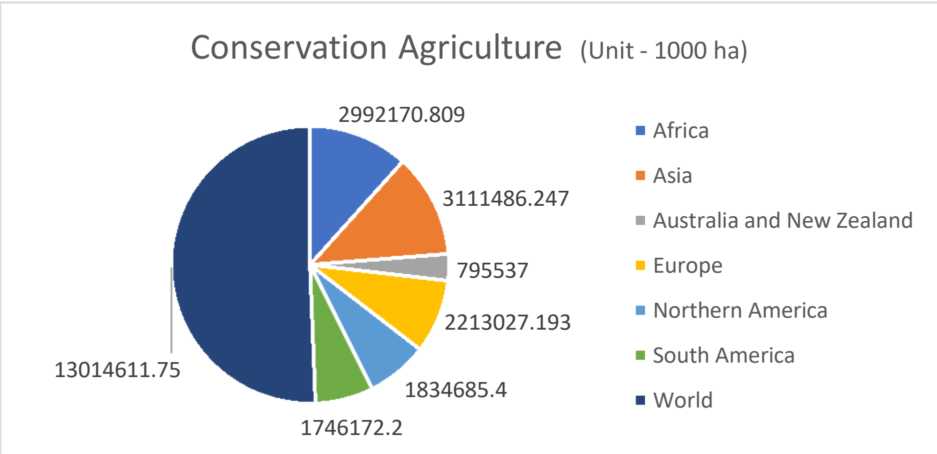

Figure 5- Extent of Adoption of Conservation Agriculture Worldwide (FAO Stats 2021)

2.3 Benefits of conservation agriculture

For any new technology to be widely accepted, it must offer clear advantages that appeal to a diverse group of farmers who recognize the disparities between their current practices and what they require. In the context of conservation agriculture, these benefits can be categorized as (Fuentes Llanillo *et al.,* 2020):

2.3.1. Economic Benefits:

1. Cost-savings in annual crops and time-saving: Direct drilling/no-tillage requires fewer passes, leading to reduced machinery depreciation and fuel and time savings. Estimated cost reduction ranges from 40 to 60 €/ha in Southern Europe and can exceed the extra costs of Conservation Agriculture (Kassam *et al.,* 2022).
2. Labour and fuel savings in perennial crops**:** Conservation Agriculture, especially direct sowing/no-tillage, significantly reduces machinery, fuel, and labor inputs. For instance, no-till olive orchards can save 60 to 80 Liters of fuel and 3 to 5 hours of labor per hectare annually compared to conventional tillage (Sofo *et al*., 2020)

3. Increase of yields: Conservation Agriculture improves soil health and water availability, leading to increased crop yields over time. Productivity and yield benefits directly contribute to greater financial gains for farmers.
4. Reduction of off-site problems: Soil erosion can lead to substantial off-site costs, including environmental pollution, public health issues, infrastructure damage, and increased water treatment costs. Implementing Conservation Agriculture can help prevent these off-site effects, benefiting society as a whole.
5. Social benefit: The large-scale adoption of conservation agriculture has brought about numerous social benefits, including improved farmer organization, enhanced community development, women empowerment, and improved food security. Additionally, it helps mitigate climate change, preserves natural resources, and meets the growing global food demand(Fuentes Llanillo *et al.,* 2020).

2.3.2. Agronomical and environment benefits:

Adopting conservation agriculture enhances agronomic benefits through various means:

1. Increase in organic matter, leading to improved soil structure, water retention, and nutrient availability.
2. Mulching with crop residues and weeds further improves soil structure and encourages earthworm activity.
3. Immediate benefits in dryland agriculture include enhanced rainfall-use efficiency, reduced soil runoff, and erosion.
4. Increase in biodiversity and carbon sequestration.

Conservation agriculture practices, such as maintaining crop residues on the soil surface and implementing a no-tillage approach, help minimize the harmful effects of raindrops, reduce runoff, and prevent erosion. Additionally, by preserving the soil cover, conservation agriculture fosters habitats for various species that prey on pests, encouraging a more balanced ecosystem. Crop rotation and cover crops further help retain genetic biodiversity, preventing the negative impacts of monoculture farming(Dang *et al.*, 2020).

Moreover, these practices aid in the accumulation of carbon in the soil, contributing to its role as a carbon sink. By increasing the organic matter content through the decomposition of roots and residues, conservation agriculture ensures the gradual release of carbon into the atmosphere. This carbon sequestration potential holds significant promise in mitigating greenhouse gas emissions and combating the adverse effects of global warming (FAO 2021)

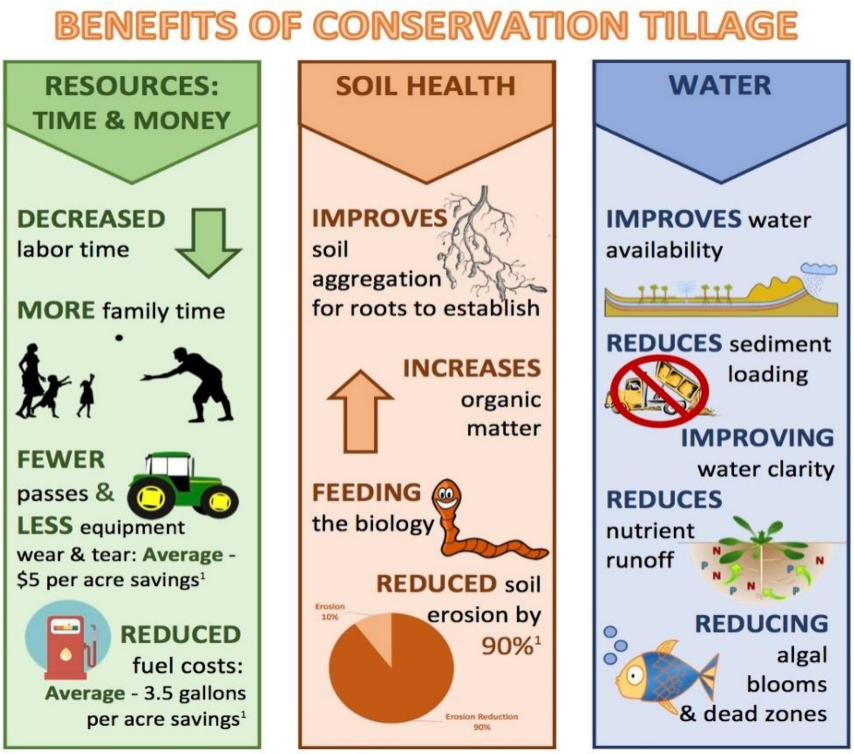

Figure 6: Benefits of Conservation Agriculture (Fox Demo Farms)

2.4. Effect of Conservation tillage on soil quality

Conservation tillage alters the physical, chemical, and biological characteristics of the soil primarily due to three modifications in the management of the soil/crop system (Blevins *et al*., n.d.). In the case of no-tillage, these alterations involve (1) the absence of soil mixing with organic residues or amendments; (2) the surface application of the majority of fertilizers, lime, and other amendments; and (3) the impact of surface mulch on retaining soil moisture and reducing soil temperature (Lal & Dick, 1991).

2.4.1. Physical Properties

Soil quality is significantly impacted by soil structure, as it plays a crucial role in influencing soil aeration, water infiltration, and root growth. Transitioning from conventional cultivation methods to conservation tillage can result in notable alterations to soil structure, particularly in terms of aggregate stability, soil water properties, and the relationships between soil air and water (Page *et al*., 2013).

Aggregate stability the adoption of conservation tillage practices frequently results in enhanced aggregate stability, a phenomenon often ascribed to higher concentrations of organic carbon in the surface layers of the soil profile (Chan *et al*., 2002; Hajabbasi & Hemmat, 2002).

Soil water

In semi-arid regions, the adoption of conservation tillage practices frequently results in reported increases in soil water storage(Thomas *et al*., 2007). The observed increase in water storage is commonly attributed to a combination of increased infiltration rates and diminished soil water evaporation (Page *et al.,* 2013).

Air water relationships

Compared to traditional methods, the reduced soil disturbance characteristic of conservation tillage may result in increased bulk density in the plough layer (Moreno *et al.,* 1997; Thomas *et al*., 2007)Increased bulk density, in turn, tends to reduce total soil porosity. When these declines in porosity coincide with increases in soil moisture, conservation tillage systems may exhibit decreased air permeability and a lower percentage of air-filled pores (Page *et al.,* 2013).

2.4.2. Chemical Properties

Soil pH

Conservation tillage management, particularly in no-till systems, is frequently associated with a decrease in soil pH compared to more traditional methods. These alterations are typically concentrated in the uppermost part of the soil profile, often within the top 5 cm (Franzluebbers & Hons, 1996), although notable differences extending to depths of 30 cm have been reported (Thomas *et al.,* 2007).

Nutrients

Under conservation tillage systems, nutrient availability can be modified due to the reduced or absent soil mixing within the tillage zone. This, coupled with the surface application of fertilizer and plant residues, can result in nutrient stratification. Residues deposited on the soil surface also tend to decompose at a slower rate compared to material that has been incorporated, potentially altering the rate of nutrient release in conservation tillage systems. Additionally, patterns of nutrient leaching may undergo changes when greater water infiltration is observed under conservation tillage (Page *et al*., 2013).

2.4.3. Biological properties

Organic matter

One of the notable impacts of conservation tillage, particularly in the case of no tillage, is the accumulation of residues and organic matter on the soil surface. This not only results in redistribution or stratification within the soil profile but is also supported by several studies demonstrating that conservation tillage systems maintain higher total amounts of organic matter in the soil profile compared to more intensively tilled systems (Lal & Dick, 1991).

Weeds

Tillage plays a role in weed population control by physically eliminating weed plants and burying seeds to inhibit germination. Practices like residue burning are effective in destroying weed seeds and reducing weed infestations (Heenan *et al*., 1990). The decreased frequency of tillage and the absence of residue burning in conservation tillage have been observed to increase the population of certain weed species(Lyon *et al.,* 1998). In certain cases, conservation tillage can act as an inhibitor of weed populations. This inhibition may arise from the suppression of weed germination in areas with ample residue cover or from alterations in temperature and moisture conditions that are unfavorable for weed growth (Page *et al.,* 2013).

Crop yield

Probably, the most critical biological aspect of a tillage system is the crop plant. A noteworthy observation is a transition period lasting 3-5 years or even longer, during which crop yields under conservation tillage initially show a decline compared to conventional tillage(Dick* *et al.,* 1991). The reasons for this phenomenon are not yet fully understood, but they appear to stem from the time required for soil structure to change the benefits of conservation tillage become apparent. This period may also encompass the time needed for farmers to learn how to effectively manage the conservation tillage system, the duration required for the establishment of an adequate residue cover, and potentially other factors that are yet to be identified (Lal & Dick, 1991).

Microbial activity

Microbiological activity in soil is significantly influenced by its physical and chemical properties. The key factors impacting microbial activity in soil under conservation-tillage practices include 1) variations in the distribution and amount of soil organic matter; 2) heightened levels of soil moisture; and 3) the duration for which conservation-tillage practices have been consistently implemented at a specific site (Lal & Dick, 1991).

2.5. Conventional vs Conservational

Soil quality effect:

Conventional tillage methods alter soil structure by impacting physical properties such as soil bulk density, penetration resistance, and moisture content. The yearly disruption and pulverization associated with conventional tillage result in a finer and more loosely arranged soil structure when compared to conservation and no-tillage methods, which aim to preserve the integrity of the soil (Rashidi & Keshavarzpour, 2007).

This variance leads to alterations in the number, shape, continuity, and size distribution of the pore network in the soil. These changes influence the soil's capacity to store and transmit air, water, and agricultural chemicals, thereby affecting erosion, runoff, and crop performance (Khan *et al.,* 2001).

In contrast, conservation tillage methods often lead to a reduction in pore space, an increase in soil strength, and the formation of stable aggregates. The pore network within soil subjected to conservation tillage typically exhibits greater continuity due to the presence of earthworms, root channels, and vertical cracks. Consequently, conservation tillage tends to minimize the disruption of continuous pores. On the other hand, conventional tillage diminishes soil penetration resistance and bulk density, enhancing soil porosity and water-holding capacity. However, the continuity of the pore network is disrupted by conventional tillage, increasing the soil's tortuosity. These changes create a favorable environment for crop growth and nutrient utilization. Nevertheless, the outcomes of no-tillage practices yield contradictory results (Keshavarzpour, 2012). A comparison of some issues between conventional tillage and CA is given in Table 2 (Hobbs *et al.*, 2008).

Crop Yield:

Shetto & Owenya (2007) reported a significant 50-75% reduction in production costs for conservation agriculture compared to conventional agriculture. Similarly, Mazvimavi *et al.* (2012) found a 39% increase in grain yields with conservation agriculture compared to traditional farming systems. Another study conducted in a dryland area observed a higher grain yield of approximately 7.3% in cases where conservation agriculture practices such as no-tillage, residue retention, and crop rotation were implemented (Rusinamhodzi *et al.,* 2011).

Table 2. A comparison of some issues between conventional tillage and conservation agriculture (Chauhan *et al*., 2012; Hobbs *et al.,* 2008)

Issues	**Conventional tillage**	**Conservation agriculture**
Soil disturbance	High	Minimum
Soil surface	Bare surface	Permanently covered
Cropping System	Monocropping, less efficient rotation	Diversified farming, more efficient rotation
Residue management	Residue burning or removal	Residue retention on the soil surface
Erosion	High wind and soil erosion	Low wind and soil erosion
Soil organic matter	Low due to oxidation of organic matter and residue removal	Soil organic carbon build-up
Water infiltration	Low	High
Weeds	Kill established weeds but also stimulate more weed seeds to germinate	Weeds are a problem in the early stages of adoption but decrease with time
Diesel use and costs	High	Low
Production costs	High	Low
Timeliness	Operations can be delayed	Timeliness of operations more optimal
Yield	Can be lower where planting is delayed	Same or higher if planting done timelier

2.6. The transition period and its effects on farmer's adoption

Despite the numerous benefits that conservation agriculture practices offer to farmers and society, their adoption in Europe remains somewhat limited, displaying significant variations among countries. Various explanations have been proposed at political, economic, and cognitive levels. Basch, G. *et al.* (2015) emphasize the influential role of the Common Agricultural Policy (CAP), suggesting that its historical focus on high yields has led farmers to prioritize maximizing yields and subsequent subsidies over reducing production costs or investing in long-term soil improvement. Additionally, the "knowledge-intensive" nature of conservation agriculture has been identified as a challenge (Lahmar, 2010), being this system relying on ecological processes that are only partially understood and highly specific to particular locations (Scopel *et al*., 2013). Farmers are required to alter their daily decision-making processes and the factors they consider in making such decisions. Therefore, gaining a deeper understanding of how farmers learn may contribute to mitigating cognitive barriers

to the adoption of conservation agriculture (Cristofari *et al*., 2017).
The change from conventional to conservation agriculture is a multi-year evolutionary process related to time and biology. It is not a short-term process and depends on the local social, economic, and biophysical situation. Kassam and Amir Kassam, (2020) suggest that adoption should be done gradually, to learn the technique through practice and to allow room for acceptance of the changes. But despite the great interest in conservation practice, especially in America, the same has not been true in Europe. Some of the obstacles to the adoption of the practice are know-how, mentality, inadequate policies, and inadequate training (Farooq and Siddique, 2015; Friedrich *et al*., 2009; Jat *et al.*, 2014), another cause is the uncertainty about its effects during the transition period after conversion from conventional to conservation (Kassam *et al.*, 2019; Pittelkow *et al.*, 2015; Rusinamhodzi *et al.*, 2011). Some reports have reported short-term negative effects (in the aforementioned transition period) from the implementation of no-tillage (NT) on bulk density (Guan *et al.*, 2014), soil resistance (Munkholm *et al*., 2003; Palm *et al.*, 2014), the saturated hydraulic conductivity of the soil (Buczko *et al.*, 2006) and on crop yields (Pittelkow *et al.*, 2015).
The aim of this thesis is then to study the evolution of some soil characteristics, and in particular hydraulic properties, during the transition phase from conventional to conservation agriculture.

3. OBJECTIVE:

Aim of this thesis is then to study the evolution of some soil characteristics, and in particular hydraulic properties, during the transition phase from conventional to conservation agriculture.

4. MATERIALS AND METHODS:

4.1. Experimental field design

The research was conducted at the Lucio Toniolo Experimental Farm in Legnaro, PD, located in northeastern Italy (45° 21 N; 11° 58 E; 6 m a.s.l). The climate in this region is characterized as sub-humid, with average temperatures ranging from -1.5 °C in January to 27.2 °C in July. Annually, the area receives 850 mm of rainfall, while the reference evapotranspiration is 945 mm, exceeding rainfall from April to September. The highest precipitation is observed in June (100 mm) and October (90 mm), with winter being the driest season, experiencing average rainfall of 55 mm. The shallow water table ranges from 0.5 to 2 m in depth, with the lowest values recorded in the summer.

The experiment commenced in the autumn of 2021, covering an area of 2 hectares divided into two replicates (1 hectare each) (figure 8). Each replicate was further divided into 3 strips measuring 13 m x 260 m. The soil type at the site is Fluvi-Calcaric Cambisol (FAO-UNESCO 2008) with a silt loam texture. The experimental plots included three treatments: the conventional tillage plot (CT) involved ploughing to a depth of 30 cm and harrowing to 15 cm, the minimum tillage plot (MT) was harrowing to a depth of 15 cm, and the no-tillage plot (NT) was sown on the residues of previous harvests (figure 7).

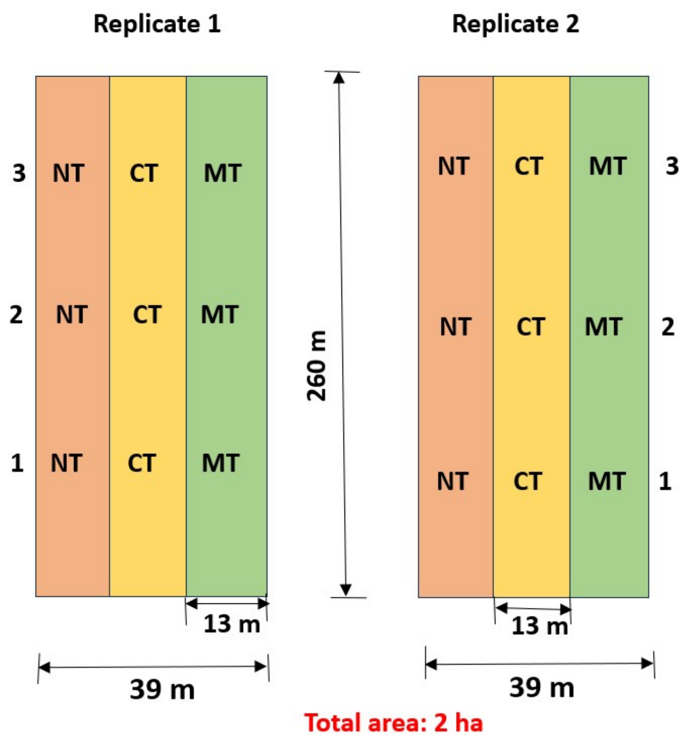

Figure 7: Experimental design

Figure 8: Image of a plot intended for experimentation

The initial implementation of the MT and NT tillage systems occurred in 2018 as part of a PhD thesis (Sartori *et al.*, 2021).

The focus crop during this research was wheat (Triticum aestivum L.), sown in two cycles (2021 and 2022) and managed conventionally. All required treatments, including fertilization, pesticides, and fungicides, were applied, as outlined in the table below.

Agronomic practices	1st CYCLE	2nd CYCLE
Sowing	28/10/2021	3/11/2022
Pre-sowing fertilization 8-16-20	**X**	**X**
Fertilization in cover crops Ammonium nitrate 27%.	**X**	**X**
Fertilization in cover crops Urea 46%.	**X**	**X**
Post-emergence weed treatment	**X**	**X**
Fungal treatment	**X**	**X**
Harvest	27/6/2022	29/6/2023

4.1.2. Field parameters:

The chosen parameters for monitoring the physical characteristics of the soil included bulk density (BD), gravimetric soil water content (GWC), saturated hydraulic conductivity (Ks), presence of earthworms (EW), total nitrogen (Ntot), total Kjeldahl nitrogen (TKN), ammonium ($NH4+$), organic carbon (Corg), total carbon (Ctot), electrical conductivity (EC). The sampling schedule is illustrated in the figure 9.

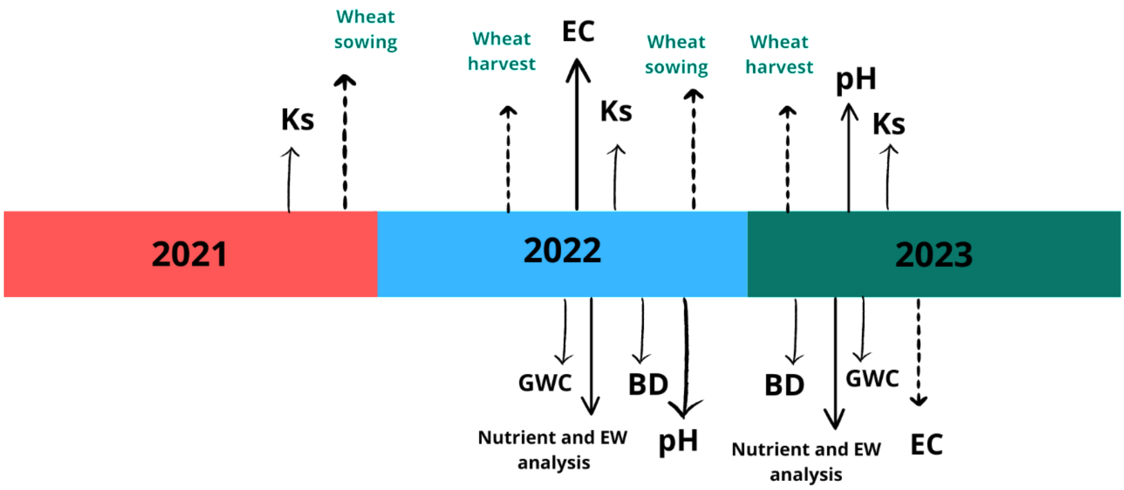

Figure 9: Sampling Schedule

4.2. Physical, chemical and biological soil analysis

4.2.1. Bulk Density

Bulk density (BD) represents the mineral particle density of soil, excluding pore space and organic matter. High bulk density indicates soil compaction or high sand content. A low bulk density, on its own, does not necessarily signify increased suitability for plant growth (FAO). Sampling was taken after each wheat crop harvest, with the initial sampling in October 2022 and the subsequent one in July 2023 (figure 10).

Samples were procured from, the upper 5 cm of soil. The wet weight was recorded, followed by dry weight determination through oven drying at 105°C for 24 hours. Through this analysis, the gravimetric water content could also be calculated.

Figure 10: a. Samples (Bulk density) are collected from the top 5cm of soil b. Soil sample

4.2.2. Hydraulic Conductivity:

Hydraulic conductivity (Ks) was assessed using a double-ring infiltrometer (figure 11) covering a 1,300 cm2 area, following the method outlined in Patel *et al*. (2019) as detailed in their study on soil infiltration dynamics. The inner cylinder, 40 cm in diameter, and the outer cylinder, 70 cm in diameter, were installed at a depth of around 10 cm. Measurement occurred in the inner cylinder, with the outer cylinder preventing lateral water flow, ensuring vertical movement. Infiltration time for a 1 cm water column was monitored, repeating until stabilization (more than 2 measurements with consistent temperature).

The parameter Ks, indicating water column infiltration under saturated conditions per unit time (Cook & Broeren, 1994), was determined at 12 points in the experimental field (2 points x 3 managements x 2 replicates = 12). Sampling times were October 2021 pre-wheat sowing, October 2022 post-wheat harvest, and July 2023 post-harvest of the second wheat sowing cycle, employing Philip's equation (Philip, 1969). The measured data were analysed according to Philip's infiltration equations (Philip, 1957) with the Microsoft Excel Solver add-in:

$$i(t) = S \times t\,1/2 + At \qquad (1)$$

$$v(t) = \frac{S\,X\,t^{-\frac{1}{2}}}{2} + A \qquad (2)$$

Where i(t) and v(t) are respectively the water infiltration (m) and infiltration rate (m sec-1) expressed in function of the time, S and A are two parameters calculated with the Excel Solver add-in, by minimizing the square difference between the predicted and the observed i(t) and v(t). The saturated hydraulic conductivity (Ks) was calculated as:

$$Ks = \frac{A}{m} \qquad (3)$$

With m as a constant equal to 2/3.

Figure 11: Double-ring infiltrometer

4.2.3. Earthworms

Earthworms play a crucial role in soil ecosystems, particularly in agriculture, where they are considered a vital macrofaunal group. The integration of practices like minimum tillage, green manure utilization, and organic fertilization is associated with a positive impact on earthworm populations (White *et al.*, 2022).

For measurement, mustard was employed following the method described by Valckx *et al.* (2011). Six grams of mustard suspended in water were used to extract earthworms from the soil surface, covering a measuring area of 25 cm x 25 cm. The earthworms were counted, and the data were recorded and subjected to statistical evaluation.

4.2.4. pH

Potentiometric determination of pH in a soil-water suspension (10:25) was conducted to assess the soil reaction level. This method, outlined in Smith 2015, "Advances in Soil Analysis Techniques," is widely utilized. The obtained values offer insights into the system's reaction level.

4.2.5. Nutrient analysis

Nutritionally, an analysis was conducted on total nitrogen (N tot), ammonium (NH_4^+), total Kjeldahl nitrogen (N tkn), organic carbon (C org), and total carbon (C tot) in the arable layer of the soil (0-20 cm). At each point, three subsamples were taken and combined to form a homogeneous sample, resulting in a total of 18 samples (2 replicates x 3 managements x 3 points in each management = 18 points) (figure 5). The analytical methods employed for these nutrients align with those described in D.M. 1999, "Official methods of soil chemical analysis." (figure 12).

Figure 12: Soil auger is used for sampling nutrient content b. Soil sample.

4.2.6. Electrical Conductivity

The electrical conductivity (i.e. σ_a) was measured using the frequency domain electromagnetic method (FDEM), applying Maxwell's equations to estimate subsoil electrical conductivity without galvanic contact with the soil surface (Smith & Johnson 2019; Anderson *et al.*, 2020). Electromagnetic data were gathered with the GF Instruments CMD-Mini Explorer (GF Instruments, Czech Republic), operating at 30 kHz with three coil spacings (0.32m, 0.71m, 1.18m).

Since the focus of this study was the shallowest portion of the soil (<1 m), only the Vertical

Coplanar Orientation (VCP) mode that is more sensitive to the shallow subsurface, with nominal exploration depths of 0.10 – 0.20, 0.20 – 0.30, 0.30 – 0.40 and 0.40 – 0.50 m, was acquired and examined.

The device was hand-carried at the soil surface, maintaining a speed of approximately 4 km h^{-1}, and parallel transects were set about 6 m apart. Measurements were logged at 0.5-second intervals, generating several hundred measurement points for each survey. Coordinates were obtained from a ProXT GPS receiver (Trimble, USA) with decimetric accuracy.

The combination of three pairs of coils and horizontal/vertical co-planar modes provided six penetration depths for each measurement point, resulting in six different apparent conductivities. The apparent conductivities measured in FDEM surveys are influenced by the presence of various subsoil materials. McNeil (1980) proposed cumulative sensitivity (CS) functions to describe the relative contribution of materials below a specific depth to the measured apparent conductivity. The normalized sensitivities (R) for the vertical coils' position (VCP) and horizontal coils' position (HCP) are:

$$R_{VCP}(z) = \sqrt{(4z^2+1)} - 2z$$

$$R_{HCP}(z) = \frac{1}{\sqrt{4z^2+1}}$$

where z is the depth normalized by the coil separation.

As mentioned previously, the σa values obtained from the EMI surveys are considered "apparent" as they represent integrated values over depth. To convert ECa measurements into a depth profile of EC, inverse methods were employed, as detailed by White *et al*. (2020) and Lewis *et al.* (2022).

The measured data underwent a filtering process to eliminate anomalous negative values and outliers (defined as values outside the mean ± 3 standard deviations). Additionally, a smoothing window was applied, replacing each data point with the average of its neighbors (size = 5). This step aimed to facilitate a smoother inversion process. To establish the maximum depth of the models, sensitivity profiles of the measurements were computed.

Subsequently, the datasets underwent inversion using the EMagPy code (*Anderson et al.,* 2022), employing the Cumulative Sensitivity (CS) forward model and the L-BFGS-B (Broyden–Fletcher–Goldfarb–Shanno) optimization method (Johnson *et al*., 2018). This optimization aimed to minimize the total misfit between observed values and predicted values from the forward model solution. EMagPy can perform quasi-2D inversions, generating inverted EC depth profiles for each measurement point.

Before the inversion process, soil profiles consisting of 12 layers with a thickness of 0.1 m were defined for each field. In this study, the inverted FDEM models were constrained to depths where the normalized sensitivity of the measurements approached zero, typically around 1.2m depth.

Afterwards, the code calculated the value of conductivity in each layer and profile, holding a final Root Mean Square Percentage Error (RMSPE).

Four layers were set in the initial inversion model, with interfaces at 0.1, 0.2, 0.3, 0.4 m and >0.50 m depth. The convergence was achieved for a final RMSP error close to 3 for the first survey and 4.7 for the second.

4.3. Meteorological data

Meteorological data were systematically monitored throughout the three-year experiment, sourced from an ARPAV (Veneto Regional Agency for Environmental Protection and Prevention) weather station positioned 100 meters from the experimental plots.

4.4. Statistical analyses

Statistical analyses were conducted to assess the impact of tillage on both soil conditions and wheat cultivation, including the interaction between them. Fixed effects encompassed tillage and sampling year, while replication was treated as a random effect, with nested considerations for repeated measurements within each treatment. Post hoc pairwise least squares mean comparisons were executed using the Fisher method to address multiple comparisons. R Studio version 3 and Infostat were employed for all statistical analyses.

5. RESULTS:

Meteorological trend:

Graph

The average monthly rainfall and temperatures for both wheat cycles are shown in figure (13). They were two climatically diverse years, the first wheat cycle was affected by low rainfall, the historical average of the last 60 years is 605.55 mm and for this first wheat crop cycle the accumulated rainfall was 331.4mm and the same for the temperatures, historical average temperatures are 17.5°C for the maximum and 8.3 °C for the minimum, and in the crop, period were 19.4 °C for the maximum temperature and 9.2 °C for the minimum. In the second wheat cycle, the accumulated rainfall was 660 mm, and the temperatures in the second wheat growing season were 7.7 °C for the minimum and 16.2°C for the maximum.

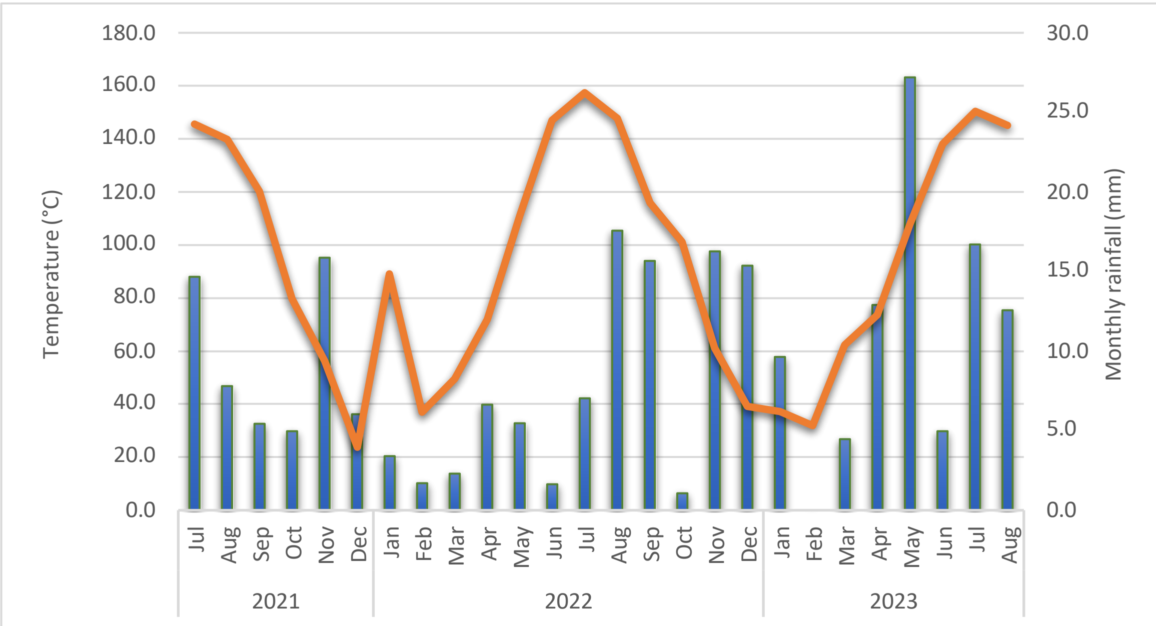

Figure 13: Average monthly rainfall and temperatures for both winter cycles

5.1. Bulk density (BD):

In the initial bulk density (BD) survey of 2022, the results indicated that no-tillage (NT) displayed the highest average BD value at 1.49 g cm^{-3}, followed by conventional tillage (CT) with 1.44 g cm^{-3}. Importantly, there was no statistically significant difference between these two treatments. Conversely, minimum tillage (MT) exhibited the lowest average BD value at 1.33 g cm^{-3}, and a significant difference was observed between CT and MT treatments.

Upon conducting the subsequent year's (2023) BD survey, higher values were recorded than the previous year, which was statistically significant (figure 14). Specifically, the CT treatment yielded an 8% higher average BD value (1.66 g cm^{-3}) compared to reduced tillage systems (MT and NT), showcasing a significant difference between CT and MT.

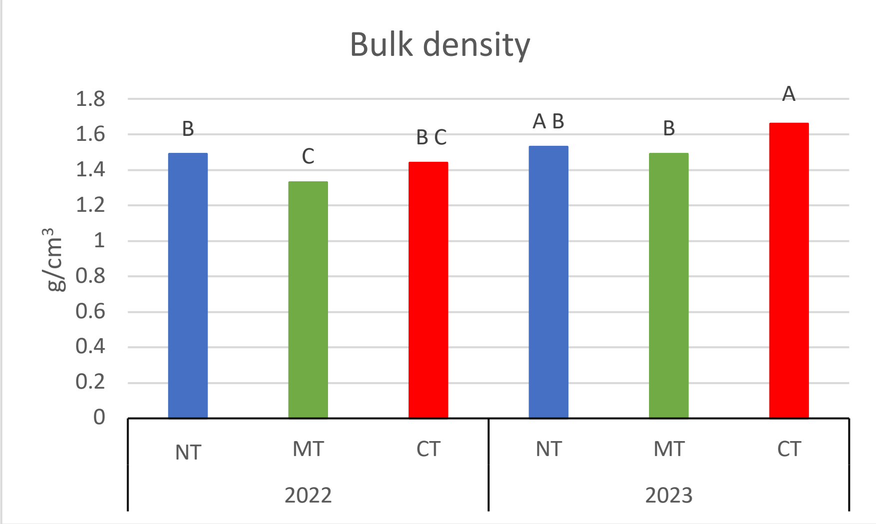

Figure 14. Bulk density in the three treatments compared in 2022 and 2023 years; CT: conventional tillage, MT: minimum tillage, NT: no-tillage. (A, B, and C represent letters that indicate a significant difference between them as a result of the post-hoc test.)

5.2. Gravimetric water content

The values obtained for gravimetric water content showed significant differences in terms of the managements, where MT showed the highest moisture value with 15.83 % as average of both sampling years, followed by NT with 15.15 % and finally CT with a value of 13.72 % moisture.

Table 3: The mean values of Gravimetric water content in different tillage system measured during two surveys (2022 and 2023) showing Significant Differences (A, B) between groups.

Tillage	Means		
MT	15.83	**A**	
NT	15.15	**A**	**B**
CT	13.72		**B**

5.3. Saturated Hydraulic conductivity (Ks):

A significant difference in saturated hydraulic conductivity (Ks) was evident between 2022 and 2023. Ks values exhibited an increase in 2022 compared to 2021 but a subsequent decrease in 2023. Within the Tillage category, conventional tillage (CT) consistently yielded the highest values, averaging 0.81 m s^{-1} across all three years, with a significant difference observed between CT and minimum tillage (MT). With this type of tillage, Ks resulted always the lowest, thus suggesting a problem for deep percolation in this treatment, probably related to a compacted layer just below the tilled horizon (first 15 cm).

Specifically, in 2022, CT achieved the highest Ks value at 1.09 m s^{-1}. Conversely, the lowest values in 2023 were observed in MT and no-tillage (NT), registering 0.20 m s^{-1} and 0.24 m s^{-1}, respectively (table 4).

Table 4: The mean values of Saturated Hydraulic conductivity in different tillage system measured during two surveys (2022 and 2023) showing Significant Differences (A, B) between groups.

Tillage	Means		
CT	0.81	**A**	
NT	0.66	**A**	**B**
MT	0.31		**B**

5.4. Earthworms:

Agricultural practices such as minimum tillage, the use of green manures, organic fertilization, are practices that benefit the population (Baldivieso-Freitas *et al.*, 2018). Regarding soil fauna, the presence of earthworms was evaluated after the harvest of each wheat crop cycle (2022-2023), resulting in a greater presence in the management planting systems with less soil disturbance removal (table 5).

Table 5: The mean values of Earthworms in different tillage system measured during two surveys (2022 and 2023)

Tillage	Means		
NT	9333.33	**A**	
MT	7733.33	**A**	
CT	6266.67	**A**	

5.5. Total Nitrogen (%):

The results showed an average total N value in 2023 higher than 0.13%, a significant difference from the 2022 total N value of 0.11%. Among the treatments, both no-tillage (NT) and minimum tillage (MT) have shown higher N total values at 0.13% and 0.12%, respectively, compared to conventional tillage (CT) at 0.11%.

The N total content has increased in 2023 in NT (0.13%) and MT (0.13%) soils, revealing a significant difference compared to the 2022 NT (0.12%) and MT soils (0.11%) (Figure 15).

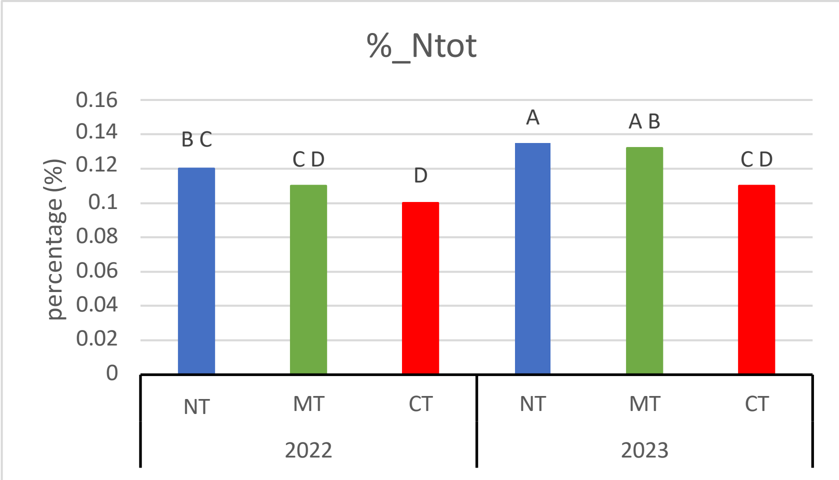

Figure 15: Total Nitrogen as measured in two surveys (2022 and 2023). Different letters represent CT: conventional tillage, MT: minimum tillage, NT: no-tillage. (A, B, and C represent letters that indicate a significant difference between them as a result of the post-hoc test.)

5.6. Total Kjeldahl nitrogen (TKN %)

Similar to the N total, total Kjeldahl nitrogen (TKN) also exhibited a significant increase in 2023 (0.12%) compared to 2022(0.09%), regardless of the treatment applied.

Among the treatments, reduced tillage (NT and MT) recorded higher values TKN values at 0.12 %and 0.11 %respectively, compared to conventional tillage (CT) (0.10%). In a comprehensive comparison, a significant difference was observed, with NT (0.13%) and MT (0.13%) showing the highest average value in 2023, surpassing CT in 2023 and MT, NT in 2022. The lowest average value was recorded by CT (0.08%) in 2022 (figure 16).

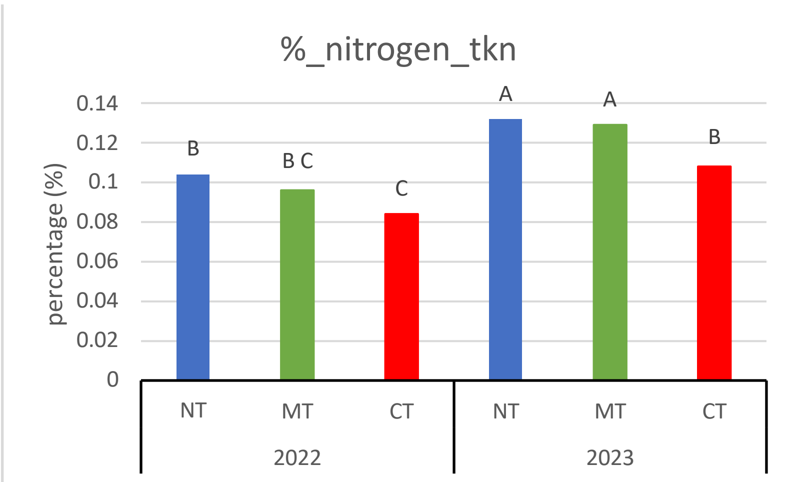

Figure 16: Total Kjeldahl nitrogen in the two different years compared in three treatments; CT: conventional tillage, MT: minimum tillage, NT: no-tillage. (A, B, and C represent letters that indicate a significant difference between them as a result of the post-hoc test.)

5.7. Ammonium (mg/kg)

Unlike the nitrogen level, the soil's ammonium content has experienced a significant decrease, dropping from 2.55 mg/kg in 2022 to 1.96 mg/kg in 2023. No significant difference was observed among the treatments. Overall, in 2022, no-tillage (NT) exhibited a significantly higher average value of 2.75 mg/kg compared to conventional tillage (CT) at 2.42 mg/kg. However, in 2023, there was no significant difference among CT, minimum tillage (MT), and NT (figure 17).

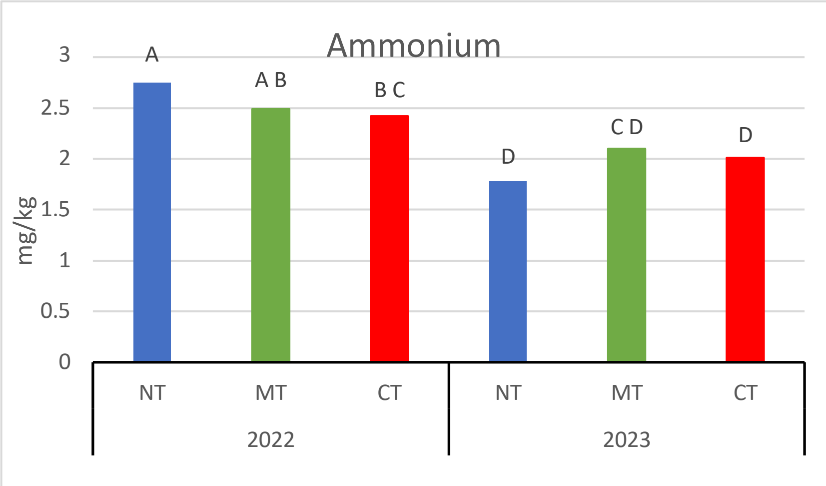

Figure 17: Ammonium in the two different years compared in three treatments; CT: conventional tillage, MT: minimum tillage, NT: no-tillage. (A, B, and C represent letters that indicate a significant difference between them as a result of the post-hoc test.)

5.8. pH

A significant difference was observed in 2023, indicating a higher pH of 8.48 compared to 2022, where the pH was 7.92. However, no significant difference was found between the treatments. Overall, there was a pH increase in 2023 across all three treatments when compared to the respective treatments in 2022 (figure 18).

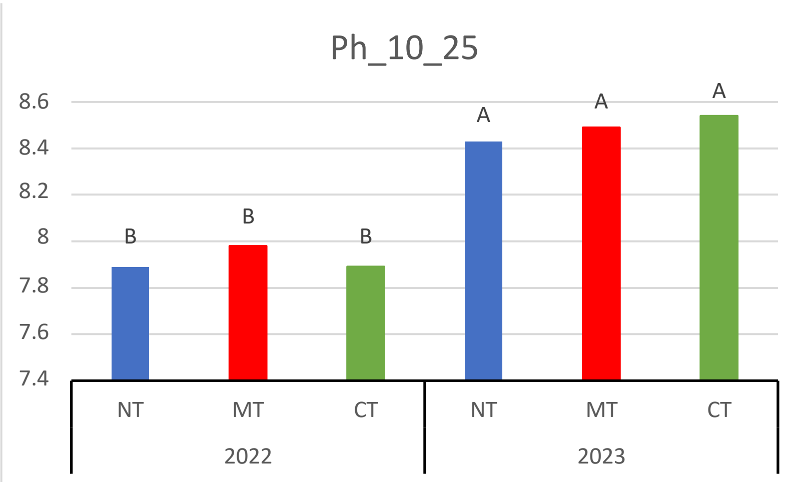

Figure 18: pH in the three treatments compared in 2022 and 2023 years; CT: conventional tillage, MT: minimum tillage, NT: no-tillage. (A, B, and C represent letters that indicate a significant difference between them as a result of the post-hoc test.)

5.9. Soil Organic Carbon (SOC %)

In the examined samples, soil organic carbon (SOC) content exhibited higher values in reduced tillage treatments (NT and MT), with 0.95% and 0.93%, respectively, compared to conventional tillage (CT). There was a significant difference between the SOC content in 2023 (0.96%) and 2022 (0.81%).

In summary, both reduced tillage treatments (NT, MT) in 2023 and NT in 2022 demonstrated significantly higher SOC content compared to CT in both years (figure 20). S If we compare between treatments, MT has an increase of 25% (5.41 t/ha) more organic carbon than CT and of 31 % in NT (6.75 t/ha) compared to CT in 5 years of implementation of conservation agriculture (figure 19).

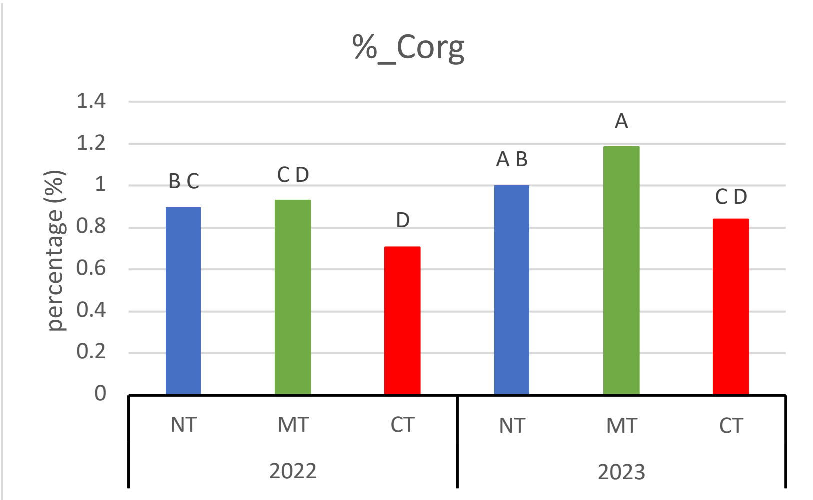

Figure 19: Organic carbon in the three treatments compared in 2022 and 2023 years; CT: conventional tillage, MT: minimum tillage, NT: no-tillage. (A, B, and C represent letters that indicate a significant difference between them as a result of the post-hoc test.)

5.10. Electrical Conductivity

In the figure we observe how conductivity increases the deeper the sampling depth, its distribution is heterogeneous throughout the field, reaching minimum values of 1 mS/m in the first centimetres of soil and up to 18 mS/m at a depth of 40 cm. In terms of sampling years, 2022 showed higher EC values than 2023, which had values up to 15% lower than the previous year (Figure 20). In MT the highest values and localised compaction were observed, in NT we have a more homogeneous distribution in terms of electrical conductivity.

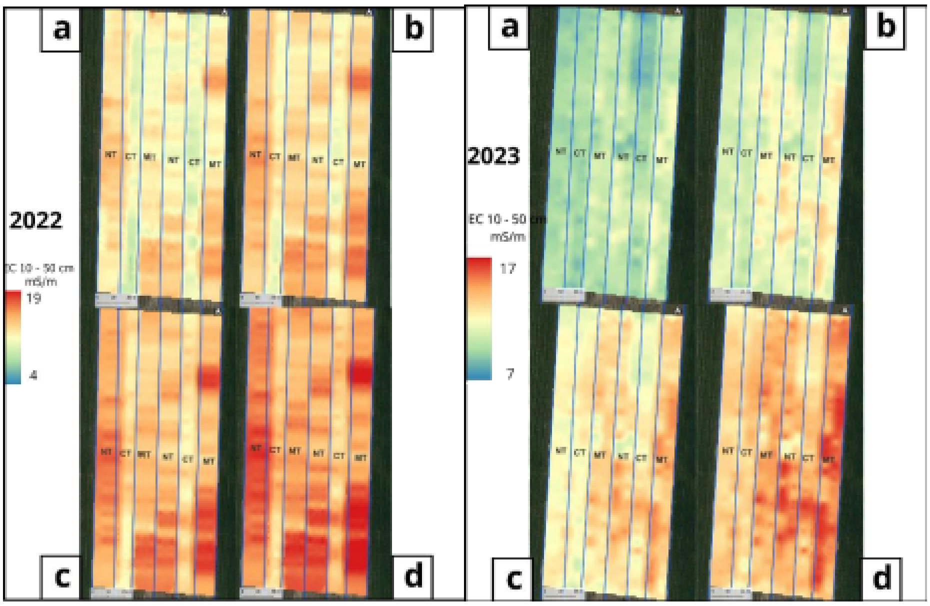

Figure 20: EC measurement at different depths in two surveys (2022 and 2023)

6. DISCUSSION:

Five years after the introduction of conservation tillage, the soil begins to show some differentiation related to tillage.

Looking at the physical traits, Ks value, was higher in CT, confirming the relevant effect of conventional tillage on soil macroporosity. With MT, on the other hand, the permeability was always the lowest, indicating a specific problem for deep percolation, probably due to the type of tillage used. Rotary hoeing, indeed, can promote the disruption of soil aggregates favoring the formation of a compacted layer just below the tilled horizon. Considering bulk density, CT and NT had similar values, followed by MT with the lowest value. The limited effects of tillage on bulk density are in accord with Hill & Cruse (1985) and Blevins and Frye (1993), reporting no significant effect of tillage methods (no-tillage, conventional tillage, and minimum tillage) on bulk density in silty-loam soils.

The BD values measured, anyway, do not affect plant growth and development according to the Natural Resources Conservation Service (USDA, 2008).

Furthermore, the observed increase in soil bulk density with time after cultivation, as noted by Osunbitan *et al.* (2005), suggests that without ongoing soil management practices, natural compaction processes may occur. This increase could be attributed to factors such as settling, compaction from natural forces, and the breakdown of organic matter.

The soil tillage system has a significant impact on soil moisture retention, with conservation tillage (MT, NT) resulting in higher soil moisture levels compared to conventional tillage. The consistently lower soil moisture content in conventional tillage (CT) over both years suggests the influence of tillage practices on soil water retention. Specifically, conservation tillage can enhance soil moisture levels by incorporating straw cover and stubble, which delay runoff, increase water infiltration, and reduce surface water evaporation (Li, 2006). In terms of saturated hydraulic conductivity (Ks), values varied across the three years. Conventional tillage (CT) consistently yielded higher Ks values than minimum tillage (MT). The higher Ks values in CT suggest enhanced water movement through the soil profile, potentially contributing to the lower soil moisture content observed in CT compared to MT.

There was no significant difference in soil pH between the no-tillage (NT) and conventional tillage (CT) practices, consistent with the findings of Rahman *et al*. (2008). However, there was an increase in soil pH over a year, indicating the influence of multiple interacting processes. Microbial activity, is exemplified by the observed increase in the earthworm population over the one year (Paul & Clark, 1996).

The tillage system significantly impacts soil nutrient content, with reduced tillage soils (NT, MT) exhibiting higher accumulations of total nitrogen, total Kjeldahl nitrogen, and soil organic carbon (SOC) compared to tilled soils (CT). These findings align with previous studies conducted by Doran (1980) Liu *et al.* (2014) and Peter Omara et al., (2019). Hazarika *et al.* (2009) reported a 14-17 percent increase in SOC in the surface soil under no-till (NT) and reduced tillage (RT) practices compared to conventional tillage (CT). Both no-till (NT) and reduced tillage (RT) practices, as studied by Zentner *et al.* (2004) and Bhattacharyya *et al.* (2006), reduce soil disturbance, enhance SOC maintenance, and contribute to improved soil quality. Arshad *et al.* (1990) found a 25% higher average nitrogen content in the surface soil under no-till (NT) compared to conventional tillage (CT) plots. Similarly, Moussa-Machraoui *et al.* (2010) reported higher average nitrogen levels under no-till (NT) due to increased organic matter accumulation. Rice and Smith (1982) observed higher soil moisture contents in no-till soils, as opposed to tilled soils, which are primarily responsible for elevated denitrifying bacteria activity.

A relevant effect was observed for Organic Carbon, which increased with conservation tillage by 20.78% and 23.38% in MT and NT respectively, corresponding to sequestration of 0.000273 t/ha and 0.00013 t/ha.

This increase serves as a positive indicator of improved soil fertility. This outcome aligns with findings from studies such as (Ebelhar and Dowdy (1990). In the same way, the tillage doesn't affect the ammonium content in the soil, and its content is decreased overall from 2022 to 2023, indicating the complex nature of nutrient dynamics influenced by tillage practices.

7. CONCLUSION:

In conclusion, this comprehensive study underscores the vital role of conservation agriculture (CA) in addressing global challenges related to food production, economic sustainability, and environmental conservation. By focusing on minimal soil tillage, permanent soil cover, and diversified crop rotation, CA emerges as a promising agroecosystem management approach. The investigation delves into the adoption challenges of CA in Europe, shedding light on the influential role of agricultural policies and the cognitive shift required by farmers.

In summary, the findings highlight the dynamic nature of soil properties influenced by tillage practices and temporal variations. The positive trends observed in reduced tillage systems across multiple parameters underscore their potential for sustainable soil management and improved agricultural productivity. Conservation tillage (MT, NT) proves beneficial for moisture retention and nutrient accumulation, contributing to improved soil health and fertility.

In conclusion, while this study provides valuable insights into the impact of conservation agriculture on various soil parameters, the complexity of soil-plant interactions calls for continued research. Conservation agriculture proves to be a competent practice in the study area, but further investigation and long-term monitoring are essential to unveil the full spectrum of its effects on soil health, fertility, and overall sustainability.

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