UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Head Office: Università degli Studi di Padova

Department of Agronomy, Food, Natural resources, Animals and Environment (DAFNAE)

Ph.D. COURSE IN: Crop Science 36th cycle

ADOPTION OF CONSERVATION AGRICULTURE IN WINTER WHEAT (*TRITICUM AESTIVUM* L.) WITH THE AIM OF SAVING WATER, PROTECTING THE ENVIRONMENT, IMPROVING SOIL HEALTH AND REDUCING CO_2 EMISSIONS.

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2024

Laudato si', mi' Signore, per sora nostra matre terra, la quale ne sustenta et governa, et produce diversi fructi con coloriti flori et herba.

Il Cantico delle Creature, San Francesco d'Assisi

Abstract

Conservation Agriculture (CA) is an ecological approach to regenerative sustainable agriculture and ecosystem management based on the practical application of three context-specific and locally adapted interlinked principles, i.e.: (i) continuous minimum or no mechanical soil disturbance (no-till seeding/planting and weeding, and minimum soil disturbance with all other farm operations including harvesting); (ii) permanent maintenance of soil mulch cover (crop biomass, stubble and cover crops); and (iii) diversification of cropping system (economically, environmentally and socially adapted rotations and/or sequences and/or associations involving annuals and/or perennials, including legumes and cover crops). These essential practices are combined and enhanced with other complementary practices of integrated crop, soil, nutrient, water, pest, labour, energy and land management practices to generate and sustain optimum performance of ecosystem services. This PhD project seeks to demonstrate the effect of CA in the short term after its implementation and its effect on soil fertility with one of the major crops in the study area, winter wheat.

The hypothesis proposed is that reducing soil tillage favors the soil's physico-chemical and biological characteristics, and the wheat crop's quality and yield. To test this hypothesis, a three-year experiment was carried out in the lowland plain of Veneto (northern Italy). Three tillage intensities were considered: conventional tillage (CT), minimum tillage (MT) and no-tillage (NT).

In the first phase, the effect of tillage on different soil and wheat crop parameters was evaluated. The results indicated that the reduction of soil tillage improved soil physico-chemical parameters and did not influence the yield and quality of the wheat crop, with an equal behavior in the three tillage treatments. As for the soil parameters that were positively affected, we have a higher percentage of moisture in the soil under NT, bulk density in the upper horizon had similar values for NT and CT and lower values for MT. Regarding the chemical part of the soil, an increase in soil organic carbon of 25% and 31% was observed for MT and NT, respectively, which corresponds to 5.41 and 6.75 t C ha^{-1}, respectively. These tests showed that, in the short term, this practice positively influences important soil parameters and does not generate negative effects in terms of crop production.

In the second phase, the overall sustainability of the system was measured using a multivariate approach to calculate a Relative Sustainability Index (RSI), using the information collected within this research project and those obtained in the preceding years by Dr. Felice Sartori who

initiated CA in the experimental system here considered. This analysis showed that reduced tillage systems (MT and NT) are more sustainable than CT, which, with the passing of time, decreased its RSI. On the other hand, in the face of adverse climatic conditions, such as those suffered in 2022 with a marked drought and extreme temperatures, the reduced tillage systems showed no negative effects in terms of grain yield and quality, the results were competitive with those of conventional tillage.

Finally, in the third phase the results obtained in this research were analysed with the results obtained since 2018, the beginning of the implementation of conservative agriculture in the field under study, where the focus was on the chemical part of the soil, its evolution over time and the soil's capacity for carbon sequestration, with positive results framed within the “4 per 1000” initiative exceeding the carbon sequestration value of 4‰ per year in the reduced tillage practices for the soil under study.

In conclusion, the reduction of the intensity of tillage had positive effects on different soil parameters, the wheat crop was not negatively affected, which makes these practices competitive in wheat production for the area under study. NT and MT have shown a tendency to increase their sustainability, which translates into positive effects not only economically but also environmentally which is of great importance if we analyze the climatic effects that are affecting agricultural production in recent years.

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Chapter 1: General Introduction

1. Introduction

Food production must increase to meet the needs of a growing population while minimising negative impacts on the environment (Foley *et al.*, 2011). We need to recognise 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 integrated set of agronomic practices with a long history of development and research. The total area of land where conservative agriculture was implemented in 2018/2019 was 205.4 million hectares which translates into approximately 14.7% of the world's total cropland (table 1) Kassam *et al*.(2022).

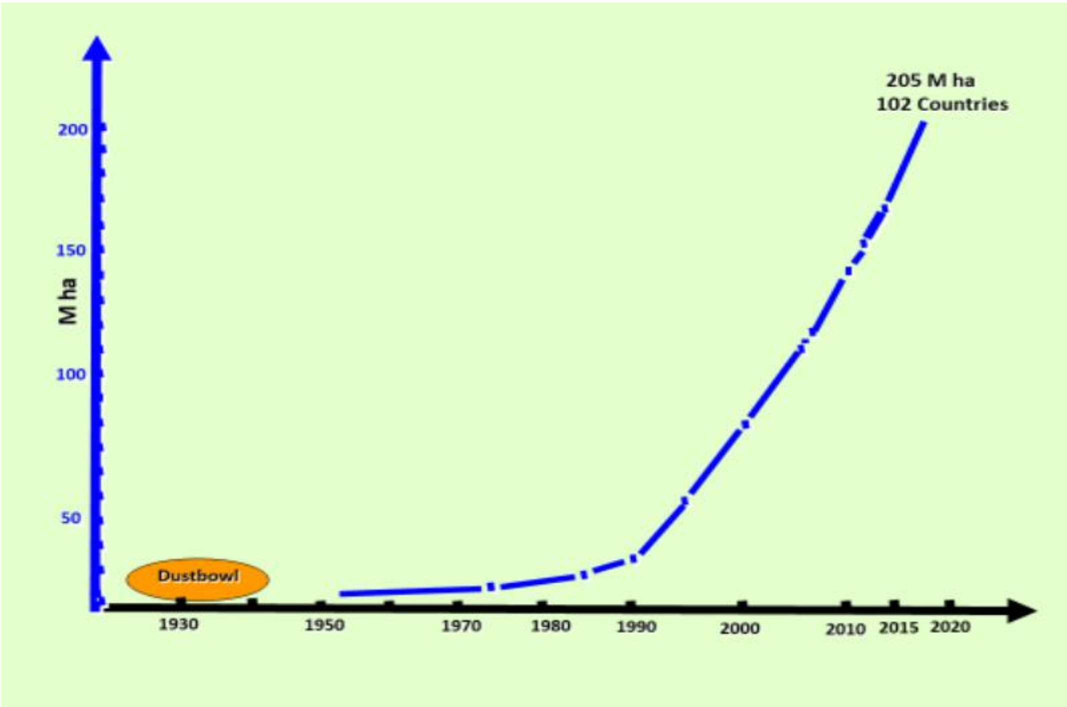

Figure 1. Developments in the adoption of conservative agriculture worldwide (Kassam *et al.*, 2022).

Farmers usually carry out annual deep ploughing to counteract compaction, but as a long-term consequence, it can contribute to the formation of plough ponds and encourage the mineralization of organic matter. CA improves soil structure throughout the soil profile while protecting organic matter, among other benefits (Hobbs, 2007; Thomas *et al.*, 1996). The agronomic practices applied in CA are based on three interrelated principles: minimal or no soil tillage in all farming operations involved, establishment of permanent vegetation cover and diversification of the cropping system (Kassam *et al.*, 2019). These practices could be very strategic for the recovery and preservation of soil quality (Meyeraurich *et al.*, 2006), as they (i) improve soil organic carbon (SOC) content; (ii) increase the abundance and diversity of soil biota; (iii) improve nutrient storage - including N - in agroecosystems; (iv) improve hydraulic conductivity, aggregate stability, soil porosity and, consequently, soil water retention; (v) mitigate soil erosion and greenhouse gas (GHG) emissions (Derpsch *et al.*, 2014; Stagnari *et al.*, 2014). However, the political and economic problems which many countries are facing lead producers to focus on short-term production, neglecting practices such as CA that can help in the present and even more in the future (Kassam and Kassam, 2021). The growth of CA worldwide has been applied to a lesser extent in Europe (5%) and almost unused in Italy (Kassam *et al.*, 2019).

However, conservation agriculture is the subject of much debate in terms of its effects on crop yields (Brouder and Gomez-Macpherson, 2014; Giller *et al.*, 2009) as well as its applicability in different agricultural contexts (Friedrich *et al.*, 2012; Stevenson *et al.*, 2014). Contradictory results have been observed in different studies, especially in the first years after the adoption of conservation agriculture, with regard to the short-term effects on soil physical parameters, which are limited to bulk density (Guan *et al.*, 2014), soil resistance (Munkholm *et al.*, 2003; Palm *et al.*, 2014) and the saturated hydraulic conductivity of the soil (Buczko *et al.*, 2006).

Pittelkow *et al.* 2015 conducted a meta-analysis in which more than 5,000 yield observations were collected from 610 studies comparing no-tillage and conventional tillage in 48 crops and 63 countries. The results showed a drop in yields in no-tillage, but this depended on local conditions, as in other situations yields were equivalent or even higher than in conventional tillage.

This study also highlights that the combination of no-tillage with residue retention and crop rotation (the basis of conservative agriculture) not only minimizes the negative effects during the transition phase but also significantly increases the productivity of rainfed crops in dry climates. This makes it an important adaptation strategy to climate change (Pittelkow *et al.*, 2015).

If we go into the technical side of no-tillage, we can define it as direct seeding on the crop stubble, without generating any soil disturbance. This practice allows the reduction of soil erosion, the reduction of energy/fuel consumption and the time required for cropping in comparison with the conventional practice (Soane *et al.*, 2012). Improvements in soil structure are obtained, which translates into improved soil microbial and enzymatic activity, infiltration and water use efficiency (Zuber and Villamil, 2016). Incorrect soil management can lead to increased bulk density as well as increased penetration resistance, which would obstruct the establishment of the seedlings of the crop and thus favour the growth of weeds, thus reducing crop yields (Sithole *et al.*, 2016). Poor soil structure also leads to loss of water through runoff, increased erosion, loss of soil carbon, altered soil pH and consequently altered nutrient availability (Li *et al.*, 2019). To reverse many of these problems, NT has been presented as a solution, but it should be remembered that the impact of this management technique on soil properties is strongly linked to climate, soil characteristics and associated cropping practices (rotation, cover crop). Therefore, its adoption should be framed within a planning process accompanied by a soil pre-study to avoid the negative effects mentioned above (Li *et al.*, 2020; Shahzad *et al.*, 2017).

Objective and outline

This PhD project aims to: 1) monitor physical, chemical and biological indicators during the transition from conventional agriculture to Conservation Agriculture; 2) monitor the wheat crop and its behavior under different sowing systems; 3) compare the chemical situation of the soil after CA application compared whit conventional management.

The hypothesis states that reducing soil tillage favors the soil's physico-chemical and biological characteristics and grain yield and quality.

To test the hypothesis, a large-scale experiment was designed to compare the three management systems: no-tillage (NT), minimum tillage (MT) and conventional tillage

(CT). Winter wheat was selected as the crop of interest; in previous cycles, corn and soybean were sown, the latter being the last crop harvested prior to the start of the experiment.

In chapter 2, soil physico-chemical parameters and the quality and yield of the wheat crop are monitored to observe the behaviour of the soil and the crop under different sowing systems. It was hypothesized that the reduction of soil tillage favours the physico-chemical characteristics of the soil and the quality and yield of the crop in question. Several indicators were selected to assess the evolution of soil compaction and nutrient content, crop quality and yield.

In chapter 3, an evaluation of different sustainability indicators was carried out in order to assess the effects of treatment combinations from a physical, chemical and biological point of view, resulting in a sustainability index capable of determining the most influential parameters in the evaluation of the system.

Finally, in chapter 4, the results of the present investigation on the chemical characteristics of the soil were compared with the results of an investigation carried out in 2018 in the same experimental area. It was hypothesized that the transition period for the study area may be in its stabilization phase.

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Chapter 2: The transition to conservation agriculture and its influence on wheat cultivation parameters and soil quality

1. Introduction

The adoption of no-tillage has been slowly but exponentially increasing since the 1960s worldwide (Kassam *et al.*, 2015). Conservation agriculture comprises mainly non-traditional farming systems (Friedrich *et al.*, 2012; Palm *et al.*, 2014) and this practice comprises 3 parts: crop diversification, cover cropping and no-tillage (NT). Its increase in cultivated land worldwide justifies the debate on the effect of NT practice on the soil's physical environment (Blanco-Canqui and Ruis, 2018). There is also much discussion on the impact of NT on crop yields (Pittelkow *et al.*, 2015a), carbon sequestration (Palm *et al.*, 2014; Reicosky, 2003), economy (González-Sánchez *et al.*, 2016), soil fertility (Briedis *et al.*, 2016) and environmental quality (Reicosky, 2003), but more studies are needed on the effect of NT on the physical properties of different soil types (Blanco-Canqui and Ruis., 2018).

No-tillage disturbs less soil and leaves more crop residues than conventional tillage and minimum tillage. It should be remembered that alteration of soil physical properties can affect crop establishment and production, for example those related to aggregate compaction and stability (bulk density, infiltration) which can affect seed emergence, root growth and crop yield, and soil dynamics which can affect water infiltration, nutrient availability, among other things (Blanco-Canqui and Ruis., 2018).

Extensive metanalysis compiling 5,463 yield observations from 610 studies suggests that non-plowing itself causes a yield penalty of around 10% overall (Pittelkow *et al.*, 2015a). However, this needs to be qualified, as yield responses differ. In the case of oilseeds, cotton and legumes, yields were similar with both NT and tillage (Pittelkow *et al.*, 2015b). Site-specific studies provide an opportunity to expand knowledge on the impact that CA can have on the soil, and thus reduce the side effects of conversion (Liu *et al.*, 2016).

For this purpose, a 3-year study was carried out in a field where conservation agriculture started to be implemented in 2018. Here, the effects on soil and crop were evaluated in 3 sowing systems (no-tillage, minimum-tillage and conventional-tillage). Through different measurements of physical, chemical and biological parameters in the whole system (soil-plant) we try to check if the system is still in a transition period and if this period affects yields.

2. Materials and methods

The experiment took place at the Lucio Toniolo Experimental Farm, located in Legnaro, PD (NE Italy, 45° 21 N; 11° 58 E; 6 m a.s.l.), where the climate is sub-humid, with temperatures between -1.5 °C on average in January and 27.2 °C on average in July. Rainfalls reach 850 mm annually, with a reference evapotranspiration of 945 mm that exceeds rainfalls from April to September. The highest rainfalls occur in June (100 mm) and in October (90 mm), while winter is the driest season with average rainfalls of 55 mm (21/12 to 21/03). The shallow water table ranges from 0.5 to 2 m in depth, with the lowest values recorded in summer.

The trial started in the autumn of 2021, with an area of 2 ha, divided into two replicates (1 ha each) and within each replicate was subdivided into 3 strips of 13 m x 260 m (Figure 1). The soil at the site is Fluvi-Calcaric Cambisol (FAO-UNESCO 2008) with a silt loam texture. The treatments within the plot were three: the conventional tillage plot (CT) was ploughed to a depth of 30 cm and harrowed to 15 cm; the minimum tillage plot (MT) was ploughed to a depth of 15 cm and then harrowed; and the no-tillage plot (NT) was sown on the residues of previous crops.

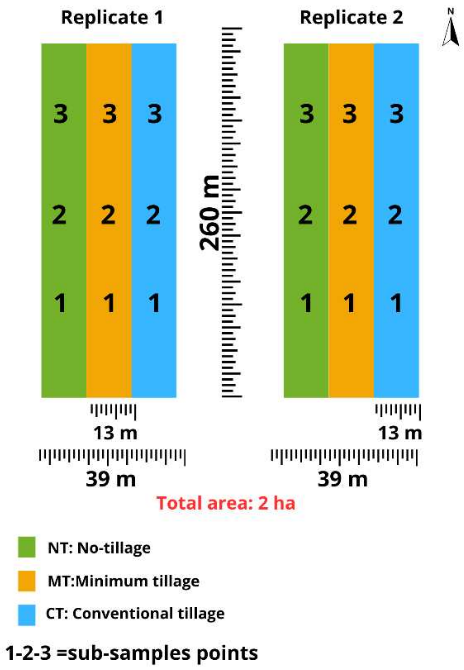

Figure 1. Experimental design.

The MT and NT tillage systems were first applied in 2018 in the framework of another PhD thesis (Sartori *et al.*, 2021a). The crop of interest was winter wheat (*Triticum aestivum* L.), sown twice (2021 and 2022), and managed conventionally, where all necessary treatments (fertilisation, fungicides, herbicides) were applied as shown in the table 1 below.

Table 1. Agronomic practices carried out during the crop cycle.

Agronomic practices	1st CYCLE	2nd CYCLE
Sowing	28/10/2021	3/11/2022
Pre-sowing fertilization 8-16-20	**32 kgN ha^{-1}**	**32 kgN ha^{-1}**
Fertilization Ammonium nitrate 27%	**52 kgN ha^{-1}**	**54 kgN ha^{-1}**
Fertilization in cover crops Urea 46%	**92 kgN ha^{-1}**	**92 kgN ha^{-1}**
Post-emergence weed treatment	**X**	**X**
Phytosanitary treatment	**X**	**X**
Harvest	27/6/2022	29/6/2023

2.1 Field surveys

The selected parameters to monitor the physical properties of the soil were: bulk density (BD), Gravimetric soil water content (GWC), saturated hydraulic conductivity (Ks), presence of earthworms (EW), total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), ammonium (NH_4^+), soil organic carbon (SOC), total carbon (C_{TOT}), apparent electrical conductivity (EC), plant available water (PAW), field capacity (FC), wilting point (WP) and percent porosity (Por) and the sampling schedule is shown in Figure 2.

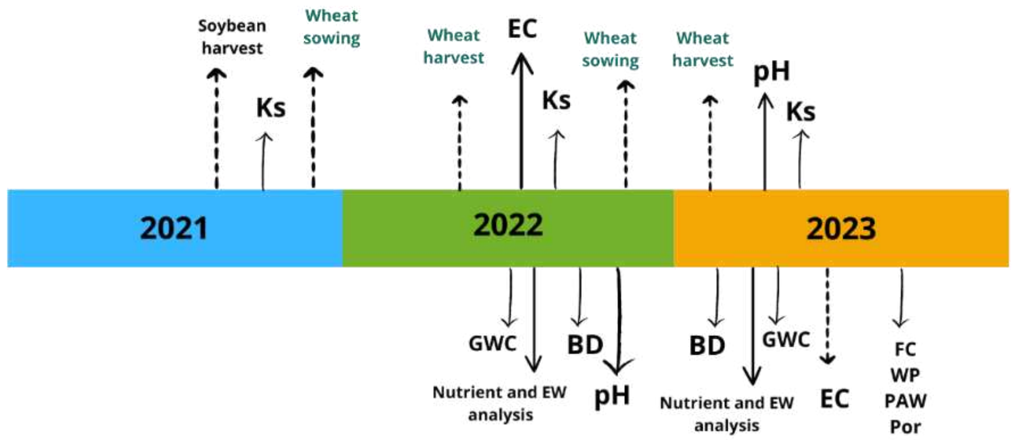

Figure 2. Timeline of the different soil measurements carried out in the experiment. Bulk density (BD), Gravimetric soil water content (GWC), saturated hydraulic conductivity (Ks), presence of earthworms (EW), total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), ammonium (NH_4^+), soil organic carbon (SOC), total carbon (C_{TOT}), electrical conductivity (EC), plant available water (PAW), field capacity (FC), wilting point (WP) and percent porosity (Por).

As far as the monitoring of the wheat crop is concerned, parameters comprising the evolution of the crop during the cycle and the post-harvest quality and yield were measured. These include the measurement of the Leaf area index (LAI), the chlorophyll index, Normalized Difference Vegetation Index (NDVI), protein during the crop cycle, crop yield, and quality of harvested grain through parameters such as Zeleny test, protein, wet gluten and specific weight (Figure 3).

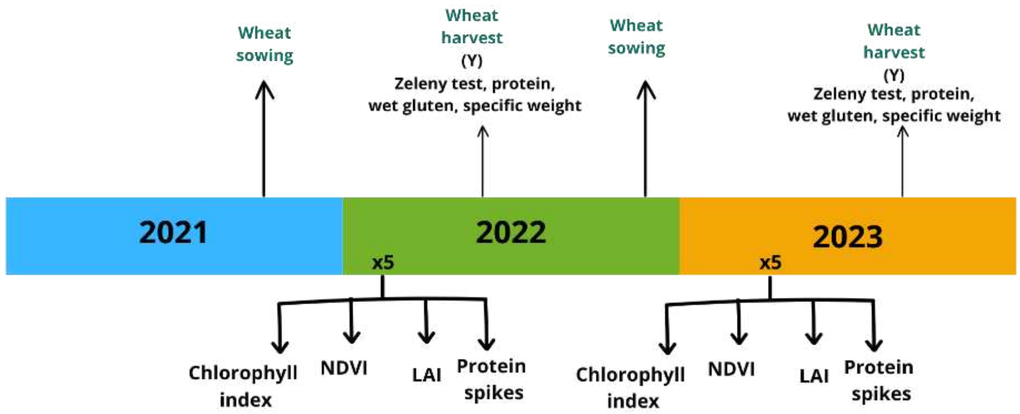

Figure 3. Timeline of the different wheat measurements carried out in the experiment. The Leaf area index (LAI), the chlorophyll index, Normalized Difference Vegetation Index (NDVI), protein during the crop cycle, crop yield, and quality of harvested grain through parameters such as Zeleny test, protein, wet gluten and specific weight.

2.1.1 Wheat crop measurements during the growing cycle

Five sampling moments (P = phenological phase) were selected for measurements in the wheat crop. At these times different indices were measured to control the crop status in the different management systems (table 2).

Table 2. Phenological phases where measurements were taken.

2022	Phenological Phase	Zadok
P1	Flowering	6.80
P2	Milk development	7.10
P3	Milk development	7.80
P4	Dough development	8.00
P5	Ripening	9.00
2023		
P1	Booting	4.50
P2	Awn emergence	5.90
P3	Milk development	7.30
P4	Dough development	8.30
P5	Ripening	9.00

The sampling times were connected to a phenological stage, but this was also affected by the weather that often delayed or advanced the sampling moment, so that in both years it varied. We tried to coincide with the phenological moments in both years, but this was impossible due to the climatic conditions of persistent rainfall during those periods and high cloud cover, which affected the results of the NDVI sampling through the ceptometer.

The measurements carried out at the different stages of cultivation are detailed below.

- Leaf Area Index (LAI)

LAI (Leaf Area Index) is a measure of leaf area per unit area of soil. According to this definition, LAI is a dimensionless quantity that characterizes the canopy of an ecosystem and, is therefore, dependent on land cover. The leaf area index determines the microclimate under the canopy, controls water interception, radiation absorption, evapotranspiration and carbon gas exchange. It is, therefore, a key component of biogeochemical cycles in ecosystems (Bréda, 2003) and is strongly related to the energy actually available for photosynthesis. The instrument used to measure LAI is the Sun Scan type SS1 DELTA-T DEVICES, equipped with a 1-metre probe that allows rapid spatial averaging of large areas and LAI mapping. The device was positioned horizontally over the canopy in full sun to determine the external incident radiation and then placed at ground level, perpendicularly to crop rows, to obtain the radiation at the soil surface. The procedure was repeated 3 times at each measuring point (2 replicates x 3 managements x 3 points in each managements = 18 points).

- Normalized Difference Vegetation Index (NDVI)

The most commonly used vegetation index is the NDVI (Normalized Difference Vegetation Index). It describes crop's vigour level and allows the identification of areas with development problems. The NDVI is the differential reflectance ratio in the red and near-infrared wavelengths (Tucker, 1979).

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)}$$

Active crop canopy sensors that measure NDVI can be used for non-destructive real-time diagnosis of the nitrogen (N) status of crops and to guide N management during the growing season (Cao *et al.*, 2018). The CROP CIRCLE ACS-430 Holland Scientific Sensor CIRCLE equipped with a graphic display, and a sensor and a power supply were used to measure this parameter. Data were taken at 1-meter canopy height, and five sub-samples were taken and averaged to obtain a sample (2 replicates x 3 managements x 3 points in each management = 18 samples).

- Chlorophyll Index (SPAD)

Nitrogen is one of the main macronutrients limiting crop yields (Naderi *et al.*, 2012). Farmers in many parts of the world tend to apply this element in excessive amounts to achieve high yields (Islam *et al.*, 2014). The SPAD-502 chlorophyll meter is a lightweight, simple, portable, diagnostic and non-destructive device used to estimate the chlorophyll content of leaves. Five sub-samples were taken and averaged to obtain a sample, and this was repeated at all 18 points of measurement (2 replicates x 3 managements x 3 points in each management = 18 samples).

- Moisture content of the different parts of the wheat crop (spikes, leaves and stems) and protein content of the spike of wheat

For moisture estimation, one linear meter of wheat plants was collected at each sampling point (18 samples in total), separated into leaves, stems and spikes. The wet weight was measured, then transferred to an oven at 80 °C until constant weight was obtained, and then the dry weight was taken. The wheat spikes were also sent to the laboratory for analysis of their protein content. These procedures were repeated at the 5 measurement moments throughout the wheat cycle.

2.1.2 Wheat grain measurements

The wheat was harvested when it reached the point of maturity (z.9) as indicated by the Zadok's morphological grading scale. In the first wheat crop cycle, the harvest date was 27 June 2022; in the second crop cycle, the harvest date was 29 June 2023. The grain obtained was subjected to grain quality and yield analysis. As for the quality of the grain, the following components were analysed using a FOSS infrared (NIR) in the laboratories of the University of Padua: Zeleny test, which measures the swelling capacity of proteins in an aqueous solution of lactic acid. As the protein particles swell, their sedimentation speed decreases; the slower the speed, the higher the quality of the protein particles; wet gluten (%) composed of proteins that will determine the technological quality of the wheat flour and in particular the viscoelastic properties of the dough obtained; protein content (on dry matter basis) is a routine analysis due to its importance as milling and processing quality, and the nitrogen compounds are analysed; and lastly the grain specific weight, which is indirectly a measure of the degree of fullness of the caryopsis and is considered an overall index of the product (D'Egidio, 2013).

2.1.3. Physical, chemical and biological soil analysis

- Bulk Density and gravimetric soil water content

Samples were taken after each harvest of the wheat crop. The first sampling was in October 2022, and the second sampling was in July 2023.

Samples were taken from the first 5 cm of the soil, the so-called topsoil. First, the wet weight and then the dry weight were recorded, followed by drying in an oven at 105°C for 24 hours. The bulk density is the oven-dry mass of the sample divided by the sample volume. Through this analysis, the gravimetric water content could also be calculated.

- Saturated Hydraulic conductivity

The hydraulic conductivity (Ks) was measured by means of a double ring infiltrometer over an area of 1,300 cm^2, as described in Morbidelli *et al.,* (2017). The inner cylinder has a diameter of 40 cm, and the outer cylinder has a diameter of 70 cm. The two rings were installed at a depth of approximately 10 cm. The measurement is made in the inner cylinder; the function of the outer cylinder is to prevent the water in the inner cylinder from flowing laterally and not only vertically. The infiltration was measured by controlling the time required for the infiltration of a 1 cm column of water. This procedure was repeated several times until stabilization was not reached (more than 2 measurements with the same temperature).

The parameter Ks measures the column of water that can infiltrate a soil under saturated conditions in a unit of time (Cook and Broeren, 1994). Measurements were made at 12 points in the experimental field (2 points x 3 managements x 2 replicates = 12). The first sampling time was in October 2021 prior to wheat sowing, the second was in October 2022 after the harvest of the wheat crop and the third sampling was carried out in July 2023 after the harvest of the second wheat sowing cycle. The measured data were analysed according to Philip's infiltration equations (Philip, 1969) with the Microsoft Excel Solver add-in:

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

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

Where *i(t)* and *v(t)* are respectively the water infiltration (m) and the infiltration rate (m s^{-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:

$$Ks = \frac{A}{m}$$

with *m* as a constant equal to 2/3.

- Earthworms

For earthworm counts, the methodology proposed by Valckx *et al.* 2011 was used. Using 6 g of mustard powder suspended in 1 litre of water (prepared 24 hours before application) and the measuring surface was 25 cm x 25 cm. Earthworms were extracted from the soil surface and counted, this sampling was repeated after harvesting the wheat crop in both cycles (2022-2023). The earthworms were counted and the data were recorded and statistically evaluated, as the aim was only to ascertain its presence in the field under study.

- pH

The pH was determined potentiometrically, in a soil-water suspension (10:25). This system is the most commonly used to define the degree of soil reaction; the method used is reported in D.M. 1999, "Official methods of soil chemical analysis".

- Chemical indicators

Total nitrogen (N_{TOT}), ammonium (NH_4^+), Total Kjeldahl Nitrogen (N_{TKN}), organic carbon (SOC) and total carbon (C_{TOT}) were analysed at depth 0-20 cm. At each point, 3 subsamples were taken and mixed to obtain a homogeneous sample; the total number of samples was 18 (2 replicates x 3 managements x 3 points in each management = 18 points). The methods used for the analysis of these nutrients are described in the D.M. 1999, "Official methods of soil chemical analysis".

- Electrical conductivity of soil

The apparent electrical conductivity (i.e. σ_a) was measured using the frequency domain electromagnetic method (FDEM) which applies Maxwell's equations to estimate the electrical conductivity of the subsoil under investigation without the need for galvanic contact between the device and the soil surface (Boaga, 2017; Pavoni *et al.*, 2022). Electromagnetic (FEM) data were collected using the GF Instruments CMD-Mini Explorer (GF Instruments, Czech Republic) which operates at 30 kHz with a combination of three coil spacing (0.32 m, 0.71 m, 1.18 m).

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.

For each survey, the device was carried at the soil surface by hand. The measurement speed was approximately 4 km h^{-1} and the parallel transects were set about 6 m apart from each other. Measurements were logged every 0.5 seconds, acquiring several hundred measurement points for each survey, and paired with coordinates obtained from ProXT GPS receiver (Trimble, USA), with decimetric accuracy.

The combination of 3 pairs of coils and horizontal/vertical co-planar modes allows us to have six penetration depths for each point of measurement and, therefore, 6 different apparent conductivities. The measured conductivities of FDEM surveys are apparent since they are influenced by the contribution of the different materials that are present in the subsoil. McNeill (McNeil, 1980) proposed cumulative sensitivity (CS) functions to describe the relative contribution of materials below a specific depth to the measured apparent conductivity.

- Water potential

The WP4C (Decagon Devices, Inc., 2015), a hygrometer using the chilled mirror dew point technique, was used to measure the water potential of the field. Plant available water (PAW), field capacity (FC), wilting point (WP) and percent porosity (Por) were measured in this study carried out at the end of the research in autumn 2023. Specifically, it brings the liquid water present in the soil sample and the water present in vapour form in the sample chamber into equilibrium and uses a mirror to measure condensation during the reading of samples in capsules. For sampling, the instrument must be calibrated: wait until the instrument reaches an internal temperature of 25°C and introduce a sample containing a 0.5 M potassium chloride (KCl) solution into the chamber. The calibration is completed when WP4C reaches a value of 2,22 ± 0,05 MPa. The useful range of measurement of the samples varies between -0.5 and -1.5 MPa, below which the wilting point is reached. The water potential of soil can be found indirectly by relating the water potential reading of the sample to the saturated vapour pressure of the air using the following equation:

$$\Psi = \frac{RT}{M_w}\, in\, \frac{e_s(T_d)}{e_s(T_s)}$$

Where:

- Ψ = water potential of the sample (Pa).

- R = gas constant (8.31 J (mol K)$^{-1}$)

- T = temperature of the sample (K)

- M_w = molecular mass of water (18.01528 g-mol^{-1})

- e_s (T_d) = saturated vapour pressure of the air at dew point temperature (K)

- e_s (T_s) = saturated vapour pressure at the sample temperature (K)

After analysis, the soil capsules were placed in an oven at 105°C for 48 hours. Samples were taken from as homogeneous an area of the field as possible. A straight line was drawn through all the treatments (in both replicates), and on that line, 5 samples were taken for each treatment x two replicates = 30 samples from the whole experimental field. Finally, the data were recorded and statistically evaluated.

2.1.4. Meteorological data

Meteorological data were monitored during the three years of the experiment. This information was obtained from an ARPAV (Veneto Regional Agency for Environmental Protection and Prevention) weather station located 100 m from the trial.

2.2 Statistical analysis

The effects of soil tillage as measured by physical, chemical and biological parameters and the effects of wheat cultivation as measured by LAI, SPAD Index, NDVI and spike protein and moisture content of crop parts and the interaction effect of these parameters were analysed using linear mixed effects models for the factors measured in soil (physical, chemical and biological) and the factors measured in the crop. Tillage and year were considered fixed effects in all statistical analyses performed, replicates were considered a random effect and repeated measures within each treatment were considered nested. Hypothesis testing was performed. Post hoc pairwise least squares mean comparisons were performed using Tukey's method to adjust for multiple comparisons, where means were compared using the least significance difference test at $P < 0.05$. All statistical analyses were performed using R Studio version 3 and Infostat Software. Finally, Pearson's correlation coefficient, which is a measure of linear dependence between two quantitative random variables, was calculated. The correlation was calculated between the soil system parameters and the measured wheat crop parameters mentioned above.

3. Results

3.1 Meteorological trend

The average monthly rainfall and temperatures for both wheat cycles are shown in Figure 4. They were two meteorologically diverse years, the first wheat cycle was affected by low rainfall, the historical average of the last 60 years is 605.5 mm, and for this first wheat crop cycle (27/10/2021 to 27/6/2022) the accumulated rainfall was 331.4 mm 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.

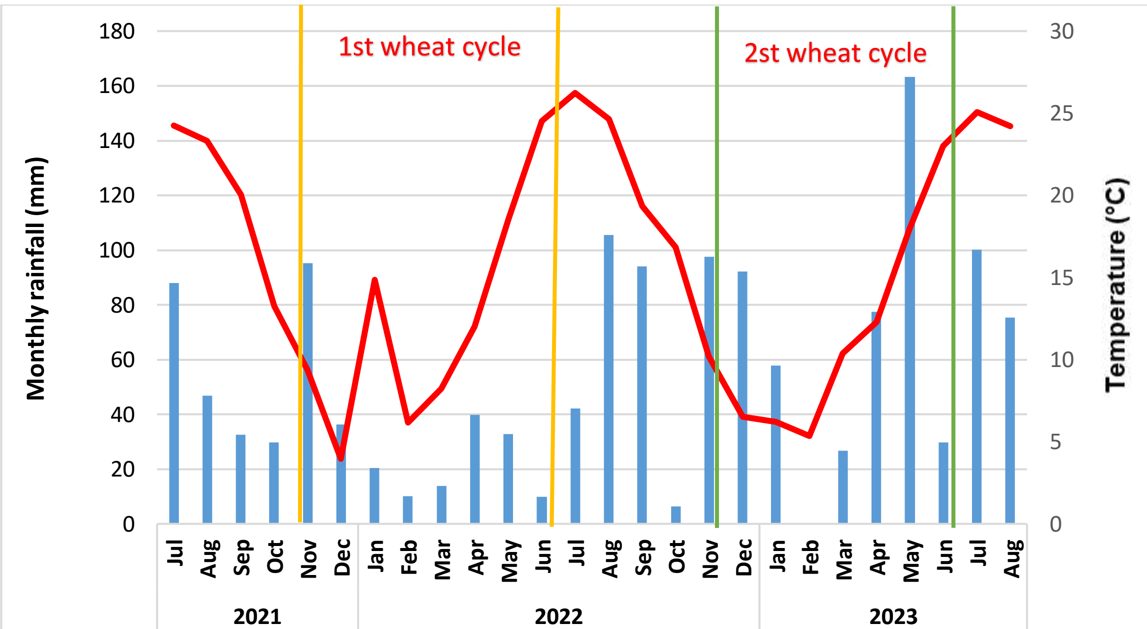

Figure 4. Average monthly temperature (red line) and monthly rainfall (blue bars).

3.2 Results of measurements on the wheat crop during the growth cycle

Measurements made in the two crop cycles during five phases of wheat cultivation showed no significant differences between managements (MT, NT, CT) for LAI, NDVI, Chlorophyll and protein. Differences only occurred for the years ($p<0.05$), with a marked decrease in the SPAD index and NDVI in the first year in relation to the extreme meteorological conditions (Figure 5). The p values of these mixed models are summarized in table 3.

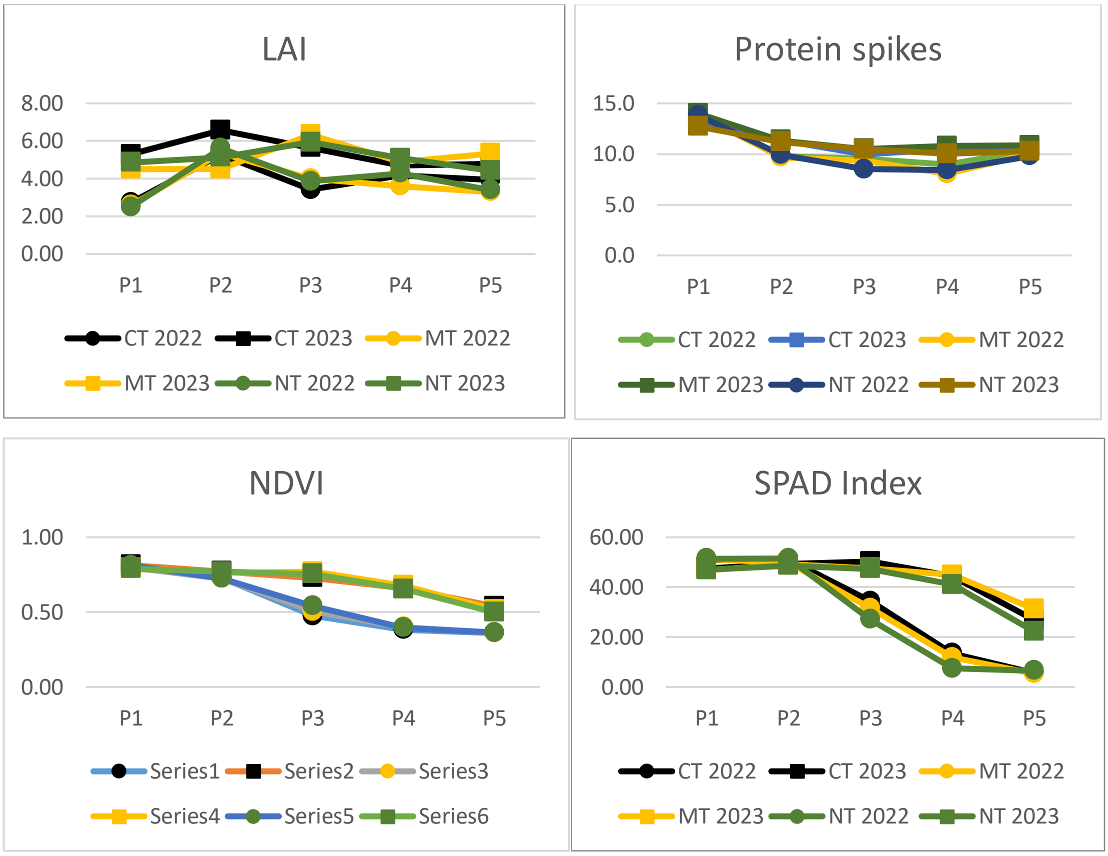

Figure 5. Results of measurements made in the two crop cycles during 5 phases. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage. Leaf area index (LAI), chlorophyll index (SPAD), Normalized Difference Vegetation Index (NDVI) and % protein content (Protein spike).

Table 3. Linear mixed model analysis of RSI output.

	Df	F	Pr > F	p-values signification codes
Spad Index				
Year	1	105.456	**<0.0001**	***
Tillage	2	1.304	0.274	°
LAI				
Year	1	70.141	**<0.0001**	***
Tillage	2	0.583	0.559	ns
NDVI				
Year	1	176.124	**<0.0001**	***
Tillage	2	0.075	0.928	ns
Protein Spikes				
Year	1	46.189	**<0.0001**	***
Tillage	2	2.238	0.110	ns

*Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 ns >0.1*

The moisture content of the different parts of the crop (leaves, stems and ears) did not show significant differences between managements. The p values of these mixed models are summarized in table 4.

Table 4. Mean total moisture of the different parts of the wheat crop in the different managements.

	Tillage	Mean	S.E	
Spikes	**NT**	51.82	8.72	**A**
	MT	51.28	8.72	**A**
	CT	49.89	8.72	**A**
Stems	**NT**	64.59	4.75	**A**
	MT	63.49	4.75	**A**
	CT	63.30	4.75	**A**
Leaves	**MT**	55.10	6.23	**A**
	NT	54.35	6.23	**A**
	CT	51.90	6.23	**A**

Means with a common letter are not significantly different (p > 0.05).

The components that were analysed for the quality of the wheat grain showed as a result non-significant differences for the wet gluten, whose means were 31.94 % for NT, 31.31 % for MT and lastly for CT a mean of 30.62%, the same for the specific weight without differences, with means of 80.84 kg hL^{-1} for MT, 80.34 kg hL^{-1} for NT and 80.32 kg hL^{-1} for

CT. The Zeleny test showed significant differences in MT and NT with values of 24.41 for MT and 22.70 for NT, for CT, the result was 23.46, which had no significant difference with MT and NT. For the protein content of the grain, we observe that there are no statistically significant differences between treatments. Only in terms of years, we have differences in protein values, where the year 2022, due to the extreme climatic situation (drought and high temperatures), the values were lower compared to 2023 because the cycle closed abruptly (Figure 6). The p-values of these mixed models are summarised in table 5.

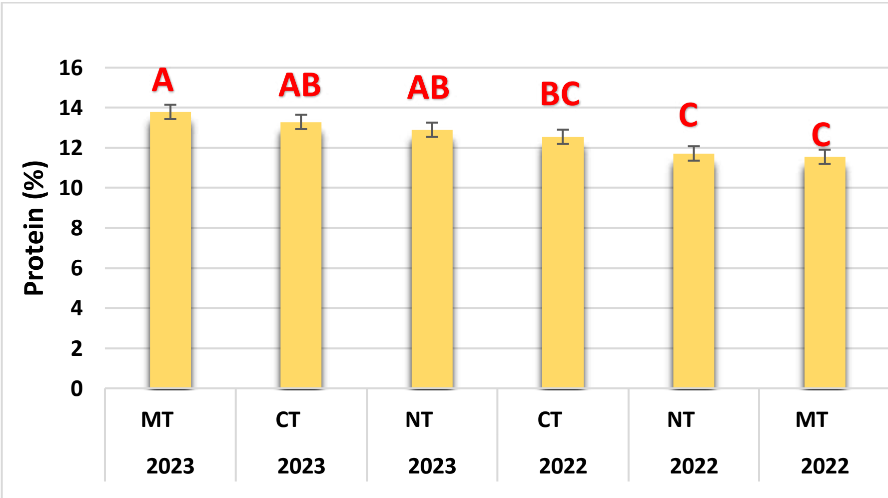

Figure 6. Grain protein content (% d.m.) at harvest in the two years of experimentation for each tillage system: MT, Minimum tillage; NT, No tillage and CT, Conventional tillage.

Table 5. Linear mixed model analysis of RSI output for protein (%)

Protein (%)	Df	F	Pr > F	p-values signification codes
Year	1	15	**0.000**	***
Tillage	2	1	0.381	ns
*Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ns < 1*				

For grain yield, the weather conditions reported above caused an acceleration of wheat maturity, which also resulted in a lower yield in the first sowing cycle (2022), with 18% less production compared to the second cycle (2023). Despite these climatic conditions, the grain yield did not differ significantly between managements; only the yield difference between years was observed due to the climatic difference described above (Figure 7). The p values of these mixed models are summarized in table 6.

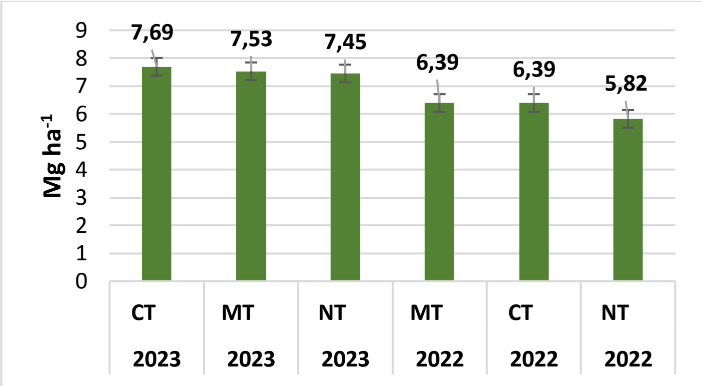

Figure 7. Grain yields at 13% d.m. for each tillage system in their respective years. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

Table 6. Linear mixed model analysis of RSI output for yield.

Yield Mg ha^{-1}	**Df**	**F**	**Pr > F**	**p-values signification codes**
Year	1	16	**0.000**	***
Tillage	2	1	0.584	ns
*Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ns < 1*				

3.3 Results of physical, chemical and biological soil analysis

3.3.1 Bulk density and gravimetric water content

Bulk density in the 0-5 cm horizon had significant differences (p<0. 05). CT and NT have shown the highest values, followed by MT, in both sampling years. The bulk density value was high, but this value did not prevent root development, as instead shown in a study conducted by Sabir *et al.* (2021), where an increase in bulk density above 1.60 Mg m^3 led to a decrease in yield and yield components in wheat (table 7).

Table 7. Mean soil bulk density (BD) over the two years of sampling.

Year	*Tillage*	*Mg m^{3}*			
2023	CT	1.66	A		
2023	NT	1.53	A	B	
2023	MT	1.49		B	
2022	NT	1.49		B	
2022	CT	1.44		B	C
2022	MT	1.33			C

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

3.3.2 Saturated Hydraulic conductivity

Hydraulic conductivity was measured at three different times, before the start of the trial (2021), at the end of the first wheat cycle (2022) and at the end of the second wheat cycle (2023). The results from this test showed significant differences ($p<0.05$) between the different tillage systems (Figure 8). These results contrast with those detailed in Alletto *et al.* (2022) where conservation farming yielded a higher value of infiltration than conventional farming but in this study it was observed that infiltration in conventional system has to be high after the soil was ploughed, then its value decreases. In Soracco *et al.* (2010) no significant differences were observed between treatments in terms of infiltration. This may be related to the transition period, which may still be ongoing, so that the stabilisation period has not yet been reached in terms of physical soil structure.

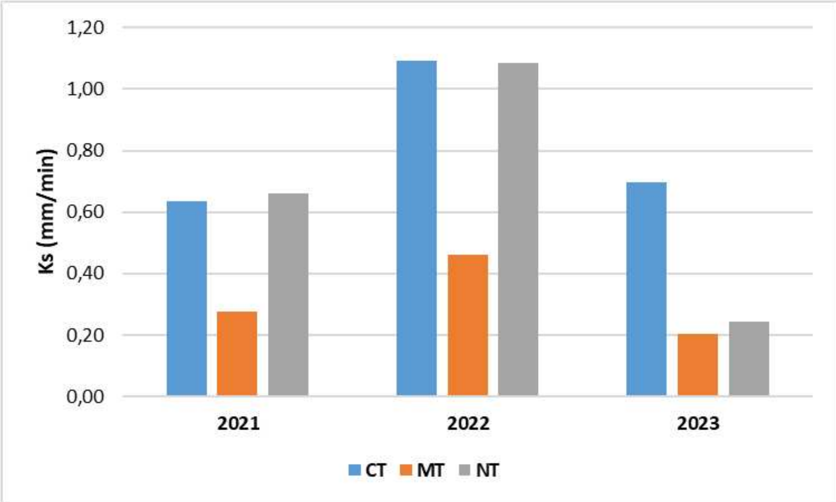

Figure 8. Averages of the 3 years (2021-2022-2023) of sampling of the Ks of the different tillage systems. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

3.3.3 Earthworms

Earthworms are one of the most important macrofaunal groups in the soil with a fundamental role in agricultural ecosystems. Agricultural practices such as minimum tillage, the use of green manures, and organic fertilization are practices that benefit the population (Baldivieso-Freitas *et al.*, 2018; Rasmussen, 1999). Regarding soil fauna, the presence of earthworms was evaluated after the harvest of each wheat crop cycle (2022-2023). Even if no significant differences were identified, a tendency of an increase of earthworm presence with the reduction of soil disturbance can be observed (Figure 9).

In Capowiez *et al.* (2009), management types did not significantly affect earthworm abundance, but did affect the ecological type of earthworms found in each plot (anecic earthworm were more abundant in RT).

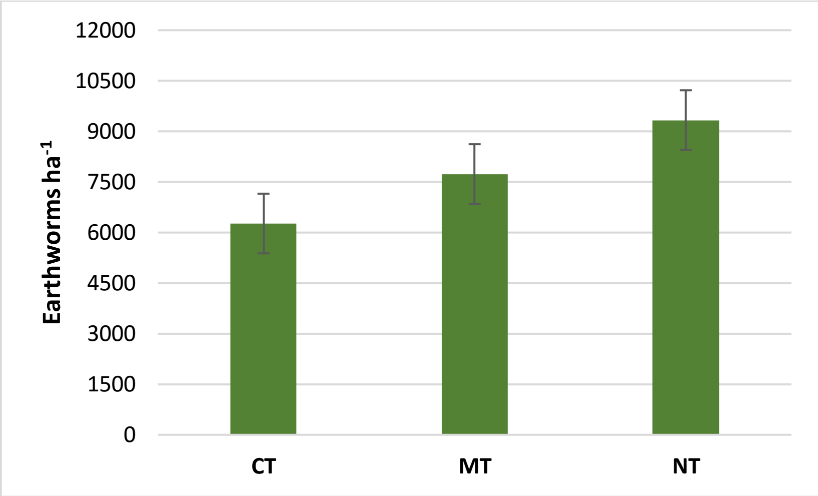

Figure 9. Means of the 2 years of sampling of the presence of earthworms in the soil. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

3.3.4 pH

As for the pH, no significant differences were observed between the tillage systems, and the mean values obtained were 8.23 for MT, 8.21 for CT, and finally 8.16 for NT. This sub-basic pH value is related with to the high presence of carbonates observable in the field.

3.3.5 Chemical indicators

Agricultural land management is one of the main drivers of global change through its influence on carbon and nitrogen cycles and greenhouse gas emissions, and one of the most important factors in terms of its effect on the properties of agricultural soils (Smith *et al.*, 2016). Conservation agriculture, typically represented by the retention of agricultural residues, crop rotation and no-tillage, has been widely practiced to mitigate the loss of nutrients caused by conventional practices (Li *et al.*, 2018). Regarding the results of the chemical analysis of soil quality, we observed significant differences ($p<0.05$) in some nutrients. Regarding total nitrogen (N_{TOT}), significant differences were observed between the different treatments at a depth of 20 cm; the same happened for total Kjeldahl nitrogen (N_{TKN}), as NT and MT have reported the highest values for this nutrient (Figure 10). For ammonium (NH_4^+), there were no significant differences, as the mean values were 2.29 mg kg^{-1} for MT, 2.27 mg kg^{-1} for NT and 2.22 mg kg^{-1} for CT.

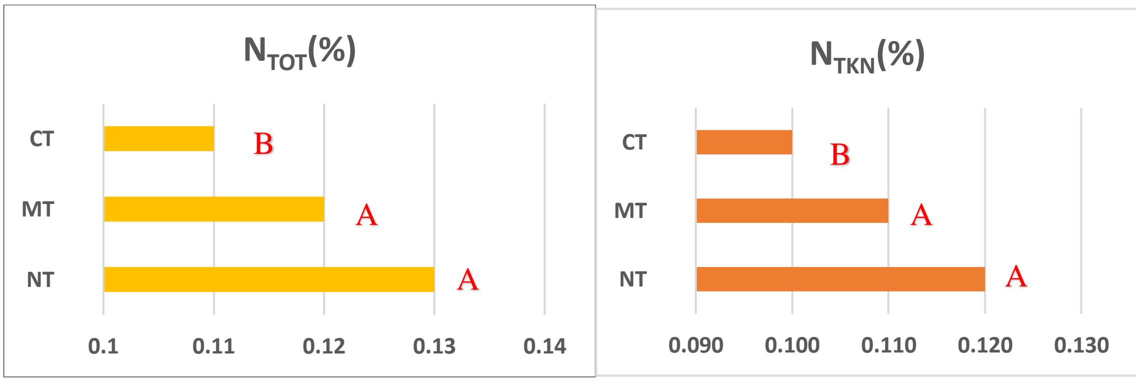

Figure 10. Average total nitrogen (N_{TOT}, %) and total Kjeldahl Nitrogen (N_{TKN}, %) in the different managements. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage at 20 cm depth.

As for the soil organic carbon (SOC), here the results also showed differences between the treatments, with NT as the treatment with the highest soil organic carbon value, followed by MT and finally CT (Figure 11). After 5 years from conversion from Conventional tillage, the SOC concentration in the 0-20 cm horizon increased significantly in MT and NT. However, considering the average BD in this horizon, the SOC stock increased by 25% in MT and 31 % in NT, corresponding to an increase of 5.41 and 6.75 Mg C ha^{-1}, respectively, after 5 years.

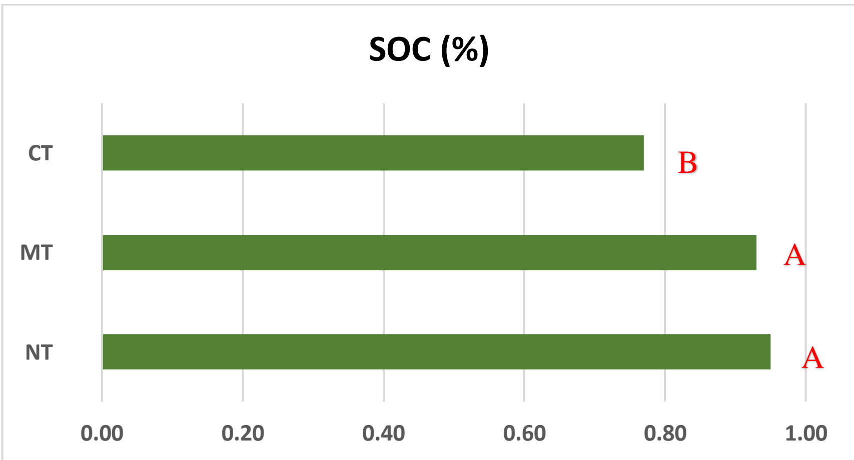

Figure 11. Average Soil organic carbon (SOC, %) for each tillage system: MT, Minimum tillage; NT, No tillage and CT, Conventional tillage.

Finally, the total carbon analysis results were not significantly different. The p values of these mixed models are summarized in table 8.

Table 8. Linear mixed model analysis of RSI output for total carbon (C_{tot}, %).

C_{tot} (%)	Df	F	Pr > F	p-values signification codes
Year	1	83.8	**<0.0001**	***
Tillage	2	1.0	0.372	ns
*Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ns < 1*				

3.3.6 Electrical conductivity of soil

The electrical conductivity was highly influenced by the moment of sampling since, in the first year (2022), the analysis was performed on October 4, 2022, after two months (August and September) with rainfall that reached almost 100 mm each month, so the soil profile had a high percentage of moisture. The second sampling was carried out on July 10, 2023; here, temperatures were higher, which translates into higher evaporation of soil water content and less rainfall in the preceding month. Figure 12 shows how conductivity increases with increasing soil depth; its distribution is heterogeneous throughout the field, reaching minimum values of 1 mS m^{-1} in the top soil and up to 18 mS m^{-1} 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. In MT, the highest values and localised compaction were observed; in NT, we have a more homogeneous distribution in terms of electrical conductivity. The variability is due to the structural variation present in the soil and the water content in the profile which has varied from year to year.

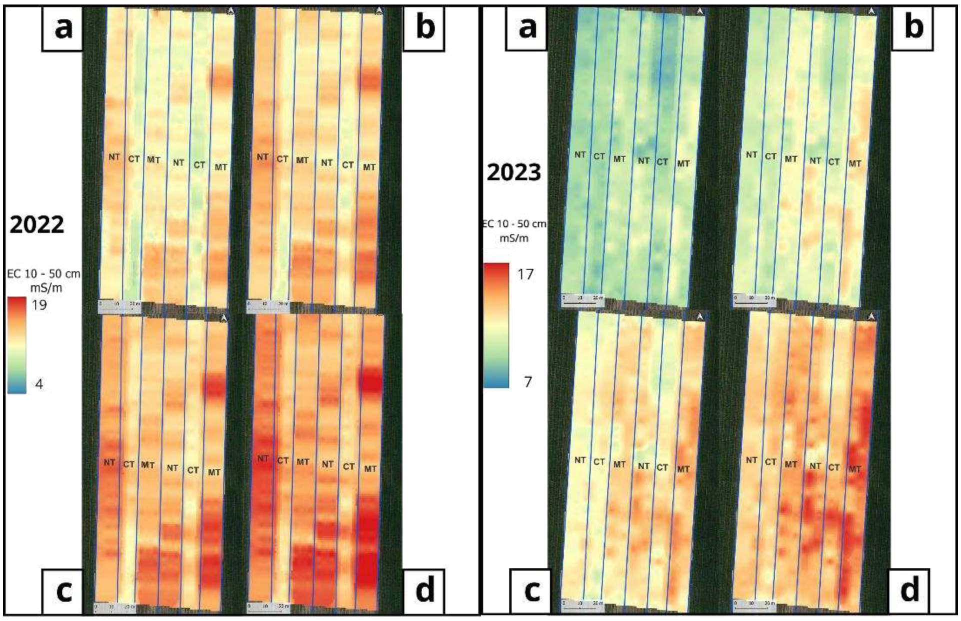

Figure 12. Electrical conductivity at different depths (a: 10-20, b: 20-30, c: 30-40 and d: 40-50 cm). MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

3.3.7 Water potential

Figure 13 shows how reduced tillage systems tend to increase available water in the surface soil profile. Statistically, no significant differences were observed between treatments, but the trend observed would indicate an improvement in soil structural condition in MT and NT, with, in turn, an increase in macroporosity and microporosity. Regarding CT porosity, there is a relative prevalence of the macroporosity component. There is a trend towards an increase in plant available water in both conservation tillages compared to the conventional, the increase was 15% in MT and 21% in NT, and the same is true in terms of field capacity and wilting point.

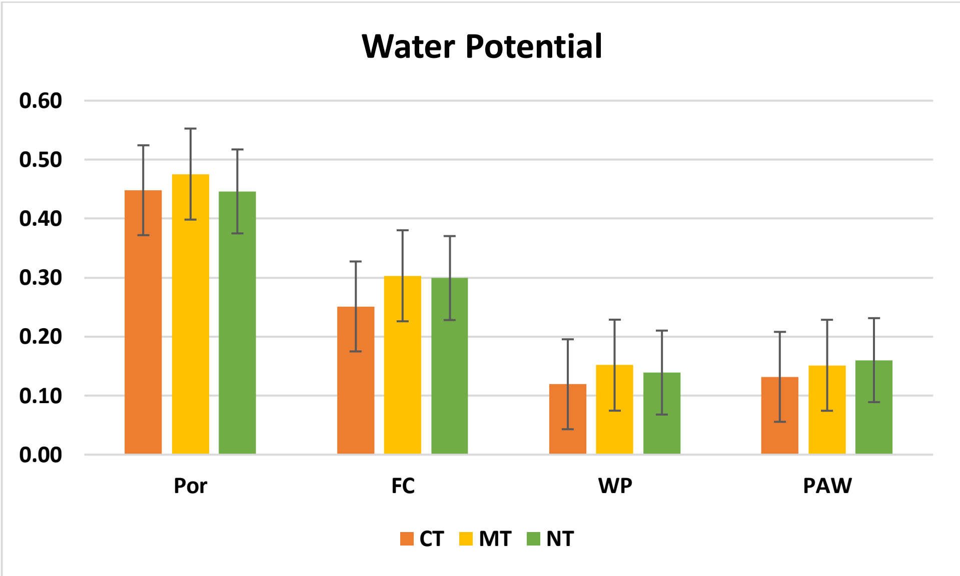

Figure 13. Means of the different managements for porosity (Por), field capacity (FC), wilting point (WP) and plant available water (PAW) measurements. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

3.4 Statistical correlation of soil-plant parameters

The correlation was calculated from data collected during the crop cycle (2021 and 2022), and the soil parameters were measured after the harvest of the wheat crop. Regarding Ks, the correlation took into account the samples taken before the first sowing of wheat and after each harvest, so this parameter was measured at three different times (pre-sowing 2021 and post-harvest), compared to the rest, which was measured at two times (post-harvest).

In Figure 14, we can observe a high positive correlation between the measured crop variables: LAI, NDVI, chlorophyll indicator (SPAD), and humidity of the different parts of the plant. As for the spikes protein, it also had a high correlation with the variables mentioned above except for LAI. Wheat yield was positively related to the analysed crop variables. As for the soil physical variables, for Ks the correlation was negative for the crop variables (LAI, NDVI, SPAD, Yield, ear protein) and also for soil N_{TN} and C_{TOT}. There was no correlation between bulk density and crop variables except for yield, which was negatively correlated, and also with N_{TKN} and N_{TOT}; for earthworms and Ks, the correlation with bulk density was positive.

The correlation between soil moisture and crop yield was negative. The soil chemical indicators N_{TKN}, N_{TOT}, C_{TOT}, and SOC reported positive correlations with the crop variables. Finally, the soil biological variable earthworm presence had no correlation with any crop variable, but it had a positive correlation with bulk density and N_{TKN} and a high positive correlation with Ctot.

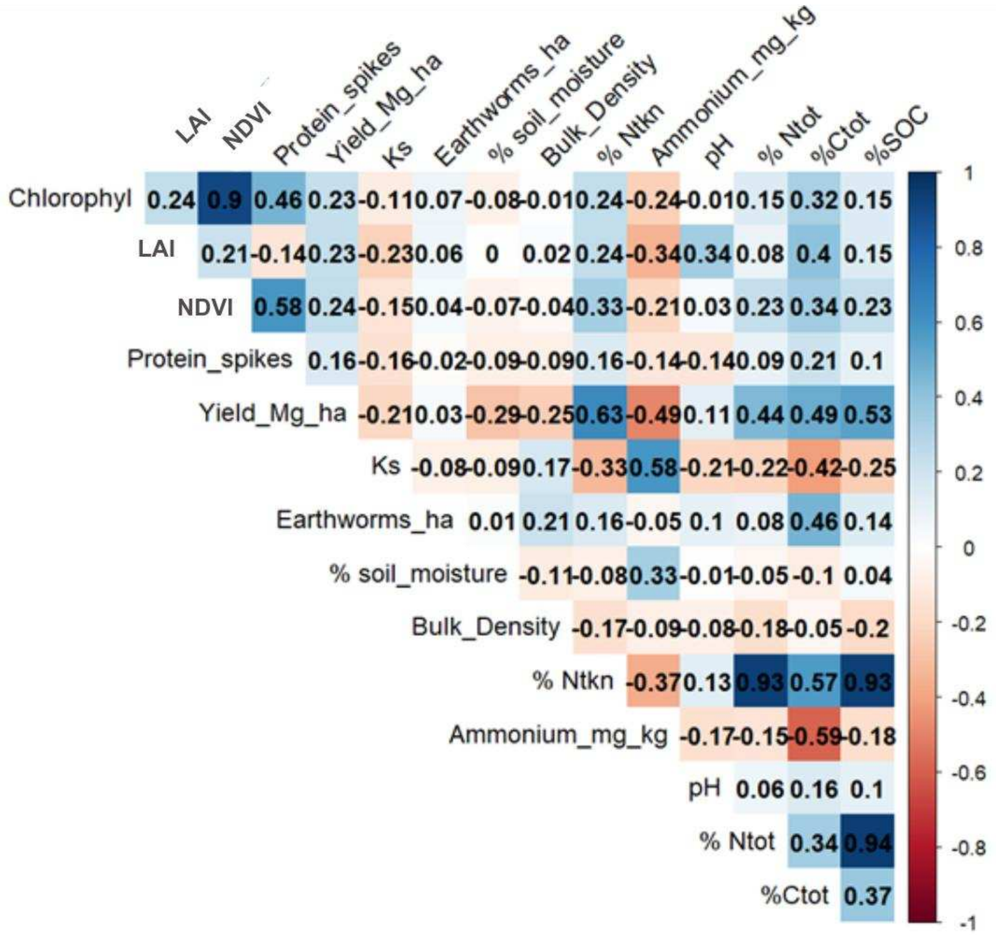

Figure 14. Graph of the Pearson correlation coefficient between the different variables measured in the soil and the wheat crop during the research (2021-2022).

4. Discussion

The tillage systems (NT, MT and CT) studied during the experiment did not prove to affect the growth potential of the wheat crop: no significant differences were observed in terms of growth parameters (chlorophyll index, NDVI, LAI), which contrasts with what was reported in Gracia-Romero *et al.* (2018), where for example NDVI was affected by tillage timing, with higher values in CT. As for the wheat crop yield, it was only influenced by inclement weather, which affected the wheat cycles in different ways. This result is similar to that of the other crops sown in the first three years of CA implementation, as reported in Sartori *et al*. (2021b), but it contrasts with the results obtained by Das *et al*. (2018), and Francis and Knight (1993), where wheat yields were higher under the conservative practices, and there was a higher fertilizer requirement in the conventional to match the yields of the conservative practice. Aryal *et al*. (2016) have shown that conservative farming in wheat has produced more than conventional. Sun *et al.* (2020) in a compilation of data have shown that arid regions, or eventual dry years will benefit in terms of yields from CA.

The two meteorologically diverse years throughout the experimentation allowed CA to be tested in different scenarios, resulting in a competitive practice in terms of crop quality and yield compared to the conventional practice for the area under study.

Regarding edaphic parameters, in bulk density, CT and NT treatments presented similar values, followed by MT with the lowest value, which coincides with what was observed in Mohanty *et al.* (2015) where MT presented lower values than CT. The values obtained in the field under study do not affect plant growth and development according to the Natural Resources Conservation Service (USDA, 2008) whose reference values are shown in table 9.

Table 9. General relationship of soil bulk density to root growth based on soil texture (USDA Natural Resources Conservation Service, 2008).

Soil Texture	*Ideal Bulk densities for plant growth (g cm^{-3})*	*Bulk densities that restrict root growth (g cm^{-3})*
Sandy	<1.60	>1.80
Silty	<1.40	>1.65
Clayey	<1.10	>1.47

For soil moisture, the values correspond to the results observed in other research (De Vita *et al.,* 2007), where NT management retained more moisture than CT. This, together with a tendency to increase available water with conservation tillage, may be decisive for crop yield in years with low rainfall such as those recorded during the time of experimentation (2022).

The results of the analysis of the presence of earthworms, a soil biological parameter, despite not showing statistically significant differences, confirmed that no-tillage promotes the presence of earthworms in the soil. The opposite occurs in conventional tillage, where their presence is lower due to soil removal, coinciding with the results observed in previous studies (House and Parmelee., 1985; Perego *et al*., 2019; Stagnari *et al*., 2020). A worldwide meta-analysis observed that the responses of earthworm presence were more pronounced in the long term (>10 years) Briones and Schmidt (2017); this parameter should, therefore, continue to be monitored in order to analyse the evolution of worm density and size over time.

Regarding nutrients, significant differences were observed in total nitrogen and total Kjeldahl nitrogen, which coincides with the positive effect of no-tillage on the increase of available nitrogen in the soil, as reported in other studies both in the short and medium term (McConkey *et al.*, 2002; Omara *et al.*, 2019; Varvel and Wilhelm, 2011) and in the long term (Salinas-Garcia *et al.*, 1997). Similar results of total nitrogen increase have been reported in Aziz *et al.* (2013). Ammonium was not affected by soil tillage, with similar values in the three treatments; López-Bellido *et al.* (2014) observed significant differences, with a higher presence in NT but in a long-term study (>10 years), which implies that the implementation period of CA is not yet sufficient to observe differences in ammonium levels in the soil under study.

Regarding soil organic carbon, significant differences were observed with results of higher value in conservation tillage treatments, compared to CT; these results coincide with different studies around the world, where it is stated that the implementation of NT is an effective management alternative to increase soil carbon sequestration (Blanco-Canqui and Lal, 2008; Mazzoncini *et al.*, 2016), which translates into an improvement of soil productivity and fertility properties (Szostek *et al.*, 2022). On the other hand, this parameter was not affected by the climatic situation that did affect other parameters under study, which coincides with what was stated by Xiao *et al.* (2020).

In terms of water potential, there were no significant differences between the managements, which coincides with the results also obtained in wheat in a comparative study of sowing systems carried out by Patrignani *et al.* (2012). The increase in terms of available water was 15% for MT and 21% for NT compared to CT, which again, in years of pronounced drought in agricultural systems, can make a difference in terms of yield.

It is important to highlight the tendency to increase the values in reduced tillage systems (NT and MT), which has also been observed in studies by Samanta *et al*. (2024) where the available water of the plant had significant differences in favour of NT in comparison with CT. Blanco-Canqui and Ruis., (2018), in a comparison of physical properties data between conventional and reduced tillage systems, observed a 44% increase in available water; similar results were obtained in Himmelbauer *et al*. (2012). Stavi *et al*. (2011) shows that even continuous no-tillage has a higher field capacity than land under occasional tillage. Fabrizzi *et al*. (2005) observed higher water storage in the soil during the critical growth phase of the wheat crop, which is very important in dry years such as the one recorded during this research.

For the hydrological constants, including hydraulic infiltration, new measurements will be necessary to analyse the evolution of these parameters, which have not been too much affected by the change in tillage in these five years of CA.

5. Conclusion

Conservation agriculture, implemented in this field since 2018, shows that the above-mentioned transition period, evidenced in numerous investigations, may have reached its stabilisation phase, as the values are equal to or higher than tillage practices (MT and CT), and no negative effects characterising this transition period are evident. For the farmer, the yield and quality values of the wheat crop can be more than satisfactory, and this improves the study if we add an economic analysis of each system, remembering that for the NT the number of practices are lower since ploughing and other secondary tillages (harrowing, for instance) are not carried out. At the structural level (infiltration, bulk density), the soil has not yet shown major changes between the different farming systems, but it has shown great changes at a nutritional level. Conservation agriculture is a competent practice in this area under study, and perhaps even more so in the face of climatic changes that the region and the world are experiencing. This has been demonstrated in developing countries (Gupta and Sayre, 2007). The decrease in costs is mostly due to oil and energy savings (Cavalchini *et al*. 2013). FAO (2001) reports economic benefits related to labour savings (reductions of up to 50%); other authors report the benefits of CA on investment efficiency and productivity (Marandola., 2012). The agricultural community has many challenges ahead, both in the global political and climatic environment, and more research on the medium and long-term effects of CA is needed to assess its benefits in these scenarios.

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Chapter 3: Reduced tillage systems: sustainability evaluation through a multivariate analysis approach

1. Introduction

Conservation agriculture encompasses three principles: minimal soil disturbance, permanent organic soil cover, and species diversification (FAO 2017). CA practices can be very strategic for recovering and conserving soil quality (Blanco-Canqui *et al.*, 2006) because decades of overexploitation have led to the exhaustion of agricultural production systems (Bhandari *et al.*, 2002; Manna *et al.*, 2005).

Pezzuolo *et al*. (2014) show how AC could be a solution, increasing the efficiency of energy use, reducing CO_2 emissions and avoiding SOC losses.

Problems during the transition from conventional to conservation farming can influence the adoption rate of this technique due to effects observed during this transition: yield reduction, need for new machinery equipment, reorganization of production, and weed management, among others. Troccoli *et al*. (2015) suggest that governments should implement political-economic accompaniment supporting and encouraging farmers to convert to CA.

Marandola *et al*. (2019) surveyed 8,092 municipalities in Italy, of which 63% implement NT, and of this percentage, 80% use the technique on the majority of their farm area. Figure 1 shows the distribution of the ratio between the Arable Utilized Agricultural Area (A-UAA hectares) under NT schemes and the total A-UAA surveyed by 2011 Agricultural Census (values in %). This adoption is the reflection of a need on the part of farms to proceed to a more complete reorganization of the way of doing agriculture, to adhere to a new paradigm, which can be assimilated to CA, with all the implications, including the economic ones, that this entails.

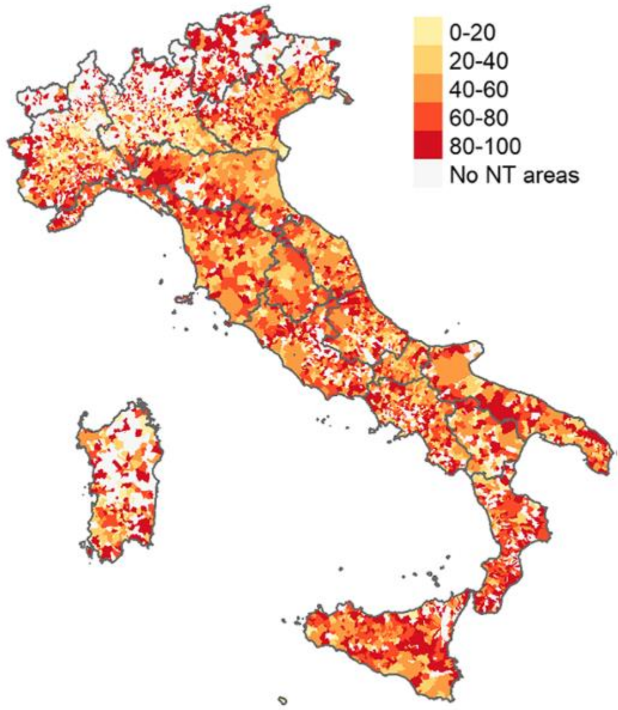

Figure 1. The distribution of the ratio between the Arable Utilized Agricultural Area (A-UAA hectares) under NT schemes and the total A-UAA surveyed by the 2011 Agricultural Census (values in %) (Marandola *et al.*, 2019).

In a study conducted by Perego *et al*. (2019) in which 20 farms in the Po valley participated, many positive effects of CA were reported when this practice was applied in the long term. All this is strongly influenced by the knowledge and skills of the farmer.

Other studies carried out in central and southern Italy have produced contrasting results. In a long-term study started in 1995 in Foggia, it was observed that there is a strong correlation between years with limited rainfall during the cultivation period and the increase in yield from no-tillage compared to conventional (De Vita *et al*., 2007).

Calzarano *et al.* (2018) obtained a high yield and yield quality in durum wheat, and soil improvement was also observed. Ruisi *et al.* (2014) obtained the highest yields with CA, especially during dry years, but no significant differences were reported in a 20-year study.

It has been observed in long-term research (25 years) carried out in Germany on different types of tillage systems, that the change from conservation agriculture has led to an increase in compaction in the deepest horizons, the formation of a plow pan below the tilling depth of the cultivator and a reduction in the hydraulic conductivity (Ks), which does not occur with ploughing that produces a loosening that leads to an increase in macroporosity and connectivity of the macropores and therefore the Ks (Schlüter *et al.*, 2018).

Because of these variations observed in the different studies mentioned above, it is useful to implement integrated soil quality indices that are based on a combination of soil properties and thus compare the impact of different management strategies. Doran and Parkin, (1994) defined soil quality as "the ability of the soil to function within limits to sustain biological productivity, maintain and promote plant and animal health". In Masto *et al.* (2007-2008) a methodology for calculating a soil quality index was outlined. This procedure consists of selecting from a number of indicators, surveyed and normalised with linear or non-linear scoring functions. The aim is to associate a high score with the observation that presents the best results.

In this chapter we proceeded to analyse the results of a 5-year (2018-2023) conversion to conservation agriculture experiment in the Veneto region of Italy and thus determine which and how a number of environmental indicators were affected by the different types of soil tillage: the conventional tillage (CT) ploughed to a depth of 30 cm and harrowed to 15 cm; the minimum tillage (MT) plot ploughed to a depth of 15 cm and then harrowed; and the no-till (NT) plot sown on the residues of previous crops.

2. Materials and methods

The experiment took place at the Lucio Toniolo Experimental Farm, located in Legnaro, PD (NE Italy, 45° 21 N; 11° 58 E; 6 m a.s.l.), where the climate is sub-humid, with temperatures between -1.5 °C on average in January and 27.2 °C on average in July. Rainfalls reach 850 mm annually, with a reference evapotranspiration of 945 mm that exceeds rainfalls from April to September. The highest rainfalls occur in June (100 mm) and in October (90 mm), while winter is the driest season with average rainfalls of 55 mm. The shallow water table ranges from 0.5 to 2 m in depth, with the lowest values recorded in summer.

The trial started in the autumn of 2021, with an area of 2 ha, divided into two replicates (1 ha each) and within each replicate was subdivided into three strips of 13 m x 260 m (Figure 2). The soil at the site is Fluvi-Calcaric Cambisol (FAO-UNESCO 2008) with a silt loam texture. The treatments within the plot were three: the conventional tillage plot (CT) was ploughed to a depth of 30 cm and harrowed to 15 cm; the minimum tillage plot (MT) was ploughed to a depth of 15 cm and then harrowed; and the no-tillage plot (NT) was sown on the residues of previous harvests.

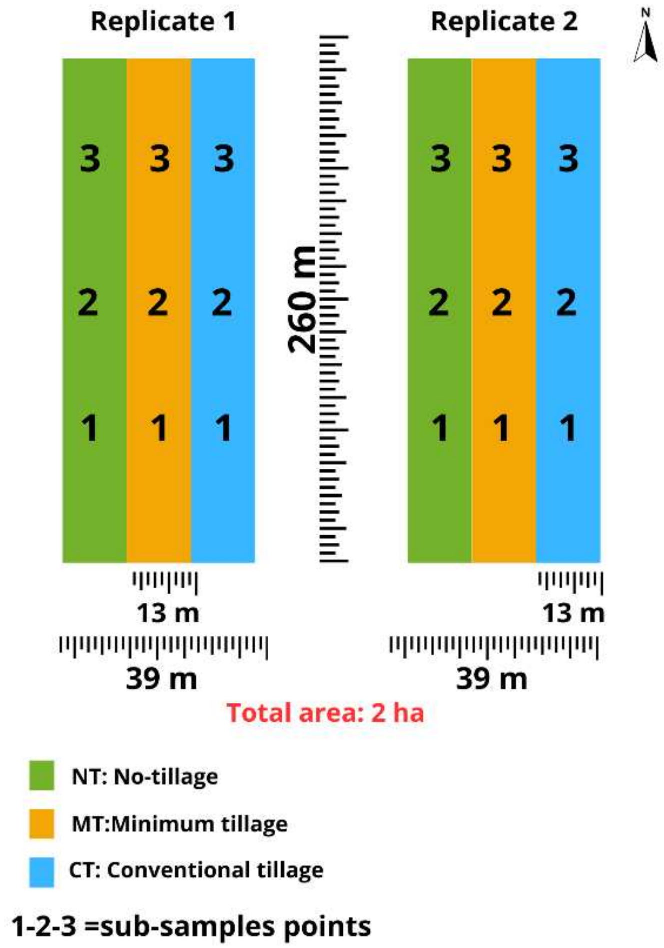

Figure 2. Experimental design.

2.1 Field surveys

A total of 9 parameters were measured in order to evaluate the evolution of environmental conditions:1) Bulk density (BD), 2) soil organic carbon (SOC), 3) Gravimetric soil water content (GWC), 4) total nitrogen (N_{TOT}), 5) total Kjeldahl nitrogen

(N_{TKN}), 6) presence of earthworms (EW), 7) saturated hydraulic conductivity (Ks), 8) pH, 9) wheat yield (Y).

Sampling of these parameters (Figure 3) was carried out after harvesting the wheat crop sown in the experimental field.

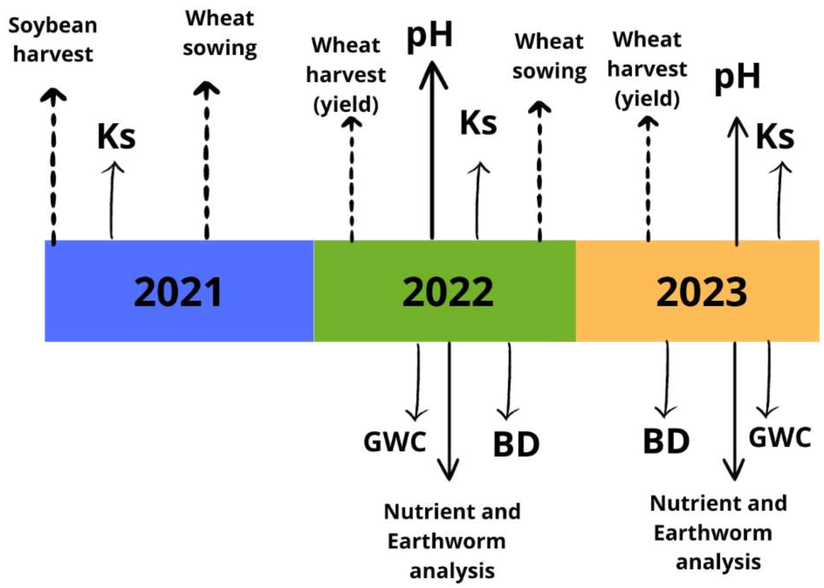

Figure 3. Timeline of the different measurements carried out on the soil and the wheat crop during the 3 years of the experiment. Bulk density (BD), Gravimetric soil water content (GWC), nutrient content: total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), soil organic carbon (SOC), presence of earthworms (EW), saturated hydraulic conductivity (Ks), pH, wheat yield (Y).

For the BD, samples were taken from the first 5 cm of the soil, the so-called topsoil. The wet weight was recorded and then the dry weight, followed by drying in an oven at 105°C for 24 hours. Through this analysis, the soil moisture (GWC) could also be calculated.

Total Nitrogen (N_{TOT}), Total Kjeldahl Nitrogen (N_{TKN}), and soil organic carbon (SOC) were analysed, in the arable layer of the soil (0-20 cm). At each point, three subsamples were taken and mixed to obtain a homogeneous sample; the total number of samples was 18 (2 replicates x 3 managements x 3 points in each management = 18 points). The methods used for the analysis of these nutrients are described in the D.M. 1999, "Official methods of soil chemical analysis". For earthworm (EW) measurement, the methodology proposed by Valckx *et al.* (2011) was used. Using 6 gr of mustard suspended in water, earthworms were extracted from the soil surface, this sampling was repeated after the harvest of the wheat crop in both cycles (2022-2023). The measuring surface was 25 cm x 25 cm. The earthworms were counted recalculated to hectare scale and the data were recorded and statistically evaluated.

The hydraulic conductivity (Ks) was measured by means of a double ring infiltrometer over an area of 1,300 cm^2, as described in Morbidelli *et al.* (2017). The inner cylinder has a diameter of 40 cm, and the outer cylinder has a diameter of 70 cm. The two rings were installed at a depth of approximately 10 cm. The measurement is made in the inner cylinder; the function of the outer cylinder is to prevent the water in the inner cylinder from flowing laterally and not only vertically.

The infiltration was measured by controlling the time implemented for the infiltration of a 1 cm column of water; this procedure was repeated several times until stabilization was not reached (more than 2 measurements with the same temperature).

The parameter Ks measures the column of water that can infiltrate a soil under saturated conditions in a unit of time (Cook and Broeren, 1994). Through Philip's equation (Philip, 1969) measurements were made at 12 points in the experimental field (2 points x 3 managements x 2 replicates = 12), and the sampling times were in October 2021 prior to wheat sowing, the second in October 2022 after the harvest of the wheat crop and the third sampling was carried out in July 2023 after the harvest of the second wheat sowing cycle. The measured data were analysed according to Philip's infiltration equations (Philip, 1969) with the Microsoft Excel Solver add-in:

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

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

Where *i(t)* and *v(t)* are respectively the water infiltration (m) and the infiltration rate (m s^{-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:

$$Ks = \frac{A}{m}$$

With *m* as a constant equal to 2/3.

The pH is determined potentiometrically in a soil-water suspension (10:25). This system is the most commonly used to define the degree of soil reaction, the method used is that reported in D.M. 1999, "Official methods of soil chemical analysis".

Finally, crop yield (Y) was measured by harvesting 1 square meter of material at each point (18 points like the other measured parameters); after harvest, a sample of grain was air-dried at 105°C to constant weight to determine dry mass weight.

2.2 Data analysis

Soil quality index is a tool that helps to quantify the combined chemical, biological and physical response of soil to crop management practices. In order to do this, we must identify which parameters are responsible for changes in soil quality and thus be able to assess agricultural sustainability (Sartori *et al.*, 2021b).

Masto *et al.* (2007) defined the methodology for the calculation of the soil quality index. A set of indicators were selected, measured and normalised with linear or non-linear scoring functions. Normalisation allows higher scores to be associated with the best-performing observation.

Andrews *et al.* (2002) describes the multivariate analysis, which allows the determination of indicators and a weighting factor for the indicators; the sample data (X_{ij}) were then normalised with a linear scoring function (Masto *et al.*, 2007), by applying the following equations:

$$S = \frac{X_{ij} - X_{i\,min}}{X_{i\,max} - X_{i\,min}} \qquad (1)$$

$$S = \frac{X_{ij} - X_{i\,max}}{X_{i\,max} - X_{i\,min}} \qquad (2)$$

$$S = \frac{|X_{ij} - 7|}{|X_i - 7|_{max} - |X_i - 7|_{min}} \qquad (3)$$

Where $X_{i\ max}$ is the maximum value measured during the survey for parameter *i*, and $X_{i\ min}$ is the smallest. The *S*-value ranges from 0, corresponding to the minimum value observed for parameter *i*, to 1, for the maximum. Equation (1) is used for the "More is better" scoring function, here SOC, GWC, Ks, EW, N_{TKN}, N_{TOT} and Y. Differently, AS, BD and PR were scored with equation (2), according to the "Less is better" approach. Finally, equation (3) was used for pH scoring.

By implementing these 3 equations, it was possible to target the highest values in the combination of treatments with the best impact on the parameters.

The Relative Sustainability Index (RSI) was calculated as the sum of the observed parameter scores, weighted with weighting factors from the Principal Component Analysis (PCA). Through the descriptions made in Masto *et al.* (2008), factors were calculated by selecting principal components (PC) that could explain at least 10% of the variability. Within each PC, the loaded factor with values >|0.2| was selected (table 4) and its correlation was measured as in Andrews *et al.* (2002). In case of correlation (r>||0.8|), only the factor with the highest loading factor was used for the RSI calculation, together with all other uncorrelated high-loading factors. The percentage of variation explained by each PC provided the PW. The RSI was calculated with equation (4):

$$RSI = \sum_{i=1}^{n} PW_i \times S_i \qquad (4)$$

The RSI was divided by the highest RSI value obtained so that the RSI could be normalised.

RSI differences between treatment combinations were tested with mixed models. All possible first- and second-order interactions between factors were tested, and the model with the lowest AIC (Akaike's Information Criterion) was selected (Schabenberger and Pierce, 2001). Post hoc pairwise comparisons of least square means were performed using the Tukey method to adjust for multiple comparisons. Microsoft Excel 2016 was used.

3. Results

Tables 1 and 2 report the average data of the observations made throughout the research from which the RSI was calculated, in conjunction with the data obtained in the research of Sartori *et al*. (2021) carried out at the same experimental site and with the same experimental design.

Table 1. Parameters selected for the calculation of the sustainability index, which were measured during the experiment carried out by Sartori *et al.* (2021). Bulk density (BD), soil organic carbon (SOC), Gravimetric soil water content (GWC), total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), presence of earthworms ha^{-1} (EW), saturated hydraulic conductivity (Ks), pH, wheat yield (Y).

Year	Parameter	Units	Average Value	Minimum	Maximum	Standard deviation	Coefficient of variation
2018	*BD*	(mg ha^{-1})	1.43	1.32	1.54	0.05	0.04
	SOC	(%)	0.83	0.64	1.07	0.12	0.14
	GWC	(%)	23.00	20.00	25.00	1.00	0.06
	KS	(mm/min)	3.4×10^{-5}	6.7×10^{-6}	1.7×10^{-4}	3.9×10^{-5}	1.15
	EW		6.17	0.00	16.00	4.69	0.76
	N_{TKN}	(mg kg^{-1})	22.97	12.85	46.90	8.91	0.39
	N_{TOT}	(%)	0.88	0.08	1.09	0.23	0.26
	pH		7.36	7.22	7.49	0.06	0.01
	Y	(mg ha^{-1})	9.96	5.41	12.36	1.62	0.16
2020	*BD*	(mg ha^{-1})	1.46	1.36	1.56	0.06	0.04
	SOC	(%)	0.82	0.63	1.01	0.11	0.13
	GWC	(%)	16.00	12.00	22.00	2.00	0.13
	KS	(mm/min)	8.7×10^{-5}	8.2×10^{-6}	3.6×10^{-4}	1.0×10^{-4}	1.16
	EW		7.44	0.00	20.00	6.21	0.83
	N_{TKN}	(mg kg^{-1})	26.11	6.49	53.41	14.37	0.55
	N_{TOT}	(%)	1.01	0.74	1.21	0.13	0.13
	pH		7.05	6.93	7.22	0.08	0.01
	Y	(mg ha^{-1})	10.04	9.28	11.09	0.55	0.05

Table 2. Parameters selected for the calculation of the sustainability index, which were measured during the experiment. Bulk density (BD), soil organic carbon (SOC), Gravimetric soil water content (GWC), total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), presence of earthworms ha^{-1} (EW), saturated hydraulic conductivity (Ks), pH, wheat yield (Y).

Year	Parameter	Units	Average Value	Minimum	Maximum	Standard deviation	Coefficient of variation
2022	*BD*	(mg ha^{-1})	1.42	1.286	1.614	0.0915	0.0645
	SOC	(%)	0.81	0.580	1.090	0.1294	0.1597
	GWC	(%)	15.50	11.852	17.976	1.7826	0.1150
	Ks	(mm/min)	0.88	0.240	2.110	0.6020	0.6843
	EW		6222	1600	17600	4066	0.6534
	N_{TKN}	(mg kg^{-1})	12.72	7.706	21.198	3.6421	0.2863
	N_{TOT}	(%)	0.11	0.092	0.138	0.0137	0.1212
	pH		7.92	7.770	8.060	0.0862	0.0109
	Y	(mg ha^{-1})	6.60	4.191	8.127	0.9634	0.1460
2023	*BD*	(mg ha^{-1})	1.419	1.286	1.614	0.092	0.065
	SOC	(%)	0.955	0.700	1.250	0.154	0.161
	GWC	(%)	14.301	9.779	18.091	2.137	0.149
	Ks	(mm/min)	0.381	0.091	1.807	0.450	1.180
	EW		9333	4800	19200	4600	0.493
	N_{TKN}	(mg kg^{-1})	1.865	1.443	2.177	0.242	0.130
	N_{TOT}	(%)	0.126	0.102	0.157	0.017	0.135
	pH		8.482	8.160	8.740	0.151	0.018
	Y	(mg ha^{-1})	7.923	5.410	9.380	1.062	0.134

The values presented in tables 1 and 2 were normalized. The average of each treatment combination is presented in Figure 4 where the measured parameters are observed. Due to this normalization, higher values are associated with improved parameters, and larger areas with an overall increase in sustainability.

Figure 4 shows how the three tillage systems were very homogeneous in 2018, the beginning of the CA. As the years the differences start to accentuate, and at the end of the 5 years (2023), a trend of differentiation between the systems is already observed; we observe a decrease in the score for CT and an increase for MT and NT (in terms of score, the larger the area, the better the yield).

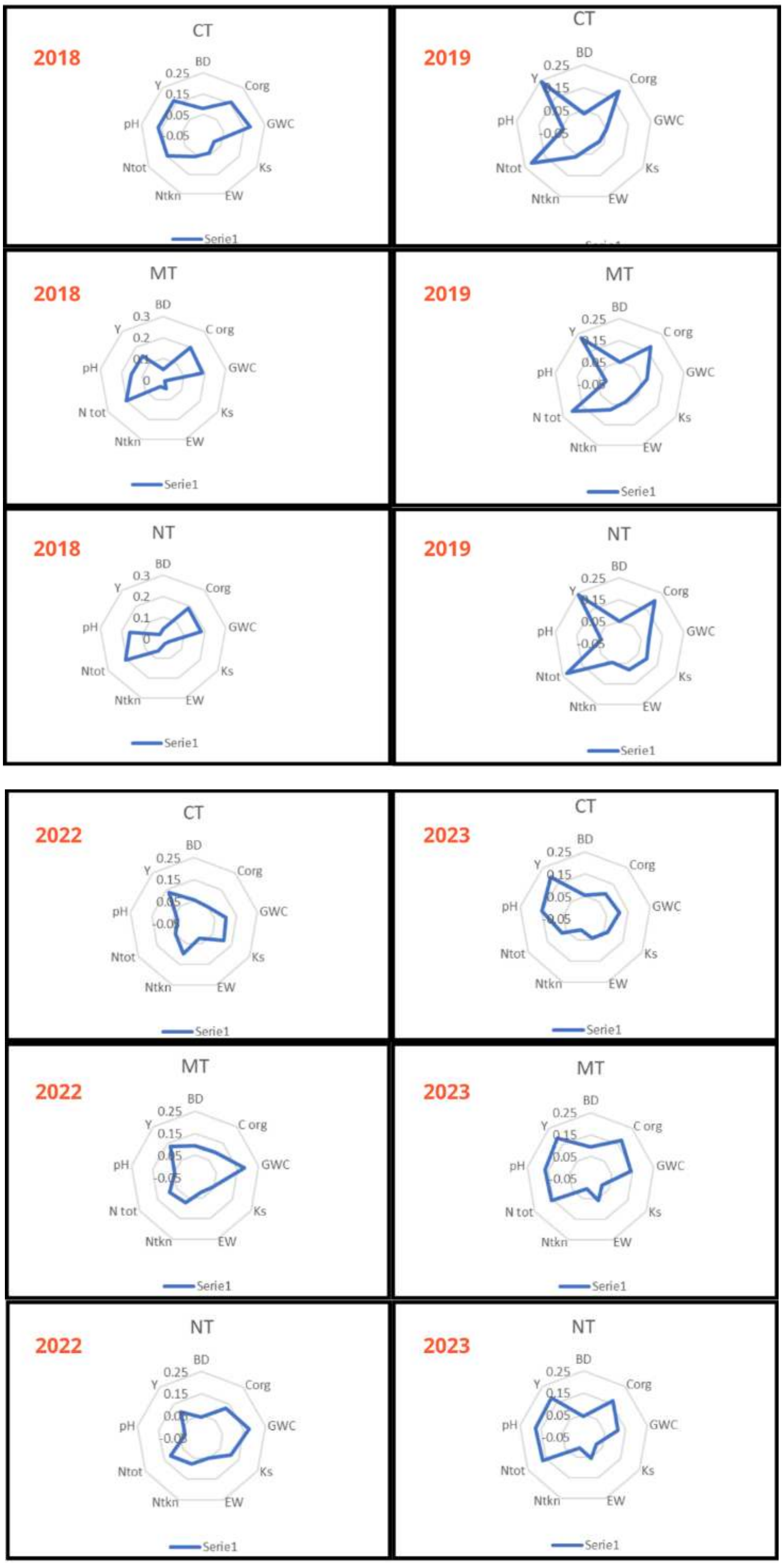

Figure 4. Physical, biological and chemical parameter scores, mean values in each treatment MT: Minimum tillage, NT: No tillage and CT: Conventional tillage, from 2018 (start of CA implementation) to 2023. Parameters: Bulk density (BD), soil organic carbon (SOC), Gravimetric

soil water content (GWC), total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), presence of earthworms (EW), saturated hydraulic conductivity (Ks), pH, wheat yield (Y). Larger area corresponds to a better performance.

The results of the PCA are shown in table 3. These data were applied to determine the parameter weights. Namely, the weight of the parameters was equivalent to the variance explained by the selected PC.

Table 3. Results of principal component analysis under different treatment combinations in different years. The factor loadings in bold are considered highly weighted, the factors in bold were included in the RSI calculation. Bulk density (BD), soil organic carbon (SOC), Gravimetric soil water content (GWC), total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), presence of earthworms (EW), saturated hydraulic conductivity (Ks), pH, wheat yield (Y).

VARIABLE SCORES	PC1	PC2	PC3	PC4	PC5
INDIVIDUAL	0.261	0.222	0.146	0.120	0.108
CUMULATIVE	0.261	0.483	0.629	0.749	0.857
WEIGHTS	PC1	PC2	PC3	PC4	PC5
BD	0.004	0.060	0.009	0.034	**0.094**
SOC	**0.149**	0.002	0.054	0.019	0.001
GWC	0.048	**0.108**	0.050	0.039	0.001
Ks	0.061	**0.076**	0.006	0.068	0.013
EW	0.044	0.003	0.057	**0.079**	0.025
N_{TKN}	0.076	0.069	**0.076**	0.005	0.017
N_{TOT}	**0.144**	0.023	0.059	0.014	0.007
pH	0.046	**0.131**	0.020	0.014	0.022
Y	**0.097**	0.077	0.054	0.015	0.034

Table 4. The loaded factor with values >|0.2| was selected and its correlation measured.

LOADINGS	PC1	PC2	PC3	PC4	PC5
BD	-0.016	-0.271	0.060	-0.280	**0.871**
SOC	**-0.570**	0.008	-0.367	-0.155	-0.009
GWC	0.183	**-0.488**	-0.340	-0.322	-0.007
KS	0.234	**0.344**	0.040	-0.563	-0.121
EW	-0.169	-0.014	0.392	**-0.657**	-0.232
N_{TKN}	0.290	0.309	**-0.518**	-0.038	0.155
N_{TOT}	**-0.552**	0.105	-0.406	-0.118	-0.067
PH	-0.176	**-0.588**	0.137	0.114	-0.205
Y	**-0.373**	0.344	0.373	0.127	0.318

In PC-1, the selected parameters were SOC, N_{TOT} and Y. Then, in PC-2 the highly weighted parameters were GWC, Ks, pH. Finally, in PC-3 N_{TKN}, in PC-4 EW and in PC-5 the BD were selected. The resulting RSI was expressed by equation (5):

$$RSI = \frac{0.261\ SOC + N\ tot\ 0.261 + 0.261\ Y + 0.222\ GWC + 0.222\ Ks + 0.222\ pH + 0.146\ Ntkn + 0.120\ EW + 0.108\ BD}{1.382} \quad (5)$$

The weighting factor for each parameter is equal to the explained variability of the selected PC for that specific factor, namely 0.261 for PC-1, 0.222 for PC-2, 0.146 for PC-3, 0.120 for PC-4 and 0.108 for PC-5. The sum of the weighted parameters was divided by 1.382, which was the highest sum of the weighted factor recorded among all observations (found in replicate 1 - NT1), so it was adopted to normalize the RSI.

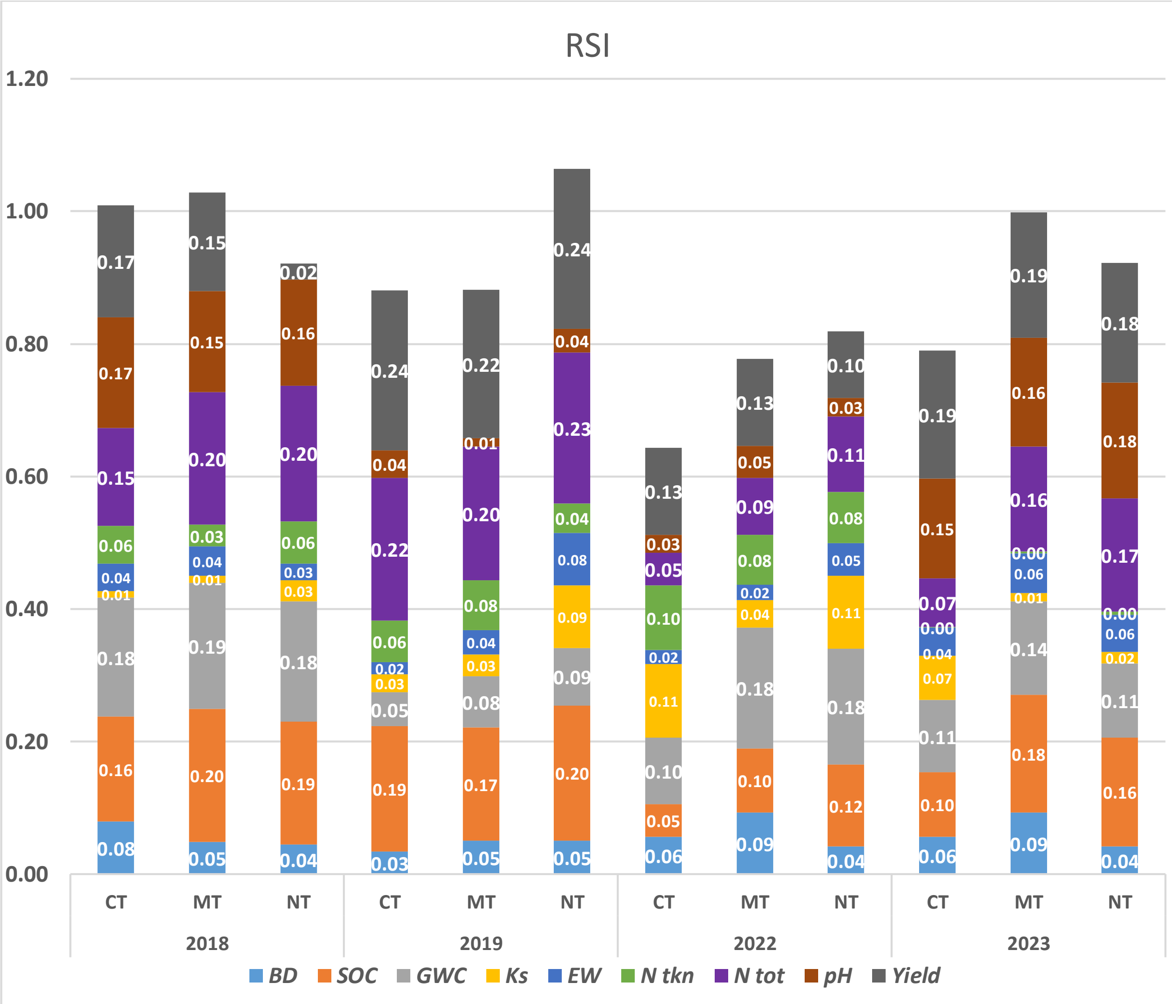

Figure 5. Mean contribution of RSI and parameters for different tillage in different years. Letters indicate significant effect according to Tukey's test ($p<0.05$). Bulk density (BD), soil carbon (SOC), Gravimetric soil water content (GWC), total nitrogen (N_{TOT}), total Kjeldahl nitrogen (N_{TKN}), presence of earthworms (EW), saturated hydraulic conductivity (Ks), pH, wheat yield (Y). MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

Figure 5 shows the average RSI for the different tillage systems, with the corresponding contribution of each of the 9 parameters. The parameters with the highest impact on the RSI are SOC, Yield and N_{TOT}.

At the beginning of the experiment (2018), the RSI values were similar for the three tillage systems. Over time, a differentiation between the CT and treatments with less soil disturbance has become evident, despite fluctuations due to year-specific climatic conditions that may affect the results. Conservation agriculture seems to have an impact on soil physics and chemistry, resulting in a significantly higher RSI value for NT and MT (Figure 6). These results were obtained in a short period of implementation of conservative agriculture (5 years).

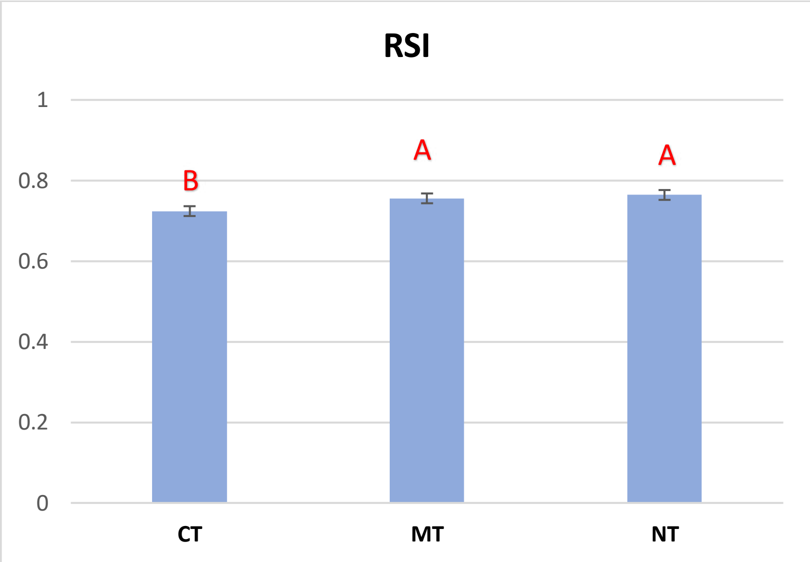

Figure 6. Mean RSI for MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

4. Discussion

The parameters that influenced the composition of the RSI were Y, N_{TOT} and SOC (18%, 17% and 16% respectively, on average), which together accounted for more than 50% of the average RSI. The climatic effects affected the absolute value of RSI, with a generalized decrease in 2022, characterized by drought conditions in spring and summer. Nevertheless, the differentiation between CT and conservation tillage treatments remained evident independently from the specific environmental conditions. This allows us to suppose that, considering the climatic changes that the world is facing, the reduced tillage systems respond positively to the measured parameters and can be proposed as an adaptation strategy to climatic changes. Aziz *et al.* (2013) calculated a soil quality index through biological, chemical and physical parameters against different sowing systems (conventional and conservation), and obtained, as a result, a higher soil quality index for conservation (NT); the parameters were similar to those of this study.

The soil where the experiment was conducted is characterized by structural inertia in response to management changes (Camarotto *et al.*, 2018; Piccoli *et al.*, 2016-2019).

Although BD values worsened under reduced tillage systems, the BD almost always remained below its threshold (1.55 g cm^{-3}) for which it is known to limit plant root growth in silty loam soils (USDA NRCS 1996). As far as soil fauna is concerned, earthworms have a low impact on the index analysis (4% on average). Despite this, the influence of earthworm activity can be relevant, in particular in NT systems. Earthworms can improve soil structure (Bertrand *et al.*, 2015) and hydraulic properties (van Schaik *et al.*, 2014) by burrowing and casting. A significant contribution made by earthworm bio-macropores to soil function and, in particular, air and water permeability, even in compacted soils can then be expected.

Both MT and NT led to an improvement of the RSI score, with similar weights of the different parameters considered. According to Issaka *et al.* (2019), both the minimum and no-tillage systems resulted in sustainable techniques, considering the nutrient cycles. As opposed to other studies (Camarotto *et al.*, 2018; Perego *et al.*, 2019; Piccoli *et al.*, 2019) clear negative effects during the transition time were not detected during this experiment

5. Conclusion

After 5 years of implementation of conservation agriculture (2018), multivariate analysis of sustainability indicators revealed a positive effect of reduced tillage management systems, confirming short-term observations on the winter wheat crop grown in 2022 and 2023. These systems seem to have a greater effect on the physical and nutritional quality of the soil and allow crop production to be maintained while improving the sustainability of the cropping system. Also for Italian conditions, reduced tillage systems can then be proposed as part of Regenerative Agriculture (Giller *et al.*, 2021; Schreefel *et al.*, 2020).

As for the RSI index, the adopted approach considered many different aspects related to the functioning of the farming systems compared, thus allowing for a holistic assessment of sustainability. This type of approach should, therefore, be preferred for comparing different farming systems, considering both the effects on crop production and soil physics, and soil functions at different scales.

The parameters that have had the greatest influence on the index are the nutritional parameters, which have shown a rapid and positive response in the short period of conversion to conservation without being influenced by the climatic conditions that affected the years of study, making it a stable and reliable parameter for the analysis of the sustainability of the system. Also the soil moisture content has been a parameter with a strong impact on the analysis which is of great importance if we take into account, again, the climatic factors that prevailed during the study, as there is a tendency of intensification of droughts in the north of Italy in the next years (Baronetti *et al.*, 2024, 2022). We must bear in mind that the main consequence of droughts in Italy has been the lack of precipitation and not the increase in temperature (Baronetti *et al.,* 2024), so we must, from now on, cultivate with a view to using and retaining water in the soil profile during the soil cycle, and in this mission, conservation agriculture is proving to be a strategic option.

As far as the physical and biological parts are concerned, we must extend the study period and see how it proceeds over time and how the nutritional input, especially in terms of organic carbon, can positively influence these parameters.

We can conclude that a holistic analysis allows us to see how the different actors involved in agricultural production influence a system's sustainability index – an approach proposed by Vogel *et al*. (2022).

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Chapter 4: Conservation Agriculture: the evolution of the Soil Organic Carbon (SOC) and perspective of carbon sequestration

1. Introduction

Conservation agriculture (AC) encompasses no or reduced tillage, cover crops, and residue retention on the soil surface. It represents a more sustainable management approach compared to conventional tillage systems. The many benefits associated with ease of crop management, energy/cost/time savings, and water and soil conservation have led to the widespread adoption of CA, especially on large farms (Giller *et al*., 2015). The practice is widespread in South America, the USA, and Australia but not Europe, where it is still developing (Piccoli *et al*., 2019).

The implications of reduced tillage management on soil organic carbon (SOC) dynamics, soil fertility and crop yields are the subject of much debate. It is important to know and understand the changes in soil physico-chemical properties following the adoption of conservation agriculture (Blanco-Canqui and Ruis, 2018). In general, conventional tillage operations such as ploughing and seedbed preparation lead to high rates of oxidation of soil organic matter (Al-Kaisi and Yin, 2005). For many soil functions, SOC plays a fundamental role. Monitoring their spatial and temporal changes is important in order to plan strategies to help minimize soil degradation and maintain or improve soil quality (Petito *et al*., 2024).

Reduced tillage practices and, in particular, no-tillage are considered to be the least invasive technique of conservation agriculture. They have also proven to increase soil carbon stocks (Giller *et al*., 2015; Luo *et al*., 2010; Pacala and Socolow, 2004; Puget and Lal, 2005; Senthilkumar *et al*., 2009). In a meta-analysis by Angers and Eriksen-Hamel, (2008), the SOC content was higher in no-till than in conventional tillage in the topsoil layers (up to 23 cm).

Perego *et al*. (2019) noted that already in the medium term SOC stocks were higher in CA. Data from Puget and Lal,. (2005) showed that SOC had higher values in NT compared to ploughing and chiselling the first 5 cm of soil. SOC oxidation rates were substantially lower in NT compared to conventional systems (Pezzuolo *et al.,* 2017). The same applies to nitrogen: Parihar *et al*. (2018) have observed increased AC of mineral N fractions (15-36% NO_3, 16-35% NH_4, 0-30 cm depth) in a 5-year trial.

Conservation Agriculture (CA) as a pathway to sustainable intensification is strongly supported worldwide. Giller *et al.* (2015) through a meta-analysis observed a pragmatic adoption of CA on large-mechanised farms and limited adoption by smallholder farmers in developing countries in particular. It has been observed that SOC sequestration rates and co-benefits vary depending on local pedoclimatic and management conditions (Francaviglia *et al.*, 2023). Soil carbon sequestration has recently become a topic of increasing interest due to its potential to mitigate or offset some of the negative effects of the increase of greenhouse gases in the atmosphere (Omara *et al.*, 2019).

There is an urgent need to move beyond dogma and prescriptive approaches to provide farmers with soil and crop management options that enable the sustainable intensification of agriculture (Giller *et al.*, 2015). The success or failure of adopting any CA practice will largely depend on the socio-economic and environmental context (Francaviglia *et al.*, 2023).

Due to these weaknesses still facing conservation agriculture and affecting farmers' adoption, we proposed a 3-year study in the Po valley, Northern Italy, where CA was implemented for the first time in 2018 in this experimental field. In this trial, the physical, chemical and biological effects on the soil of this production system were evaluated, comparing 3 tillage practices: MT - minimum tillage, NT - no tillage and CT - conventional tillage. We monitored the evolution of soil organic carbon (SOC) and nitrogen in the first 20 cm of soil depth.

2. Materials and methods

The experiment took place at the Lucio Toniolo Experimental Farm, located in Legnaro, PD (NE Italy, 45° 21 N; 11° 58 E; 6 m a.s.l.), where the climate is sub-humid, with temperatures between -1.5 °C on average in January and 27.2 °C on average in July. Rainfalls reach 850 mm annually, with a reference evapotranspiration of 945 mm that exceeds rainfalls from April to September. The highest rainfalls occur in June (100 mm) and in October (90 mm), while winter is the driest season with average rainfalls of 55 mm. The shallow water table ranges from 0.5 to 2 m in depth, with the lowest values recorded in summer.

The trial started in the autumn of 2021, with an area of 2 ha, divided into two replicates (1 ha each) and within each replicate was subdivided into 3 strips of 13 m x 260 m (Figure 1). The soil at the site is Fluvi-Calcaric Cambisol (FAO-UNESCO 2008) with a silt loam texture. The treatments within the plot were three: the conventional tillage plot (CT) was ploughed to a depth of 30 cm and harrowed to 15 cm; the minimum tillage plot (MT) was harrowed to a depth of 15 cm; and the no-tillage plot (NT) was sown on the residues of previous harvests.

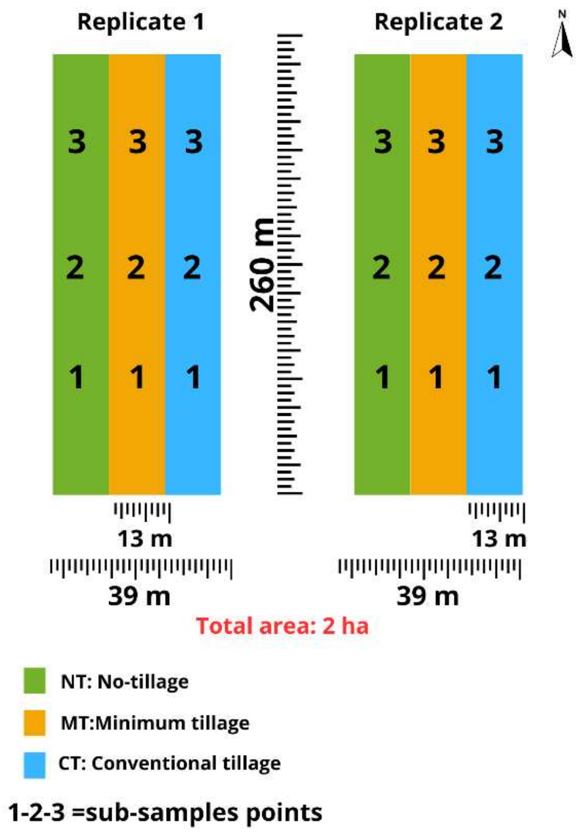

Figure 1. Experimental design.

The first application of the MT and NT tillage systems was in 2018 in the framework of another PhD thesis (Sartori *et al.*, 2021a). In the first three years of experimentation, the crops sown were maize (2018, 2019 and 2020) and soybean (2021), followed by winter wheat (*Triticum aestivum* L.), sown twice (2021/2022 and 2022/2023), and managed conventionally. After all the spring-summer crops, three different types of winter cover crops were used: bare soil (with free natural vegetation), winter wheat cover crop or tillage radish cover crop.

2.1. Field survey

All the measurements in SOC made on the experiment are considered here. The data for the beginning of the experiment (March 2019) and after the first year of experiments (October 2020) are those reported by Sartori *et al.* (2021). The subsequent measurements, taken in July 2022 and July 2023 after the wheat harvest, have been collected during the present PhD period (Figure 2).

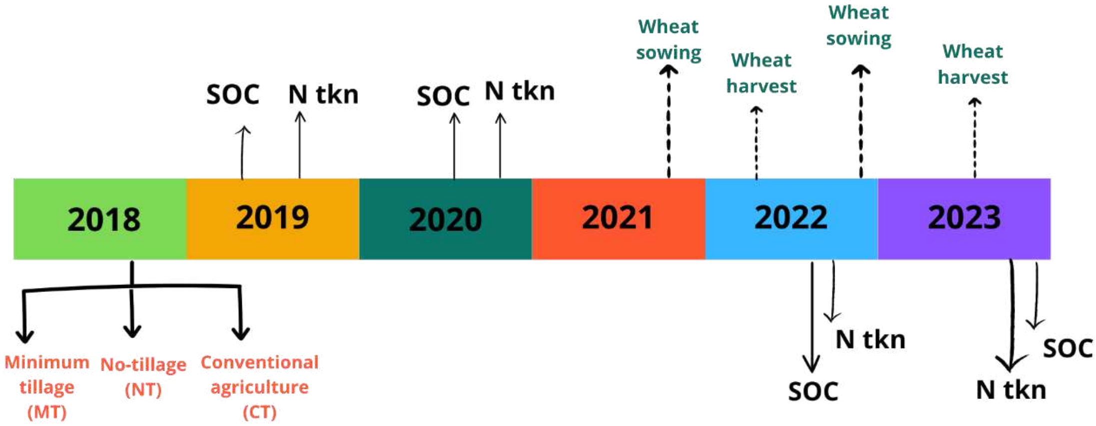

Figure 2. Timeline since the implementation of conservative agriculture, detailing sowing practices for the years analysed, chemical parameters measured in the field: soil organic carbon (SOC), total Kjeldahl nitrogen (N_{TKN}).

Total Kjeldahl Nitrogen (N_{TKN}) and soil organic carbon (SOC) were analysed in the arable layer of the soil (0-20 cm). At each point, 3 sub-samples were taken and mixed to obtain a single homogeneous sample per point; the total number of samples was 18 (2 replicates x 3 management x 3 points in each management = 18 points). The methods used for the analysis of these nutrients are described in the D.M. 1999, "Official methods of soil chemical analysis".

The SOC concentrations were transformed in SOC stock values considering the Mass Equivalent approach (Wendt and Hauser, 2013). Considering the sample with the lower BD, an equivalent soil mass of 2267 Mg ha^{-1} was considered, and the average depth of the equivalent soil mass layer was 16.0±0.17 cm.

2.2. Statistical analysis

Soil tillage effects and their interaction were analysed using mixed effects models. Tillage and year were considered fixed effects in all statistical analyses performed; replicates were considered a random effect and repeated measures within each treatment were considered nested. Hypothesis testing was performed. Post hoc pairwise least squares mean comparisons were performed using Tukey's method to adjust for multiple comparisons, where means were compared using the least significance difference test at $P < 0.05$.

3. Results

The average N_{TKN} stock, despite some fluctuation in the different years, has not had significant variations across the soil tillage treatments implemented (Figure 3). This contrasts with what has been reported in Tabaglio *et al.* (2009) where nitrogen had increased in the no-till systems already in the short implementation period. At the same time, the C/N ratio remained constant, thus indicating a regular evolution of organic substances, independently from the type of tillage.

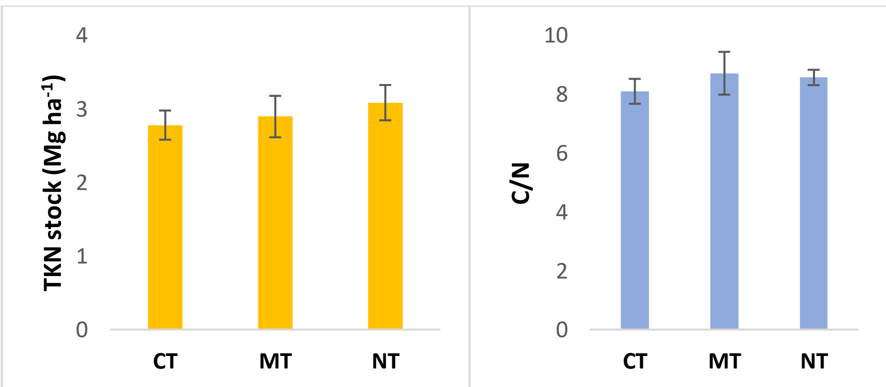

Figure 3. Average N_{TKN} (Mg ha^{-1}) and C/N ratio, in the different management systems. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

On the other hand, as reported in Chapter 2, the SOC increased in conservation tillage systems (MT and NT). Analyzing the evolution from the beginning of the experiment, an increase in SOC was observed in all tillage managements (Figure 4).

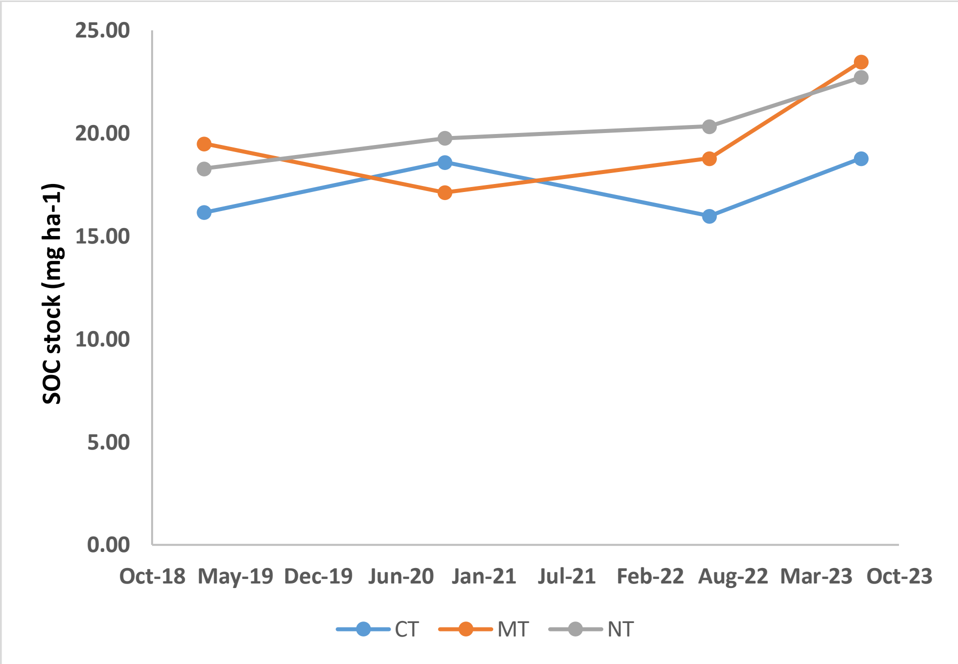

Figure 4. Evolution of Soil Organic Carbon (SOC) stock. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

The ANOVA showed a significant effect of both 'Year' and 'Tillage' factors ($p= 0.031$ and $p=0.034$ respectively), with an increase of the SOC stock in years and a higher C content in NT (tab. 1).

From the observed SOC stocks, the potential sequestration rate of the conservation tillage systems was evaluated, assuming as a base line the CT treatment.

Potential sequestration was then obtained by considering the SOC stock difference between the last (T_1) and the first (T_0) sampling for each treatment.

$$\Delta SOC_i = SOC_{i;T1} - SOC_{i;T0}$$

Where *i* refers to the specific tillage treatment considered.

The sequestration rate for MT and NT treatments was then obtained as:

$$Seq_i = \frac{\Delta SOC_i - \Delta SOC_{ref}}{T}$$

Where ΔSOC_i are the variation of SOC stock with MT or NT, ΔSOC_i is the variation of SOC stock in the reference treatment (CT) and T is the time span in years from T_0 and T_1.

The two conservation tillage practices showed an appreciable potential for C sequestration. In MT the estimated value is of 0.31 Mg ha^{-1} year $^{-1}$ while in NT it is higher, reaching 0.41 Mg ha^{-1} year $^{-1}$.

These values are in accordance with other Authors, reporting for Mediterranean conditions C sequestration rates in NT ranging from 0.29 to 0.72 Mg C ha^{-1} $year^{-1}$ (Aguilera *et al.*, 2013; De Sanctis *et al.*, 2012; Gonzalez-Sanchez *et al.*, 2012; Mazzoncini *et al.*, 2016; Morari *et al.*, 2006) and for MT 0.054 to 0.135 Mg C ha^{-1} $year^{-1}$ (Haddaway *et al.*, 2017). Our data are also in agreement with the meta-analysis carried out by Freibauer *et al.* (2004) at the European scale.

Table 1. Variation of the SOC stock (Mg ha^{-1}) on time. MT: Minimum tillage, NT: No tillage and CT: Conventional tillage.

		Tillage			
Sampling	**CT**	**MT**	**NT**	**Mean**	
March 2019	16.16	19.49	18.29	17.98	**b**
October 2020	18.60	17.12	19.77	18.49	**ab**
July 2022	15.98	18.78	20.33	18.36	**ab**
July 2023	18.78	23.46	22.71	21.65	**ab**
Mean	17.38	19.71	20.27	19.12	
	b	**ab**	**a**		
ΔSOC (Mg ha^{-1})	2.62	3.97	4.42		
Seq (Mg ha^{-1} $year^{-1}$)	0.00	0.31	0.41		

4. Discussion

Since the introduction of conservation tillage in 2018, in terms of soil nutritional parameters, nitrogen has shown an increase since the beginning of the trial, with values of 2.36 Mg ha-1 (2019) and 3.57 Mg ha-1 (2023) for CT, 2.24 Mg ha-1 (2019) and 3.86 Mg ha-1 for MT and 2.37 Mg ha-1 (2019) and 4.03 Mg ha-1 (2023) for NT; beyond the increase, no significant differences were observed between tillage. In terms of SOC content, it showed a relevant evolution in less than 5 years of implementation of conservation tillage. It should be noted that starting in 2018, the crop succession was three years of maize (2018, 2019, 2020), then soybean (2021), followed by two years of winter wheat (2022 and 2023). In the first years of experimentation, after the spring-summer crops, winter cover crops were sown in the three treatments (Sartori *et al.*, 2021a), thus increasing the overall SOC input. This probably allowed an increase in the surface SOC stock also in conventional tillage. In any case, both conservation tillage practices allowed a greater increase in SOC compared to the conventional practice. Considering the differential increase over the baseline (CT), NT proved to be more effective in C sequestration, and this is in agreement with the results from Varvel and Wilhelm, (2011) and Halvorson *et al*. (2002). Mrabet (2006) in a compilation of data, observed that the use of reduced tillage systems significantly improved carbon and nitrogen sequestration in surface soils, both in tropical and temperate soils. CO_2 emissions from agriculture are reduced by the carbon sequestration observed in no-tillage systems (Nicoloso and Rice, 2021).

It should be noted that this calculation only takes into account the surface layer (0-20 cm); reduction or elimination of soil tillage may reduce the input of organic materials in the deeper layers. A proper assessment of the sequestration rate should then also consider the SOC dynamics along the whole profile. On the other hand, the SOC stock in the upper layer is more effective from an agronomic point of view, and a possible SOC enrichment in the first 20 cm may have positive effects on both C sequestration and crop productivity.

These results are important not only in their chemical effect on the soil through the increase in nutrients but also from an economic point of view. The need for nitrogen fertilizer application is reduced, as the crop finds greater availability in the soil and for the soil fauna, which will consequently bring about improvements in the physical-biological parameters of the soil system.

In 2021, the COP21 proposed the “4 per 1000” initiative to combat climate change, intensify and adapt agriculture to climate change and improve food security. The initiative aims at 4‰ annual carbon sequestration by the soil (Minasny *et al*., 2017). From the results obtained in this research, we can affirm that this soil under study, through the practice of conservation agriculture, allows to exceed the objective of the initiative since the values exceed 15‰ per year for MT and 20‰ for NT of carbon sequestration; similar results were obtained in Dal Ferro *et al*. (2020) where the practice of MT in combination with the use of organic inputs achieved the objective of the initiative along the entire soil profile (90 cm depth).

5. Conclusion

The monitoring carried out from 2018 to 2023, in terms of the implementation of conservation agriculture, on this experimental field allowed not only to compare the different management approaches of the cropping systems but also to evaluate the short and medium-term evolution of the availability of nitrogen and organic carbon in the soil. After 5 years of application in this experimental field, conservation agriculture has shown in a short time a positive effect on soil fertility, specifically on the nutritional aspect with a significant increase in SOC in the 20 cm soil depth sampled for subsequent laboratory analysis. This shows that the application of conservation agriculture in the Po valley is feasible and allows it to meet environmental goals such as the 4 per mille initiative, which aims to mitigate CO_2 emissions.

By developing the technical skills necessary for conservation agriculture, it is possible to bridge the gap between conservation and conventional systems in the early period. Pradhan *et al*. (2018) suggests the institutionalization of CA at the regional level to improve the sustainability approach of the technology required for producers and thus accompany producers in the adoption of this production technique.

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Chapter 5: General Conclusions

Many studies on the adoption of CA refer to the relevance and duration of the transition period, reporting negative effects both on the soil and on the yield and quality of the crop under study in the short and medium term (5-10 years). However, in the first part of this doctoral project, it was ascertained that 5 years after the introduction of CA, the soil benefits positively from the effects on physical and nutritional characteristics, reflected in unit yields which are not statistically different from CT. The results achieved allow us to affirm the value of the conservation management system, which is economically competitive also due to the importance of the crop under study for the country and in particular in the area under study. At the same time, the adaptability of these conservation practices to climate change is underlined, as in two completely different years for temperature and rainfall regimes – 2022 with high temperatures and low precipitation, and 2023 with temperature and precipitation trends within historical values. These practices prove to be competitive and respond positively to such situations.

There are still parameters, especially physical and biological, that have not shown any difference or improvement under reduced tillage, especially in terms of soil infiltration, which had a high variability throughout the study, showing that these factors still require time to demonstrate how they are affected by tillage systems. It should be noted that no negative effects on these parameters were observed for the reduced tillage systems.

The same happens with soil biology; there is a tendency for a higher presence of earthworms in reduced tillage systems, but it is still necessary to monitor this parameter and infiltration to see its evolution and behaviour over time.

These results are important in the current political, economic and climatic context, in which an economically competitive production practice is necessary, but at the same time capable of respecting, improving and preserving the environment, and consequently the soil, in order to maintain/increase its capacity to produce the food needed for the growing world population. A clear example of this is the carbon sequestration potential of the soil, which exceeded the expectations proposed by the "4 per 1000" initiative launched during COP21 (Minasny *et al.*, 2017), which is part of a global agreement to mitigate carbon emissions and which in turn can contribute to the "Green Deal" goal of making Europe the first climate neutral continent by 2050 through integrated actions based on healthier agricultural systems based on sustainable (environmental and economic) practices, including soil carbon management and biodiversity enhancement (Simoniello *et al*., 2022), and contribute to Article 3.4 of the 1997 Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) which recognizes the role of SOC in reducing atmospheric CO_2 concentrations.

As we can see, farmers face many challenges in the search for a yield capable of meeting the needs, especially economic ones, of the farm, and conservation agriculture proves to be an effective practice in the face of these challenges. Despite these positive results from CA, the adoption rate of conservation agriculture in Italy remains low (only 4% of the area has adopted CA (ECAF, 2020). Pagliacci *et al*. (2020) in a study conducted in the Veneto region (Northern Italy), the same area where this PhD project was carried out, observed that the financial factor has not been an impediment to the adoption of climate-smart agriculture (CSA) practices, including no-tillage, by local farmers; but that non-financial factors, often overlooked by policy-makers (such as the provision of information and advice to farmers), act as important barriers, especially in the Veneto region, as well as across southern Europe, where a large share of farms are managed on a part-time basis, which may result in a lack of knowledge on the part of farmers to adopt CSA practices.

It is also worth highlighting the importance of long-term studies in specific sites, which allow us to generate knowledge that can be made available to producers – studies that have allowed our PhD project to affirm that the implementation of CA has been a strategy that has benefited the production system. This study has shown that this production system can be adopted in the area under study in this type of soil with proper management. This has been reinforced through the relative sustainability index that allowed us to evaluate the system as a whole over time and involve each variable under study, which allows us to present CA as a sustainable and competitive production alternative, in addition to the positive economic effects (less fuel use) and consequently, also the positive effect on the environment.

We suggest to continue the research, as there are many important parameters in a production system that have not yet expressed their potential or allowed to explain the effect of conservation agriculture in the Padana plain and to continue monitoring the positive results obtained in this study period and to attach others that can give an even broader view of this production practice and its behavior in the study area.

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Acknowledgements

To Professor Michele Pisante and Professor Antonio Berti, for guiding me, for patiently training me not only professionally, but also as a human being. Thank you for believing in me and giving me this opportunity to grow.

I would like to thank my family, my parents Sergio and Adriana and my sisters Lorena and Virginia, who have been able to accompany me from a distance, and not just a short distance, and to hug me in every difficulty and joy.

To my friends in Argentina, who have never forgotten me, and continue to be "at the foot of the cannon" supporting me in every path I take in this life, especially Lara, Pini, Chris, Jenni, Fer, Nati and Vero.

To every worker in the experimental farm “Lucio Toniolo” at Legnaro, for working side by side with me in the field and patiently teaching me.

To my colleagues in the office, for making the working hours pleasant and entertaining, for helping and encouraging me whenever I needed it.

To Marta, Justin, Veronica and Fabio for being supportive and there for me at all times.

To Alessandra, Elena, Caterina and Bianca, God put them on my path here in Italy and that made everything easier, thank you friends.

To Fra Nico, friend, brother in faith, thank you not only for keeping me close to God, but also for making me a better person every day and above all for believing in me in the way you do.

To the friends I have made during my time in Italy.

Finally, but most importantly, thanks to God, for the gift of life and for every blessing he has given me, for every person he has put in my path, and for bringing me to Italy to meet the Figures of St. Francis of Assisi and St. Anthony of Padua, two saints who light my way.