HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

DOCTORAL (PHD) DISSERTATION

Impacts of soil tillage on soil physical properties, crop yield and quality: Insights from a long-term experiment in Endocalcic Chernozem soil

A dissertation submitted in Partial fulfilment of the requirements

for the degree of Doctor of Philosophy

at Doctoral School of Plant Sciences,
Hungarian University of Agriculture and Life Sciences

By

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Gödöllő, Hungary

2026

The PhD School

Title: Impacts of soil tillage on soil physical properties, crop yield and quality: Insights from a long-term experiment in Endo calcic Chernozem soil

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DECLARATION

I, Maimela Maxwell Modiba formally declare that this dissertation is my original work and has not been presented for a degree in any other university. No part of this dissertation may be reproduced without prior permission of the author and/or Hungarian University of Agriculture and Life Sciences.

____________________________________ Date________________________________

DECLARATION BY SUPERVISOR

This dissertation has been submitted with the approval as supervisor.

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Dedication

I dedicate this dissertation to my late mother whose teaching, sacrifices, and unwavering support and encouragement growing up has made me the person I am. To my brother and sister who has provided me with shoulder to learn when things get tough has powered me throughout this PhD journey.

To my supervisors, Dr. Barbara Simon, the late Professor Marta Birkás, and Dr. Igor Dekemati, your guidance, teaching and encouragement have shaped my academic knowledge. I will forever be grateful for your mentorship

To Dr. Caleb Melenya Ocansey, who always helped when I needed guidance. You are hall of fame in my book.

I dedicate this dissertation to the whole administration staff of the Hungarian University of Agriculture and Life Sciences for the help and making Hungary a home for me from the moment I arrived at the University till date.

To all the professors and lab technicians at the Hungarian University of Agriculture and Life Sciences thank you for your unwavering support and assistance this work would have been possible without you.

I dedicate this dissertation to the Department of Higher Education and Tempus Foundation for granting me the opportunity to further my studies in Hungary. The knowledge I have acquired has made me aware of things that I was unfamiliar with.

Table of Contents

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisors, Dr. Simon, Dr. Dekemati, and Professor Birkás, for their invaluable guidance, mentorship, and supervision throughout the course of my research. My sincere appreciation also goes to Dr. Caleb Melenya Ocansey for his constant support and willingness to assist me with my PhD work whenever I needed help. I am grateful to Ildikó Gergely, in the Soil Science Laboratory, for her technical assistance and continuous support during my experiments. I would also like to thank my fellow research student Dr. Hanaa Tharwat Mohamed Ibrahim for her kind help and collaboration during field data collection and laboratory analyses.

List of Tables

List of Figures

List of abbreviations and acronyms

%: Percent

°C: Degrees Celsius

BD: bulk density

CA: Conservation agriculture

CT: Conventional soil tillage

D: Disking

DC: Deep cultivation

DT: Deep soil tillage

FT: Freeze-thaw

m/m%: mass per mass percentage

GLMM: Generalized linear mixed models

JM: Józsefmajor Experimental and Training Farm

K: Potassium

Ksat: Saturated Hydraulic conductivity

L: Loosening

LCD: Liquid Crystal Display

m: Meter

Mg m^{-3}: megagrams per cubic meter

mm: Millimeter

MP: Moldboard plough

MPa: Mega Pascal

MT: Minimum soil tillage

NT: No-till

NUE: Nutrient use efficiency

MP: Moldboard Ploughing

RW: Root weight

SC: Shallow cultivation

SD: Standard deviation

SMC: Soil moisture content

SOC: Soil organic carbon

SOM: Soil organic matter

SPR: Soil penetration resistance

ST: Shallow soil tillage

t ha^{-1}: Ton per hectare

TDR: Time domain reflectometry

TN: Total nitrogen

ZT: Zero soil tillage

1. GENERAL INTRODUCTION

1.1. Background

Since the human discovery of soil tillage post hunter and gathering era, it remained a pivotal aspect of land preparation influencing numerous soil properties and crop productivity. Recent developments in scientific studies are focusing on intricate relationships between soil physical properties, crop yield, and soil tillage practices.

Soil penetration resistance (SPR) is a physical characteristic of soil that reflects the combined effects of various soil properties, including bulk density (BD), soil moisture content (SMC), porosity, and permeability. These properties are influenced by the distribution of particle sizes, soil structure, and the presence of mineral and organic matter (Soane et al., 1980). Soil penetration resistance serves as a key indicator of soil compaction (Mohieddinne et al., 2019). Compacted soil increases resistance to root growth (Correa et al., 2019; Unger and Kaspar, 1994), hinders soil fauna movement (Dekemati et al., 2019b, 2021; Plum, 2005), diminishes porosity (thereby slowing water and air movement), and reduces nutrient mineralization rates (De Neve and Hofman, 2000). Furthermore, it promotes surface runoff over infiltration, which can be critical for soil moisture retention during dry periods.

In anthropogenic soils, compaction often results from technological processes (Zadorozhnaya et al., 2018; Zhukov and Zadorozhna, 2016), such as the use of soil preparation machinery. Soil tillage operations can significantly modify soil structure, potentially affecting SPR and, as a result, plant growth. However, soil tillage can preserve, enhance or degrade soil health (Birkás et al., 2015; Madari et al., 2005). Frequent ploughing of the soil to the same depth and outside the recommended moisture range can induce plough pan (Eliasson, 2005; Gerasimov and Katarov, 2010; Han et al., 2009; Sakai et al., 2008; Salokhe and Ninh, 1993). Contrastingly, conservation soil tillage (CA) is characterized by its holistic approach to enhance and preserve soil health by reducing soil disturbance and retention of crop residues, consequently improving crop yield (Busari et al., 2015; Sanaullah et al., 2020).

Similarly, SMC is crucial for crop development and is affected by soil tillage practices through alterations in soil porosity (Blanco-Canqui and Ruis, 2018; Mehra et al., 2020), water retention capacity (Mwiti et al., 2022), and evaporation rates (Strudley et al., 2008; Unger and Cassel, 1991). The quantity of moisture is crucial in crop production in sense that excessive moisture cripples' gaseous diffusion in the soil leading to anaerobic conditions for crop roots, while deficient induces crop drought stress. The latter phenomena contribute negatively to crop output.

The climate in Hungary is characterized by a humid subtype of the continental climate, featuring extended warm periods and notable temperature variations throughout the year (Mezősi, 2017). Hungary predominantly experiences a warm temperate climate (Cfa), characterized by extremely hot and dry summers. (Kertész and Mika, 1999). And the different soil types present an interesting area for investigating the effects of soil tillage on soil properties and crop productivity. The study area located near the town of Hatvan, is in an agriculturally important region characterized by its fertile soils (Chernozem) and production of different crops.

The topic of soil tillage effects on soil physical properties has been extensively studied globally (Moraes et al., 2014; Nunes et al., 2015). From these (Bogunovic et al., 2015; Dekemati et al., 2021, 2019b, 2019a; Jug et al., 2024) different studies a myriad of response has been observed to have been influenced by specific location factors such as climate, soil type and type of soil tillage equipment utilized. To develop sustainable agricultural management strategies in Hungary, it is crucial to examine how soil tillage methods, SPR, SMC, and crop productivity interact with one another in this specific region.

1.2. Problem statement

Soil compaction is one of the growing concerns in field crop production, which is heightened by aggressive soil tillage methods. It occurs due to several reasons, such as increased machinery traffic, particularly outside suitable soil moisture conditions (wet periods). Secondly, the type and method of soil tillage equipment employed, i.e. repeated ploughing / disking of the soil to the same depth results in the formation of a plough or disk pan. If the resultant pan formation is not addressed, several soil processes are affected due to the intricate relationship of soil properties. For example, soil compaction results in a decrease in soil porosity, which plays a vital role in soil hydrological processes (Horn and Smucker, 2005; Kuncoro et al., 2014). A decline in soil porosity affects soil gaseous exchange consequently affecting plant root proliferation (Kim et al., 2010).

Evidently, there is no doubt that soil tillage practices in agriculture, particularly crop production, play a pivotal role. However, there is a lack of localized information on how these practices shape the soil physical properties and their interplay with other factors, such as climate and crop productivity at regional level in Hungary. This shortfall of knowledge acts as a barrier that prevents successful localized strategies to augment soil health, climate resiliency, and sustainable crop production under changing environmental conditions. The complex interplay, consisting of SPR, SMC, and crop growth and yield dynamics, underscores a need for detailed investigation to classify effective soil tillage practices, building healthy climate resilient soils and enhancing crop yield. Furthermore, knowledgeable way forward in crop production is limited by the lack of substantial approach that combines the effects of soil tillage, weather, and soil properties on crop productivity make informed decisions. This limitation is specifically vital to local areas in Hungary due to its terrestrial diversity and different climatic conditions, which require specific location approaches to land selection.

The current study aims to tackle these challenges by conducting a complex analysis of soil tillage practices in JM Experimental Farm near Hatvan in Hungary, with the objective of providing practical recommendations for sustainable agricultural practices that promotes soil conservation without negatively affecting crop productivity. This research seeks to integrate soil physical properties, weather patterns, and crop yield data under various soil tillage practices, to develop an extensive understanding of the complex relationships regulating agricultural outcomes in Hungarian regional level.

The results of this research will provide insights into the scientific environment, policy-makers, farmers, and extension officers. The purpose of this research is to determine the best soil tillage methods for the Endocalcic Chernozem soil and climatic conditions, to improve agricultural decision-making processes that enforce resiliency of sustainable agriculture at regional level in Hungary.

1.3. Justification of the study

Various authors have highlighted that effectively managing soil in a sustainable manner can result in heightened resilience to severe weather events, at least in the near future (Glaser et al., 2013; Jentsch et al., 2011; Schmitt et al., 2010; Schmitt and Glaser, 2011a, 2011b). Effective sustainable soil management primarily begins with the selection of soil tillage methods deemed holistic to the environment. For that reason, this underscores familiarity of the relationship between soil tillage and soil physical properties, such as SPR, SMC, and crop yield and yield components. By studying the effects of soil tillage practices on SPR, SMC, root weight (RW), grain yield and yield quality parameters, the study will provide insights to farmers, policymakers and crop advisors for the best agricultural practices that can be implemented to enhance soil climate resiliency.

1.4. Study objectives

1.4.1. General objective

To investigate the influence of soil tillage practices on soil physical properties and sustainable crop yield in Hungary using a multidimensional analysis comprising meteorological and soil-specific variables.

- **Objective 1**: Investigate the impact of soil tillage practices on soil physical properties.
- **Objective 2**: Assess soil tillage effects on crop yield.
- **Objective 3**: Explore the combined effects of weather, soil tillage, soil physical properties, and crop yield.
- **Objective 4**: Identify soil tillage methods for soil health and water dynamics.
- **Objective 5**: Determine soil tillage methods enhancing overall crop productivity.

1. LITERATURE REVIEW

Literature review chapter discusses different soil tillage practices in agriculture. It presents the understanding of relationships between various soil tillage methods on soil physical properties, health, quality and crop yield. It starts by explaining soil tillage principles categorically (conservation and conventional soil tillage methods) and their importance in agriculture. It conceptualizes conservation soil tillage (CA) and concisely reviews the effect of soil tillage on soil physical properties and crop yield. Furthermore, it succinctly explains the combined effects of weather, soil tillage, and soil properties on crop yield. It highlights the implications of CA on sustainable crop production. It ends by providing a summary and conclusion of the latter mentioned subtopics of the literature review.

2.1. Conventional soil tillage

Conventional soil tillage method involves the utilization of mechanical devices, such as mouldboard ploughs, chisel ploughs, disks, harrows, and rollers, to disrupt and invert the soil. This approach results in significant soil fragmentation and the removal of crop residues. It has been linked to a range of negative consequences, including soil erosion, a reduction in organic matter content (Fernández et al., 2017; Lal et al., 2007; Zhao et al., 2022), increased compaction (Dekemati et al., 2021; Nebo et al., 2020), soil crusting (Al-Shammary et al., 2023), and increased soil moisture loss (Dekemati et al., 2019b, 2019a; Karlen et al., 1994). Conventional soil tillage comprises of implements that are aggressive to the soil state, such as ploughs. A plough, particularly a mouldboard plough (MP), is an implement used to cut and invert the soil, while reducing the soil cover (Dekemati et al., 2019b; Zeng et al., 2020) and enhancing SOM oxidation in the process (Lal et al., 2007). Moreover, this process is also known to be detrimental to beneficial soil fauna by directly injuring or killing them (Johnston et al., 2015) or by manipulating conducive conditions for their survival (Dekemati et al., 2019b).

Ploughs come in different forms or shapes, and they are also manufactured for varied purposes. For instance, the latter mentioned MP is generally used to cut and invert the topsoil together with previous residues and weeds. Moreover, it facilitates deeper application of fertilizers in the soil. Due to its working depth of approximately 35 cm, MP can be significant to break any existing compaction within the 0-30 cm depth.

According to Finch et al. (2014) “chisel ploughing is a term used to describe the work done by a heavy-duty cultivator with special spring or fixed tines; unlike the ordinary plough, it does not move or invert all the soil”. Long term studies have stressed out that; consistent use of MP can have negative soil structure effects ultimately leading to crop yield penalties. In contrast, chisel ploughs are considered less structural destruction land management operations with reduced soil inversion and at least 30% soil cover retention. This qualifies it as a conservation tillage method (Logsdon, 2013). Residue retention is governed by the working velocity of the operating machine and depth of operation. For instance, slow velocity and shallow tillage depths increase residue quantity (Zeng et al., 2020).

Disk ploughs are particularly effective for working with virgin, rocky, and moist soils, as they efficiently slice through crop residues and navigate over roots (Abdalla et al., 2014). In contrast to the chisel plough, the disk plough achieves superior mixing of soil and residues, irrespective of the soil tillage speed. The blades of disk ploughs are concave, typically resembling segments of hollow spheres. The operation of a concave disk blade involves lifting, breaking up, partially turning over, and shifting the soil to one side. These disk blades are positioned at an angle, referred to as the disk angle, relative to the direction of travel, and at a tilt angle from the vertical; disk angles range from 42° to 45°, while tilt angles range from 15° to 25° (Abdalla et al., 2014).

2.2. Conservation tillage (CT)

Conservation soil tillage (CA) methods encompass any soil tillage technique that minimizes soil disturbance and leaves at least 30% of crop residue on the soil surface (Derpsch et al., 2010; FAO, 1993). These methods include no-till, minimum tillage, strip tillage, ridge tillage, mulch tillage, and reduced tillage, among others. Minimum tillage (MT), on the other hand, entails a reduced level of soil manipulation, typically achieved using primary soil tillage implements and limited ploughing (Busari et al., 2015). As mentioned by Kovács et al. (2023) it is a recent technique where soil tillage is restricted to narrow strips or rows, while disturbing a narrow zone 15–20 cm in width by 15–20 cm in depth_(Licht and Al-Kaisi, 2005). This soil tillage practice's interest was heightened by no-till and conventional soil tillage's negative effects on poorly drained soils (Al-Kaisi et al., 2002). No-tillage (NT) involves planting seeds directly into undisturbed soil with retained stubble residues (Kovács et al., 2023; Morris et al., 2010a). According to Busari et al. (2015), NT refers to land cultivation with minimal soil surface disturbance, with the only disturbance occurring during planting. This tillage method is typically favoured in large scale crop production due to the availability of machinery. However, in small scale crop production it can still be practiced with direct seed sowing using hand-hoes or a sharpened stick end to aid in opening the hole on the soil to put the seed(s).

Ridge tillage is an agricultural practice where crops are sown in rows either atop or beside ridges that are created at the beginning of the planting season (Busari et al., 2015). This soil preparation technique involves cultivating crops on soil that has been mechanically raised to achieve certain objectives, which depend on factors like soil characteristics, climate, and the type of crop being grown (Lal, 1991). The adoption of ridge tillage was aimed at addressing various challenges, including weather conditions in certain areas (Gursoy et al., 2011) and it also created a favorable environment for tuber crops (Van Balen et al., 2023). From the time of harvest until the next planting, the soil is left undisturbed, apart from nutrient injections. Seeds are planted in a seedbed on ridges using implements such as sweeps, disk openers, coulters, or row cleaners, while the crop residue remains on the surface between the ridges (CTIC, 1992).

Strip tillage entails disrupting the soil solely in narrow strips, while the remainder of the field remains undisturbed (Trevini et al., 2013). Recent strip tillage systems are equipped with a combination of discs to concentrate soil disturbance into narrow strips subsequently maintaining straw residue on the surface between the rows (Morris et al., 2010b). Its characteristics of disturbing on narrow strips of soil, while leaving the other part undisturbed it is considered a conservation tillage practice. Strip tillage in USA consist of a narrow-disturbed band of 10-30 cm in width and hilled to 80-200 mm above the surrounding soil (Morris et al., 2010b).

In mulch tillage, the soil is disturbed before planting. Tools such as chisels, field cultivators, disks, sweeps, or blades are employed. This tillage method serves as an alternative in environments where no-till practices are ineffective. It is more suitable for heavier soils, high crop residues, cover crops, plow downs, and the addition of organic amendments like compost and manure.

2.3. Significance of soil tillage methods in agriculture

Advancements in agricultural practices and a growing awareness of the importance of soil health have evolved the significance of soil tillage methods in agriculture (Srivastava, 2025). This evolution is driven by the need for sustainable farming practices that minimize soil degradation and promote soil conservation and sustainable crop production. As a result, goal-specific soil tillage practices, such as CA, have been developed to minimize soil degradation (Montgomery, 2007). The earliest awareness of this goal was brought about by the American Dust Bowl in the 1930s, a severe disaster caused by extensive wind erosion resulting from intensive CT practices (Mrudula et al., 2025). Consequently, there was an urgent need to address the deleterious effects of soil tillage.

A study by Lal et al. (2007) discovered ploughing causes a decrease of SOM concentration due to fast mineralization and associated release of crop available nutrients. The loss of SOM affected soil physical parameter, such as structure. A key factor in soil function is its structure (Bronick and Lal, 2005). Conservation soil tillage methods have been proposed primarily to increase SOM and enhance carbon storage. These improvements contribute to better soil structure and help develop soils resilient to extreme climatic conditions. Such soil tillage practices focus on minimizing soil disturbance and maximizing plant biomass retention, thereby protecting the soil from harsh environmental stresses. Recent studies have further corroborated these findings. For instance, conservation soil tillage practices facilitate SOC sequestration, improving soil health and mitigating greenhouse gas emissions (Lal, 2018). Additionally, conservation agriculture, which includes CA, leads to significant increases in soil health and supports stable crop production under long-term warming conditions (Lal, 2018). These findings underscore the importance of adopting CA practices to enhance soil.

The chisel plough was then more favoured than the moldboard plough as a primary soil tillage practice due to its adherence to conservation agriculture principles. Chisel ploughs are not only for fracturing and tilling of the soil, but they also maintain at least 30% residue cover of the preceding crop on the surface (Hill and Stott, 2000). Conversely, the secondary soil tillage practices did not change, and thus soil erosion continued. Discovery of herbicides relieved farmers' reliance on soil tillage as the main practice to control weeds and made it possible for practicing NT. However, even NT proved not to be the panacea to all soil and soil tillage related problems.

Currently, a wide group of soil tillage tools exist, each designed to accomplish one or more particular objectives. The disk ripper, for instance, is a primary soil tillage implement commonly utilized to break up compacted soil layers. By breaking compaction layer, it creates a deeper loosened environment for plant roots to proliferate vertically freely. Moreover, the soil allows greater water infiltration. Disk ripping offers deeper soil disturbance than a moldboard plough, moreover it regularly retains 35-45 percent crop residue to cover the soil surface. This protects the soil from harsh climatic conditions, prevents soil moisture loss, and reduces wind and water erosion (Haddaway et al., 2017).

Ridge soil tillage involves cultivating crops on soil that have been mechanically hilled to achieve a specific objective, with the goal being determined by variables, such as soil characteristics, climate, and crop type (Lal, 1991). The ridge furrow (RF) systems emerged independently across Asia, Africa, and America (Janick, 2002; Lal, 1991; Mo et al., 2017). In certain regions, ridge soil tillage is employed to prevent late planting due to slow warming of the soil (Gursoy et al., 2011). The use of ridges also offers other advantages, such as moisture and soil conservation, lodging prevention and field microclimate improvement (Chen, 2000). In dry and semi-dry areas, the ridges formed through RF cultivation expand the soil volume available for crop root development and simultaneously enhance the water supply for plants (Han et al., 2025). Ridge furrow cultivation is predominantly used in Europe for growing potatoes, sugar beets, onions, and carrots (*Daucus carota L.*) to boost root volume, reduce soil density, and facilitate the harvesting process (Van Balen et al., 2023).

In contrast, vertical soil tillage involves vertically working the soil to prevent the creation of horizontal layers or density changes. This practice is typically carried out to reduce the size of the residue from the previous crop, ensuring that planting is not impeded by excessive residue (Smith and Warnemuende-Pappas, 2015), thereby accelerating soil warming during sowing. Vertical soil tillage equipment typically uses coulters designed to cut crop residues into small pieces and partially incorporate them into the soil with minimal disturbance (Chen et al., 2016; Zeng and Chen, 2018), thus preventing soil compaction. Most vertical-till equipment consists of vertical coulters set at angles ranging from 0° to 10°. However, vertical soil tillage is not suitable for crop fields with minimal crop residues and nitrogen incorporation, as a significant amount of fertilizer is left on the surface and lost to volatilization.

Strip-till is a conservation soil tillage method that involves intensive soil tillage in a narrow strip where crops are planted, while leaving the areas between rows untilled, utilizing specialized equipment (Figure 1). This approach keeps most of the field undisturbed and covered with crop residues (Potratz et al., 2020). At least 50–75% of the soil remains covered with plant residues (Jaskulska et al., 2020; Townsend et al., 2016). Modern machinery allows for strip-till to be executed in a single pass, making it suitable for crops with wide (Idowu et al., 2019), medium (Jaskulska et al., 2018), and narrow (Jaskulska et al., 2018) row spacing. It merges the benefits of CT, plough soil tillage, and no-till systems. Research comparing strip-till, CT, and NT has shown that strip-till and CT enhance maize grain yield compared to NT (Licht and Al-Kaisi, 2005; Temesgen et al., 2012; Vetsch et al., 2007). In northern Benin, Yemadje et al. (2025) found that water productivity for cotton and maize was similar under CT, strip soil tillage, and NT, with strip soil tillage showing an average yield reduction of 9.7% compared to CT. Pöhlitz et al. (2019) , using traditional physical measurements and computer tomography, determined that soil properties in strip-till rows and those after soil tillage with surface mulching were comparable.

Figure 1. Different strip soil tillage roller crumblers. A-Cleated roller, B-Rubber press wheel, C-The steel wheel. Source: (http2, 2025)

Field cultivator

Field cultivators are primarily employed as a spring secondary soil tillage to break the big soil clods resulting from primary soil tillage and to place and bury fertilizer at a certain soil depth. They can also be a great alternative to herbicide to control weeds in the field. However, for effective control, the height of weeds is important as indicated by Figure 2b.

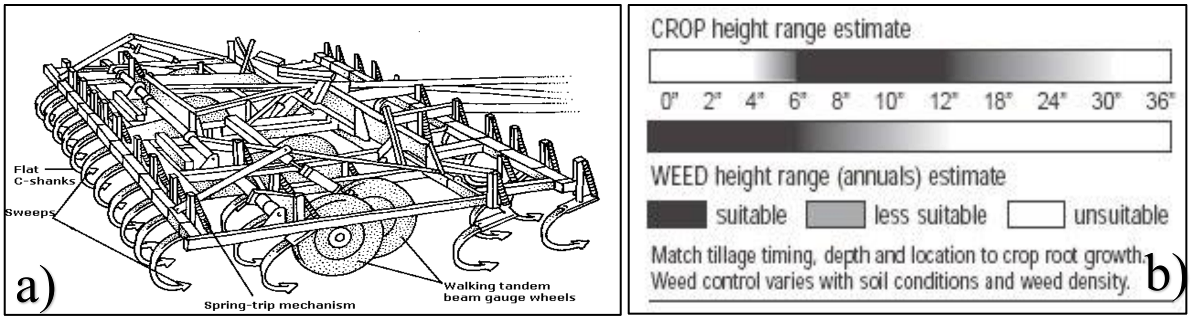

Figure 2. Description of field cultivator and crop and height estimate. (a) Field cultivator with sweeps and (b) Crop height range estimates (on the right). Source: (http1, 2001)

No-till

Early reports on NT reported that by 1980 two thirds of cropland in the United States of America had already adopted this practice. This was due to evidence of reduction in elimination of soil erosion and reduction in energy inputs by 7% in maize and 18% in soybean production simultaneously increasing or without compromising yields compared to CT practice of MP followed by D (Phillips et al., 1980). Ensued meta-analyses have complex performance trade-offs. Xia et al. (2021) synthesized 49 studies in their meta-analysis and they revealed that NT moderately reduced crop yield (median -1.9 %). Furthermore, they highlighted that retaining crop above ground biomass in NT system was central driver of yield gains (median + 8.2%). Other review study stressed that while NT may fall short in yield under some conditions, yet when it is combined with residue retention and crop rotation, it enhances rainfed production, particularly in moisture deficient climates. This makes NT a potential climate-adaptation tool (Pittelkow et al., 2015). Regarding other factors, NT delivers tremendous positive ecological benefits. Some of these benefits have been highlighted by Skaalsveen et al. (2019). In their review they elucidated that NT practice that adheres to full conservation agricultural principles improved water retention and purification functions relative to CT in north-western Europe. Long-term NT systems of 13-31 years have shown that regenerate a permanent web of soil pores and stable macroaggregates deeper to 50 cm depth. These are improvements that promote water dynamics, carbon protection, and microbial habitats. In Southern Brazil, Bensen et al. (2024) discovered that coupling NT with cover cropping enhanced soil carbon stocks and maize yields. They noticed that after four and half years there was approximately 80 Mg ha^{-1} of carbon compared to ~61 Mg ha^{-1} of CT, emphasizing the importance of NT's role contributing to SDG 13 and agricultural production. Long-term field data from subtropical Ferralsols and other weathered soils confirm this: Brevilieri et al. (2024) reported significantly higher soil C and N after >20 years under NT with fertilization, and

Amorim et al. (2024), using a 15-year NT dataset in the Lower Mississippi River Basin, documented ~25% greater SOC stocks and improved Soil Management Assessment Framework soil-quality indices relative to continuous soil tillage. These recent, peer-reviewed findings support a cautious generalization: NT increases or preserves SOC and can enhance nutrient availability where residue retention (as shown by Figure 3) and appropriate fertilization are applied, but effect size depends on time since adoption, climate and management (Amorim et al., 2024; Brevilieri et al., 2024).

Further regional instances underscore the agronomic and ecological importance of NT. In South Africa, NT enhanced soil micronutrient levels (Fe, Mn, Cu, Zn) and modified their distribution across different soil depths over 17 years, particularly when combined with nitrogen fertilization, highlighting the complex impact of NT on nutrient dynamics (Zulu et al., 2022). On smallholder farms, NT boosted soybean yield, phosphorus availability, and utilization efficiency, underscoring its advantages in resource-constrained settings (Chauke et al., 2022). Li et al. (2022a) compared NT and plough/rotary systems in rice–wheat rotations and found higher seedling root biomass and root activity (0–20 cm) and an associated increase in wheat spike number and grain yield under NT, especially where NT improved topsoil nutrient concentrations and gave a more stable hydrothermal environment. Nurbekov et al. (2024) found that the combination of no-till (NT) practices with residue retention and legume-based crop rotations led to an increase in root residues, soil humus, and wheat yields over four seasons in arid, rainfed trials, with grain yields often significantly surpassing those of conventional soil tillage. These recent field findings suggest that NT encourages the proliferation of surface roots and early plant vigor, especially when coupled with effective residue management, crop rotation, and nutrient practices, potentially boosting grain yields and root mass. However, the advantages for roots and yield can be negated if NT is implemented with uncontrolled wheel traffic or poor residue and nutrient management (Li et al., 2022a; Nurbekov et al., 2024).

Figure 3. No-till planter at the JM experimental farm near Hatvan (Source: Dekemati Igor)

2.4. Conservation soil tillage effects on soil penetration resistance

Crops thrive in environments that provides conditions such as the state of looseness, structure and moisture availability (Birkas et al., 2014). Majority of field crops roots prefer an SPR of less than 2 MPa and a 45-50 % pore ratio. These conditions provide adequate moisture availability, allows roots to extend and exploit larger soil volume for water and nutrients. Moreover, higher soil pore ratios allow adequate oxygen required for healthy root growth. A highly compacted soil does not provide a conducive environment to crops, moreover it becomes even more worse if compaction coincide with water and nutrients shortage (Birkas et al., 2014).

SPR is a measure of soil quality and is considered more relevant than bulk density (BD) for evaluating soil strength (Bengough and Mullins, 1990). This parameter represents the pressure exerted by soil particles conveyed by the cone index. This can be a significant agronomic pointer in ranking soil penetration resistance to plant roots by soil layers. In essence, higher SPR acts as a barrier to crop root extension in search of soil resources such as water and nutrients (Araki and Iijima, 2005; Bengough et al., 2011; Colombi and Walter, 2017; Lipiec et al., 2012; Nosalewicz and Lipiec, 2014; Siczek et al., 2015; Valentine et al., 2012). Thus the inability to exploit the available soil resources lead to poor crop growth and performance as reported by various laboratory and field studies

(Barraclough and Weir, 1988; Botta et al., 2010; Colombi et al., 2017a; Colombi and Walter, 2017, 2016; Grzesiak et al., 2014; Young et al., 1997).

The SPR increases with the number and intensity of soil tillage operations and when conducted under inappropriate soil moisture conditions (Blanco-Canqui and Ruis, 2018; Materechera, 2009). Improved soil physics, such as reduced soil bulk density and strength improved soil porosity, and increased soil porousness resulting from using a of reduced soil tillage and cover crops (Blanco-Canqui et al., 2011; Haruna et al., 2018). However, the SPR difference resulting from land preparation methods may differ due to other factors such as soil type, crop rotation, and management practices (Bogunovic et al., 2015; Sartori et al., 2022). Hence, the effect of CA on SPR is not agreed upon, with some studies observing differences, and others no differences. For example, Jabro et al. (2015) reported lower levels of SPR under deep soil tillage (DT) compared to shallow soil tillage (ST) and no-till (NT) for three consecutive cropping seasons. In Hungary, Dekemati et al. (2021) observed statistically higher SPR in the plough treatment at depths of 30-40, 40-50, in 2016 and 10-20 cm in 2018. Nebo et al. (2020) found a 40% higher SPR under conventional soil tillage (CT) compared to NT on a clay-loam Haplic Cambisol in South Africa. Similarly, Jug et al. (2024) observed a greater in SPR at a depth of 75-80 cm under plough soil tillage, while SPR values under shallow conservation soil tillage (CTS) treatment were generally consistent at and were significantly lower than those produced by plough soil tillage. A two-dimensional SPR representation showed that the top layer of minimally resistant soil (0-1 MPa) was extended from approximately 5 cm in NT to approximately 8 cm in CT due to disk ploughing (Nouri et al., 2019).

2.5. The effects conservation soil tillage on soil moisture content

Evidence from studies has shown the benefits of CA on temporal and spatial moisture conservation. In central Europe, Dekemati et al. (2019b) measured the effect of six soil tillage methods on SMC in Hungary. They reported that with regards to spatial differences SMC was greater under DC and NT relative to P. In relation to temporal differences DC (11.22%) had greater SMC in 2017 compared to NT (9.62%), and P (9.30%). In China, Yin et al. (2023) reported greater SMC under two NT systems (NTSM- no-till with straw mulching cut at 25-30 cm and NTSS- no-till with straw cut at 3-5 cm) between 0–30 cm soil depth at various wheat phenological stages on an Aridisol 2014–2016. The SMC between jointing and booting stage with NTSM and NTSS was higher by 7.0–10.6% and 5.0–7.7% relative to conventional soil tillage without straw retention (CT), respectively. Furthermore, NTSM SMC differed by 4.7–7.1% relative to conventional soil tillage with straw incorporation (CTS). Xu and Mermoud (2003) examined how management practices affect the temporal variation in soil hydraulic properties for CT, NT, and subsoiling soil tillage (SS). They found that SS resulted in reduced evaporation and increased infiltration into deeper soil layers. Stanek-Tarkowska et al. (2018) reported higher moisture in a four-year period on a Haplic Luvisol in Poland under RT (tine cultivator to 10 cm) compared to TT (moldboard plough to 25 cm). Soil water content (SWC) was notably higher under reduced soil tillage (RT) compared to traditional soil tillage (TT) at depths of 0-5, 5-10, and 10-15 cm. The soil in the RT system exhibited the greatest SWC values at 0-5 cm depth. In the RT system, the volumetric SWC increased by 18%, 16%, and 17% in the 0-5, 5-10, and 10-15 cm soil layers, respectively, when compared to TT. Liu et al. (2013) conducted a three-year study (2007-2009) on a Eum-Orthrosols at an apple orchard in the loess plateau of Shaanxi Province, China. They observed greater moisture retention under SS treatment at 0-20 cm and 20-40 cm during the three-year study periods except for 2007 at 0-20 cm where ploughing with mulch retention (PTS) and ploughing without mulch (PT). Moreover, NT with residue retention consistently maintained higher SMC throughout the growing period, while acceptable moisture quantities were recorded with PTS and lower levels of SMC with NT without residues. Likewise, Thierfelder et al. (2012) reported greater SMC measurements under CA practices compared to CT on a five year study in southern African countries. They measured greater SMC at 0-10 cm, 10-20 cm, and 20-30 cm in all the investigated seasons except for the first season at 0-10 cm where SMC was significantly similar in CT (21.4 mm) as compared to CA (21.3 mm). Bogunovic et al. (2015) investigated the effect of ploughing (CT), subsoiling (SUB) and ploughing across the slope (PA) on temporal SMC and SPR.

In the loess plateau of Shaanxi Province, China Zhang et al. (2022b) conducted a 12-year study on a Calcisol investigating the effect of NT, SS and CT on seasonal rainfall distribution, water storage spring maize yield and water use efficiency (WUE). In type-A, ST enhanced the SMC in the 60–200 cm (sowing), 100–180 cm (jointing), 60–160 cm (tasseling), and 120–200 cm (filling) layers by 5.6%, 10.0%, 9.4%, and 12.4%, respectively, when compared to CT. NT significantly boosted the soil water content by 8.0% in the 100–180 cm layer during the jointing stage, by 12.1% in the 80–160 cm layer during the tasseling stage, and by 14.0% in the 100–200 cm layer at the maturity stage, relative to CT. In type-B, both NT and ST increased the soil water content during the sowing and tasseling stages. Contrastingly, Zhang et al. (2018) conducted a ten-year experiment on the loess Plateau, China. They found that NT had lower SMC in multiple years under winter wheat (2008, 2010, and 2012). The measured SMC in NT was 155.4 mm, 87.2 mm, and 286.9 mm in 2008, 2010, and 2012 respectively compared to CT with 171.0, 124.9, and 323.7 mm in similar investigated years. Moreover, the average water use efficiency in their study was significantly similar. A long-term effect of soil CA on SWC, penetration resistance, crumb ratio and crusted area was conducted in Hungary. They reported that no significant differences of SMC in all investigated soil tillage treatments (Loosening, Ploughing, Tine soil tillage, Shallow Tine soil tillage, Disking and Direct Drilling) (Bogunovic et al., 2019). Slawinski et al. (2012) conducted a three-year study in Poland on two soil types (Eutric Fluvisol and Haplic Cambisol) assessed the two-soil tillage method traditional soil tillage (TT) comprised of moldboard ploughing to 25 cm depth and reduced soil tillage (RT) with a tine cultivator to 10 cm. On a Eutric Fluvisol they observed no differences in mean annual SMC at 5, 15, and 30 cm in 2007. In 2008, SMC was significantly greater under RT compared to TT, measured SMC was 18.9, 18.11, and 19.00 % vol at 5,15, and 30 cm relative to TT with 13.68, 14.51, and 17.93 %vol respectively. In 2009 SMC was significantly greater at 30 cm under RT (17.13 % vol) compared to TT (12.64 % vol). Jemai et al. (2013) compared the effect of 3- and 7-years NT to CT on soil water storage in a dry subhumid area of Tunisia. They reported higher plant available water (PAW) in both NT systems compared to CT. The PAW measured at 0-30 cm was 0.37 and 0.32 cm^3 cm^{-3} relative to CT with 0.24 cm^3cm^{-3}. Moisture measured a field capacity (FC) was also greater under NT systems, with the following values NT3 (0.45 cm^3cm^{-3}), NT7(0.43 cm^3cm^{-3}), and CT (0.31 cm^3cm^{-3}).

Conservation soil tillage alone may not be adequate to achieve higher moisture levels. The process that aids CA to regulate soil moisture balance may be explained by the evaporation and evapotranspiration. Yin et al. (2023) found a decrease of evapotranspiration intensity under no-till wth straw mulch at jointing and early wheat filling stage, yet at both indexes increased at early-filling to maturing stage. This plays a pivotal role to address the moisture requirement at various phenological stages. In Vienna, Austria Liebhard et al. (2022) studied three soil tillage methods (NT, CT, and RT) on a Chernozem soil. They reported that temporal evaporation rates depend on development on the canopy and soil cover. Therefore, CT and RT treatments showed greater unproductive moisture decline during early crop development resulting from sparse canopy and lack of residue retention as compared to NT.

In a study investigating effects of soil tillage in dry, rainy, dry-rainy, and rainy-dry seasons on soil physical, chemical, and biological properties, Dekemati et al. (2020) reported higher (21.4 w/w^{-1})

SMC under shallow tine soil tillage compared to lower (20.4 w/w^{-1}) SMC observed under P in dry season. Similar to dry, season, the rainy season seasons showed higher SMC under shallow tine soil tillage compared to P (25.1 w/w^{-1}). Moreover, in rainy-dry seasons SMC STT was 26.0 mm higher and 26.2 compared to P which measured 25.3 mm, however in dry-rainy season the two-soil tillage treatments were not different. Kitonyo et al. (2018) investigated soil tillage effects on water storage in subhumid Embu area in Kenya. In their study they observed that during long rains there was no significant difference between CT and NT irrespective of residue retained or not retained. However, during short rains CT (419 mm) stored greater water quantity compared to NT (379 mm), both treatments had no mulch. In the short rains of 2015/16 season, soil tillage and mulch did affect evapotranspiration however there was a 6% reduction of evapotranspiration under NT relative to CT. A study by Niu et al. (2023) on an Ali-Perudic Argosols in Guizhou Province, China investigate precipitation variability and CA on SMC, yield and quality of silage Maize (*Zea mays* L). The SMC was measured at various crop phenological stages (seedling, jointing, big trumpet, tasseling, and seed setting) and at various soil depths (0-20, 20-40, and 40-60 cm). They observed higher SMC under CT (0.267, 0.250, 0.238, 0.198,0.244 g g^{-1}) compared to NT (0.248, 0.237, 0.216,0.186, and 0.227 g g^{-1}) at 0-20 cm. Similar domination of CT was observed at 20-40 cm, however at 40-60 cm soil tillage did not have any effect on SMC. Researcher in humid Westen Pannonian Croatia studied soil tillage and straw management impact on soil structure, compaction and soybean yield on Fluvisols. They posited that on average CT (34.7%), MT (35.9%), and RT (33.8%) did not differ. Similar pattern was observed when SMC was measured at different soil depths except for 0-10 cm, whereby CT (31.6%) significantly decreased SMC compared to MT (34.8%). However, compared to RT (32.3%), SMC did not differ significantly nonetheless moisture was higher than CT (Brezinščak and Bogunović, 2021). In a temperate continental region of Croatia Bogunovic et al. (2018) studied soil tillage management impacts on soil compaction, erosion and crop yield on a Stagnosols soil type. They found out that soil tillage did not affect SMC under CT, NT, and deep soil tillage (DT) from 2007-2014 except for 2013.

2.6. The effect of conventional soil tillage on soil penetration resistance

While CT reduce SPR by loosening the soil, repeated passes and the subsequent breakdown of soil aggregates often lead to increased compaction and higher soil density in the long term (Bogunovic et al., 2019). This phenomenon is particularly observed in subsoil layers, where the heavy machinery associated with CT can induce significant compaction (Wang et al., 2022). Additionally, the removal of crop residues through incorporation associated with CT results in lower SOM content, thereby diminishing aggregate stability and increasing susceptibility to compaction, ultimately elevating SPR (Herzfeld et al., 2021; Wang et al., 2022). This subsoil compaction can impede root growth and nutrient uptake, thereby limiting crop productivity (Van den Putte et al., 2010).

Despite the negative consequences of CT, it offers immediate soil compaction reduction. For example, Jug et al. (2024) found that moldboard ploughing in silty clay loam reduced SPR by more than 40% in the 0–20 cm layer relative to NT in the first week following soil tillage. Similarly, Zhao et al. (2022) demonstrated through meta-analysis that CT consistently reduces surface SPR across diverse soil types, thereby promoting early root elongation and crop emergence.

However, the benefits CT on SPR are often short lived (Kuhwald et al., 2020). Sartori et al. (2022) reported that within 6–8 weeks of rainfall and machinery passes, SPR in CT soils often exceeded that of conservation systems, reflecting rapid reconsolidation. Earlier experiments discovered that variability of SPR between tilled and NT treatments were great immediately post soil tillage, but decreased quickly to comparable levels at the end of the season (Franzen et al., 1994; Lopez et al., 1996; Yavuzcan et al., 2005). This indicates vulnerability of soil to re-compact under CT and deep soil tillage management (Bogunovic et al., 2018).

While CT is effective in reducing SPR at the surface in the short term, (CA) systems often deliver superior long-term outcomes. Silva et al. (2023) found that NT plots maintained lower subsoil SPR after two decades, largely due to increased soil organic carbon and biological porosity. However, rainfall and farm machinery wheels accelerate quick reconsolidation of the ploughed layer, undoing previous advantage (Acquah and Chen, 2022).

Under CT managed fields the spatial SPR quantity is generally lower at the rhizosphere, whereas beneath the implement working SPR is higher. Long-term field trials highlight that repeated CT frequently produces a compacted horizon, often referred to as a plough pan, just beneath the tilled zone. While over time, NT plots developed increased biological porosity and decreased subsoil SPR, which facilitated deeper root growth and improved drought resistance (Silva et al., 2023).

After 24 years of experimental conduction, our data showed that CT resulted in lower soil compaction level compared to NT after 11 years and NT after 24 years at 0–10 cm depth (de Moraes et al., 2016). A study conducted by Hernández et al. (2019) in northwest Ohio and Wooster of humid continental climate with soil types fine, illitic, mesic Mollic Epiaqualfs. They observed that SPR at

20 cm depth of 2.32 MPa magnitude increases while NT adjusted penetration resistance while under NT it ranged between 1.5 and 2.0 MPa which was significantly lower than plough soil tillage at Wooster. Sojnóczki et al. (2024) compared the effects of drought on SMC and SPR in CT and non-CT soil tillage systems in eastern Hungary on a chernozem soil. They measured SPR in May and August 2021 and they reported that in August, SPR was significantly greater under CT from 10-60 cm compared to RT. The SPR under CT was 3.54,5.83,7.62,7.33, and 6.46 MPa at 10-20, 20-30, 30-40, 40-50, and 50-60 cm respectively compared to RT which measured 2.33, 4.07, 5.94, 6.53, 6.08, and 5.48 MPa respectively.

The response of soil tillage effects on physical properties relies on texture. For instance, Jug et al. (2024) highlighted that soil high in clay content reconsolidate quicker, while sandy soils maintain lower SPR for longer.

Timing relative to soil moisture content is critical. Weyer and Boeddinghaus (2016) noted that ploughing under near-saturated conditions can smear pore walls and compact soil, inconsistently increasing SPR later in the season. Bogunovic et al. (2019) observed SPR value below 2.1 MPa between March and June in humid soil. However, Chen et al. (2014b) reported higher SPR values between 2.5-17.5 cm depth despite higher SMC measured between 0-10 cm, particularly under NT.

However, operations when the soil is in a very dry state could result in high clod formation and increase the potential of moisture loss. Moreover, there is a possibility of higher dust formation which may develop due to multiple soil tillage trips in the top layer (Gallardo-Carrera et al., 2007). Greater dust magnitude is an indication of unsuitable soil tillage practices and poor soil quality (Dekemati et al., 2021). Furthermore, this dust could leach during rainfall or irrigation thus forming or contributing to the existing compact layer (Birkás et al., 2004; Dekemati et al., 2021; Morris et al., 2010a).

The literature demonstrates that while CT is effective in reducing SPR immediately after disturbance, its benefits are short-lived and often outweighed by long-term increases in subsoil resistance. Soil texture, and moisture at soil tillage, all mediate these dynamics. By contrast, NT systems, though initially associated with higher surface SPR, tend to improve subsoil conditions through enhanced biological activity and structural stability. Thus, CT should be viewed as a short-term remedial strategy rather than a sustainable solution for managing SPR.

2.7. The effects of conventional soil tillage systems on soil moisture dynamics

Soil structure, including parameters, such as SPR and total porosity, plays a crucial role in determining the least limiting water range and plant available water in the soil (Eden et al., 2020). Studies have shown the destructive effects of CT on soil structure, leading to increased soil sealing which negatively impacts soil moisture infiltration (Ramos et al., 2019). In their research, conducted on a Fluvisol in semiarid Mediterranean climate area in Spain, they observed low SMC in the surface layer under CT (0.21 $m^3 m^{-3}$) management relative to NT (0.20 $m^3 m^{-3}$) management.

The removal of soil residues and the exposure of bare soil by ploughing results in negative soil impacts. As mentioned by Dekemati et al. (2021) deficient residue availability in P (Dekemati et al., 2019b, 2019a) can be destructive on soil physical properties in various ways, such as extreme soil temperature (Dahiya et al., 2007), enhanced SMC loss (Kader et al., 2017), and higher soil structure weakening and soil settling (Nanko et al., 2015) resulting from raindrops. The latter-mentioned consequences of soil tillage all contribute to reduced SMC under ploughed soils. Dekemati et al. (2021) further stressed that ploughing reduced the proportion of crumbly aggregates in the soil and increased dust and clod ratio relative to DC and SC.

Blanco-Canqui and Benjamin (2013) discussed how changes in SOC accumulation affect the behaviour of soil physical processes and properties. Undoubtedly, the water retention capacity of the soil has been related to changes in SOC concentration (Hudson, 1994). The addition of organic matter to the soil usually increases the water holding capacity of the soil. This phenomenon occurs due to the addition of organic matter, which increases micropores and macropores in soil either by binding soil particles or by providing favourable conditions for soil organisms. According to Ulery (2005) some SOM can retain up to 20 times its dry weight in water. Hudson (1994) reported that the available water holding capacity in soils increased by 3.7% for each 1% increase in SOM content. The water-holding capacity of soil is a function of adhesive and cohesive forces acting on soil water, and as pore space increases, there is a corresponding increase in the water holding capacity of the soil. In general, enhancement of SOM (de Moraes Sa et al., 2009) and porosity (Gao et al., 2016) are among the outcomes attributed to improved performance under CA systems relative to CT systems, thus enhancing water infiltration and storage. Pervaiz et al. (2009) found higher SOC under deep soil tillage which significantly increased SMC relative to conventional soil tillage.

In some studies, primarily focusing on the effect of soil tillage have reported differing results regarding its effects on soil moisture content. For example, classical studies by Kováč et al. (2015)

reported an average higher SMC after 3 years under CT relative NT on medium clay loam Haplic Chernozem soil. Contrastingly, Afshar et al. (2022) reported that mouldboard-CT plots had the lowest available water content (0.20 cm^3 cm^{-3}) among soil tillage treatments, compared to 0.24, 0.23, and 0.23 cm^3 cm^{-3} in chisel-CT, shallow soil tillage (ST), and NT, respectively. Dekemati et al. (2021) obtained significantly higher SMC at deep cultivation (DC) relative to ploughing (P) in 2016, while in 2017 and 2018 significantly greater SMC observed at DC relative to shallow cultivation (SC). Bogunovic et al. (2019) found no differences in SMC between treatments in the years 2010, 2011 and 2018. Similarly, Al-Wazzan and Muhammad. (2022) found no differences in soil moisture from planting to eight weeks after planting between conventional and NT.

Moreover, meta-analysis by Blanco-Canqui and Ruis (2018) mentioned that studies examining NT practices and soil organic carbon (SOC) have consistently found that NT leads to a concentration of SOC in the top 5 to 10 cm of soil. Consequently, the increased SOC content in the shallow layers (less than 10 cm deep) resulting from NT practices likely enhanced wet aggregate stability and water retention capacity, while decreasing soil susceptibility to compaction. Aggregate stability is one of the significant properties influencing soil hydrological processes, as reported by various studies (Veloso et al., 2025; Zhou et al., 2022) on the positive outcomes of aggregate stability by conservation soil tillage.

Madarász et al. (2016) highlighted positive impacts of NT are only realized after 6 years of application. Singh et al. (2016) reported that soil tillage increased soil structural components, such as porosity and water holding capacity, while bulk density (BD) was decreased after 5 and 9 years of implementation on a sodic soil (Busari et al., 2015; Wang et al., 2006). The benefit of NT is that it reduces the evaporation rates and increases water retention capacity in the dry years. Bogunovic et al. (2019) observed a decrease of moisture in the summer periods, predictably due to higher temperatures.

2.8. The effects of soil tillage on overall crop yield

Numerous studies (Das et al., 2018; Dekemati et al., 2021; Khorami et al., 2018) have assessed the effect of soil tillage on crop yields. The results obtained showed great variation in yield due to moisture and nutrient use efficiency (NUE) (Davis, 1994). Additionally, crop yield is also influenced by the soil structure, which affects it through a range of root-related mechanisms, including those that are moisture-related (Munkholm et al., 2013). In semi-arid zones, crop returns are normally greater under NT because of the greater moisture preservation, relative to CT (Buschiazzo et al., 1998), however in rainy conditions, CT treatments may yield greater crop returns (Alvarez and Steinbach, 2009). Xu et al. (2019) pointed out that practicing NT for 11 years enhanced crop yield to 7.5 Mg ha^{-1} compared to CT which yielded 7.1 Mg ha^{-1}, however NT produced lower crop yield relative to subsoiling (8.0 Mg ha^{-1}).

No-till systems are associated with high soil fertility due to increased SOM thus enhancing total nitrogen (TN) availability. TN has a significant role in elevating soil fertility, promoting the degradation of plant residues, enhancing crop production, and ensuring the efficient coordination of water and fertilizer (Li et al., 2017; Matson et al., 2002). Liu et al. (2021) reported greater TN and SOM under NT, plausibly advancing maize grain development, and increasing maize yield. In another study conducted in 2017 and 2018 in hills of Nepal, the authors confirmed the effectiveness of NT in reducing SOM losses and TN, thus increasing maize yield 0.52 Mg ha^{-1} relative to CT (Chalise et al., 2020). In contrast, Khorami et al. (2018) observed significantly lower yields under NT (2.40 t ha^{-1}) compared to RT (3.60 t ha^{-1}) and CT (3.48 t ha^{-1}) in the semi-arid region of Iran irrespective of greater TN observed under NT during examination on the impact of CT and RT and planting with NT on various wheat genotypes.

In a meta-analysis by Pittelkow et al. (2015) they observed an increase of crop yields of 7.3% under rainfed conditions of dry climates. However, under humid conditions crop yields decreased irrespective of applying NT with other conservation measures. This shows that the benefits of these practices in relation to crop yields are realized under water scarcity environments or in dry cropping seasons as confirmed by studies of Dekemati et al. (2019b).

Furthermore, poor soil physical quality, such as extreme soil density of zero tilled topsoil is viewed as a principal cause of yield declines (Ball et al., 1994; Carter, 1991). Wang et al. (2015) demonstrated that the subsoiling-rotary soil tillage rotation mode was the most effective in enhancing the yield and income of winter wheat–spring maize rotation systems in the Loess Plateau, followed by the NT–subsoiling method. This may be largely attributed to the crop planting system. Bio pores resulting from distinct plant roots particularly under NT systems creates a network of micropores that can be utilized by succeeding crop roots (Suzuki et al., 2013) to explore deeper soil horizons for water and nutrient absorption.

In addition to soil mechanical conditions, water stable aggregate stability plays a vital role on how soil respond to adverse climatic conditions such as heavy rainfall events. Moreover, their effects on soil moisture, gas, temperature, and SPR consequently indirectly affect crop production (Kochiieru et al., 2020). Generally, soils rich in mineral nutrients are associated with higher yields under conducive climatic conditions. However, it has been reported that these chemical elements may have negative or positive impact on soil water aggregates stability which can be aggravated under various soil tillage methods. Kochiieru et al. (2020) revealed that an increase in total potassium in intensively managed soil heightened clay dispersion on a Cambisol and Retisol. Consequently, authors in Thailand implied that in the tropical soil, enhanced soil aggregate stability was observed due to greater potassium (K) resulting from reduced soil tillage (Phocharoen et al., 2018).

2.9. Identification of soil tillage methods to enhance crop yield

To identify soil tillage methods that improve crop yields, the method must provide or improve the soil health status to satisfy the physiological needs of the crop. Crop yields decline vary under different climate, soil stresses, and management strategies. For example, some authors mentioned the effects of soil strength as a potential primary factor that prevents proper root growth (Colombi et al., 2017; Nosalewicz and Lipiec, 2014; Siczek et al., 2015) of crops, thus resulting in yield penalties (Colombi et al., 2017; Colombi and Walter, 2017, 2016). This increase in soil strength is related to conventional land management. Based on their meta-analysis study, Schneider et al. (2017) stressed that deep soil tillage (DT) (subsoiling and deep ploughing) proved to be the best soil tillage for increasing yield in compacted soils with marginal rainfall. Moreover, they also highlighted that soil texture plays a vital role on the success of DT as soil with low silt (>70% silt) was negatively affected by deep soil tillage. Zhao et al. (2023) reported in general NT negatively affected wheat (*Triticum aestivum*) and maize (*Zea mays*) yields, however when considering soil texture, maize yields increased on sandy soil. They further reported that DT increased yield of both crops under monoculture with higher application of nitrogen (<300 kg ha^{-1}) in semidry areas relative to CT in China. Results from individual studies suggested that yield decline is normally associated with root growth deformity resulting from high soil density. Feng et al. (2018) observed significant root length mass of 13% relative RT in a Mollisols of Northeastern China. Furthermore, ST enhanced maize grain yield and biomass by 6.3% compared to RT which managed a 3.7% increase. Sun et al. (2017) reported that subsoiling notably improved the grain yield by 6.21%, 8.92%, and 10.09%, of low, medium, and high-seeding populations respectively on clay loam soil in Henan province. They attributed the grain increase to improved dry matter accumulation improved grain filling under subsoiled treatments relative to NT. A study conducted in Croatia investigated soil tillage physical management, earthworm abundance and crop yield on a silt loam Stagnosols. They observed lower crop yields under conservation soil tillage (CA) treatments relative to CT treatments. However, in periods of rainfall the effect of soil tillage on yield was more pronounced under ploughing (Dekemati et al., 2021). In Hungary Dekemati et al. (2019b) studied the effects of different soil tillage methods on soil physical properties, earthworm abundance and crop yield on an Endocalcic Chernozem. In their study they observed higher yields under SC (9.32 Mg ha^{-1}) compared to D (7.92 Mg ha^{-1}) and NT (8.05 Mg ha^{-1}) which had the lowest yields.

It can be concluded that crop yields are not solely affected by soil tillage effects. Other factors, such as soil texture, weather, precipitation significantly contribute to yield losses or gains. Hence, these ecological factors and cropping systems must be reflected on when adopting soil tillage methods to increase crop yield (Zhao et al., 2023).

2.10. Factors influencing crop yield under different soil tillage practices

Many studies have reported that yield and quality parameters of crops under conventional and conservation soil tillage involves hard to foresee interaction of various parameters (Morris et al., 2010a; Romaneckas et al., 2020; Wozniak et al., 2014). These parameters can be categorized into physical, chemical, and biological. Some of the soil physical parameters influencing crop yield are bulk density/SPR, soil moisture content (SMC), and soil temperature. Chemical parameters affecting crop yields are SOM, pH, and nutrient availability while biological parameters include earthworm abundance.

2.10.1. Soil physical parameters

Soil moisture content

Soil moisture is one of the factors that highly influence SPR, since the pressure that penetrates a certain volume of soil heightens with soil moisture loss (Bengough et al., 2011; Grzesiak et al., 2014). Repeated ploughing to the same depth under unfavourable conditions soil moisture conditions result in plough pan (Dekemati et al., 2019a). These occurrences further decrease the number of soil pore spaces thus affecting the amount of water infiltration in the soil. Admittedly, in arid and semi-arid regions the lack of soil moisture is the principal factor limiting crop production (Debaeke and Aboudrare, 2004; Zhang et al., 2014). However, ecologically friendly methods, such as NT, subsoiler, and SC increase SOM which promotes soil structure. Improved soil structure is characterized by low BD which mediate soil pore ratio, drainage and infiltration. These further allow proliferation of crop plants, to penetrate deeper in the soil to access water and nutrients stored in the subsoil thus increasing crop yield. As highlighted by Kuang et al. (2020) and Li and Hou. (2015) that sub-soiling soil tillage significantly enhances water stable aggregates of > 0.25 mm, infiltration capacity, and the water retention across the soil profile.

Soil temperature

There are various factors, such as organic matter, soil bulk density, inter-aggregate contact, and water content that influence difference in soil temperature resulting from several soil tillage methods (Shukla et al., 2003; Su et al., 2007; Van Wie et al., 2013). Li et al. (2022b) reported lower maize yields in the high latitude areas of northeast China. Their conclusion was based on Stone et al. (1999) who recommended enumeration of cumulate temperature of soil as opposed to air temperature. Soil temperature in a cool-temperate climate might pilot at least a quarter of the crops development's lifecycle. Hence, they suggested that the ≥ 10°C accumulated soil temperature could be the reason for the decline in maize yield under NT with 100% residue coverage and NT with 70% residue coverage relative to CT without residue cover. A study by Wang et al. (2018b) reported positive results of subsoiling compared to NT on soil temperature in Huang-Huai-Hai area of China on a clay loam soil. In their study subsoiling increased soil temperature and soil moisture storage compared to NT thus improving growth of maize. Additionally, they observed a decline in seedling matter which they attributed to high compaction and low soil temperature._The use of straw mulching generally associated with NT can enhance the albedo and decrease the thermal conductivity of the surface of the soil. This reduces the amount of solar energy that penetrates the soil, leading to a substantial decrease in soil temperature (Horton et al., 1996; Li et al., 2013). While results from Yin et al. (2020) are in line with the latter statement, other authors also highlighted that the reduction in soil temperature from NT affects early growth stages which harms crop development (Obia et al., 2020; Pittelkow et al., 2015). This is in line with Pramanik et al. (2018) who mentioned that generally, an increase in soil temperature induces rapid germination and crop emergence. Moreover, this process accelerates microbiological processes, including root development and water absorbency of root cells. Conversely, above normal range, soil temperature may restrict positive effects, and the quantity of restriction can heighten at very extreme temperatures in the soil profile.

In general soil temperature in ploughed fields exceeds that of NT fields. However, this might be governed by atmospheric temperature during measurements, as a study by He et al. (2010) in semi-arid Northeastern China reported higher temperature under RT and NT compared to CT (ploughing to 20 cm depth). In 2005, RT and NT raised the average daily soil temperature by 0.7–1.88C during the period of 15–30 days after sowing (DAS) (late April to mid-May) and by 0.2–1.38C during 150–162 DAS (late September to mid-October) compared to CT. In a separate study, Liu et al. (2021) found that soil temperatures were lower at 10 am, but increased by 4:30 pm under conventional soil tillage (CT) compared to no-soil tillage (NT) and strip soil tillage (ST), suggesting that ploughing was ineffective in controlling temperature. Furthermore, maize yields were notably higher with ST and NT than with CT ($P < 0.05$). Compared to CT, the 1000-kernel weight rose by 8.5% and 4.6% under ST and NT, respectively, and maize yields increased by 14.9% and 11.9%. In the black soil regions of China, known for their high-altitude, humid, cool climate, Liu et al. (2015) examined the effects of moldboard plough soil tillage (MOT), rotary soil tillage (ROT), reduced soil tillage (RET), combined soil tillage (COT), and no soil tillage (NOT). They discovered that NOT significantly decreased spring maize yields compared to MOT, with yields being about 47%, 61%, and 38% higher in MOT than in NOT. The researchers linked the reduced maize yields to delayed emergence due to lower temperatures.

2.10.2. Chemical parameters affecting crop yields

Soil Organic Matter

The impact of soil tillage techniques on SOM turnover is generally determined by factors, such as the frequency and timing of soil disturbance, the depth of soil disturbance, and the degree of soil-residue mixing. These factors have been studied extensively in the literature, by researchers, such as (Cookson et al., 2008; Dou et al., 2008; Machado, 2011) contributing valuable insights. Crop residue incorporation soil tillage practices increase the rate of decomposition regarding local climatic conditions, cultivation intensity, and residue burial which may promote SOM reduction (Beare et al., 1994; Mikha et al., 2014; Paustian et al., 1996). Whereas, in NT systems, the retention of crop roots and above ground biomass at the surface increase SOM build-up relative to CT or RT systems. For instance, seminal studies by Kern and Johnson (1993) conducted various trials and observed higher SOM content under NT relative to CT particularly in the first 0-8 cm. After 8 years Shao et al. (2016) observed increased SOM by 5.65% (Subsoil – Maize + NT – Wheat + mulch) and 4.77% (Ridge soil tillage + mulch for both crops) on wheat-maize rotation under conservation soil tillage in the 0-20 cm depth. Liu et al. (2021) reported increased yields of 12.9% and 14.9% under NT and SS respectively in their study on the effects of soil tillage on newly reclaimed soil in Shaanxi Province, China. They attributed the yield increase to regulated soil temperature, and increased SOM and TN content, which improved maize physiological growth and consequently grain yield. Kitonyo et al. (2018) observed visible soil tillage during the third season, when NT resulted in a 6% decrease in grain yield compared to CT. This suggests that the negative impact of N immobilization in NT on yield becomes apparent shortly after its adoption.

While ploughing is often linked to the reduction of soil organic matter (SOM), which is crucial for enhancing crop yields, other researchers have noted that minimizing soil tillage can lead to yield reductions (Pittelkow et al., 2015). Typically, yield improvements associated with ploughing are ascribed to enhanced soil physical structure rather than an increase in SOM. For example, Burger et al. (2023) found that the yield increase observed with deep ploughing on Dystric Cambisols in Essemühle was more strongly associated with root growth due to decreased BD and increased soil moisture, rather than with SOC accumulation. Despite the scarcity of comprehensive studies directly linking these attributes, this review can nonetheless employ the mechanistic framework that elucidates this phenomenon. It is well-established that ploughing disrupts soil aggregates and accelerates SOM mineralization, ultimately leading to reduced SOC and diminished aggregate stability, thereby affecting soil water retention, nutrient balance, and root proliferation, factors essential for achieving higher yields. It is crucial to acknowledge, however, that crop performance is also contingent upon soil texture, as well as weed and disease pressures.

Nutrient availability

Growing processes in plants are regulated by internal signals that require satisfactory provision of mineral nutrients from the soil through the root and to the shoot. Thus, mineral nutrients disposal for plant development can be a major constraint on many environments globally (Dotaniya et al., 2015). Previous studies have shown notable effects of conservation soil tillage on ecosystem services rendered by the soil. This includes soil productivity, nutrient circulation, and crops (Blanco-Canqui and Ruis, 2018; Fageria, 2002). Generally, soil tillage effects on nutrient dynamics are principally pronounced on a short-term scale. This occurs due to change in the physical properties through burial of below and above ground crop biomass and mineral or natural fertilizers (Neugschwandtner et al., 2014). Moreover, decreased nitrogen availability could be enhanced by seeping owing to high SMC, and the presence of preferential flow pathways under no soil tillage (Shipitalo et al., 2000). Soil TN plays a crucial role as the primary component of soil nutrients, and it is vital for the sustenance of various organisms (Song et al., 2020), which plays a vital role on the development and growth of plants (Fang, 2013). Iqbal et al. (2007) reported significantly lowest N under DT relative to ZT, MT, CT methods. Dimassi et al. (2014) conducted differentiated soil tillage methods for four decades and observed significantly greater C and N in the 0-5 cm depth in NT treatments relative to full inversion soil tillage by 64 and 73%, respectively. Dikgwatlhe et al. (2014) observed significantly higher N concentration and stock under NT at 0–5 cm depth relative to moldboard plough with maize residues removed (PT0), moldboard plough with maize residues incorporated (PT), and rotary soil tillage with maize residues incorporated (RT) in 2004 and 2012. The SOC has various importance in crop production. The most significant one related to crop yield is the regulation of the presence of naturally compiled nutrients (Billings et al., 2021). Dekemati et al. (2019b) reported significantly greater SOC under NT at 0-10 cm compared to SC, L, and P. Singh et al. (2020) conducted research on the effect reversed conservation soil tillage on various soil properties. In their study they reported greater SOC in the 0-5 cm depth under NT relative to RT.

Soil pH

Soil pH is fundamental in crop production. Plant genes vary; thus, some crops can thrive under acidic soil, and some prefer alkaline. Generally, most crops prefer a neutral pH of about 5.5, while above that it can result in yield or affect the overall plant crop (Limousin and Tessier, 2007). Various authors highlighted that the most yield-restrictive factors of crops are acidic soils (Fageria and Nascente, 2014; McLaren and Cameron, 1996; Sumner and Noble, 2003). Despite over application of synthetic fertilizers, it has been reported that soil pH can also be affected by soil tillage practices (Turmel et al., 2015). After 5 years López-Fando and Pardo (2009) reported a lower pH in the upper layer of NT compared to MP. However, in the lower layer (20-30 cm) they observed higher pH in NT compared to MP. This was attributed to series of biogeochemical process such as mineralization of organic matter, nitrification of surface-applied N fertilizer and root exudation. Wright et al. (2007) under CT continuous cotton, obtained significantly greater pH than RT cotton or cotton followed by maize. Moreover, yield was decreased under continuous cotton. A meta-analysis study reported that conservation soil tillage has the potential to enhance yields under alkaline soil conditions. These means that conservation soil tillage may be able to lower the pH of soil. A plausible reason for that is related to residue retention under this soil tillage system. The decomposition of plant residue enhances cation concentration and increases H^+ concentration (Zhao et al., 2022). The application of this soil tillage practice could prove more beneficial for saline-alkali environments (Chen et al., 2021). Another meta-analysis reported that NT decreased soil pH by 1.33% relative to CT however, there was no significant difference observed for yield under NT (Zhao et al., 2022).

2.11. Biological parameters affecting crop yield

Biological parameters are defined as measurable attributes of living components and their activities in the soil and plant system. They mediate the transformation of organic matter, nutrient mineralization, soil structure formation, water relations, and plant health. Through these mechanisms, biological parameters translate management into crop performance. Understanding these biological mediators is therefore essential to explain why identical soil tillage systems sometimes produce different yield outcomes across soils, climate, and time scales.

Weeds and pests represent formidable biological constraints on crop productivity, capable of reducing yields by 10 % to over 50 % depending on the crop, agro-ecological zone and management regime. For instance, in winter wheat, the weed wild oat (*Avena fatua*) has been demonstrated to cause large yield losses when left uncontrolled. An experiment in Germany found significant reductions in winter wheat yield owing to *A. fatua* competition (Jäck et al., 2017). In the United States and Canada, research estimates potential yield losses of around 23.5 % in winter wheat under minimal weed control scenarios (Flessner et al., 2021). Meanwhile, in sunflower (*Helianthus annuus*), studies show that if weeds are allowed to remain during the crop's growth, seed yields can decline by 17.6-40.1 %, and under full season weed interference even up to 47.7 % (Zadorozhnyi and Chernelivska, 2025). Although specific published yield-loss percentages for winter oat are less frequent in the literature, comparable competitive weed pressures in cereal systems suggest substantial vulnerability. Infestations of the parasitic witchweed (*Striga hermonthica*) in cereals across Africa have produced yield losses from 21 % up to 100 % in unmanaged conditions (Benjamin et al., 2024). In rice systems globally, weed competition alone has historically been estimated to cause losses of approximately 37 % (Velasquez et al., 2024). Pests, such as stem borers and the fall armyworm (*Spodoptera frugiperda*) can inflict losses of 20–40 % or more where control is absent and cropping systems are vulnerable. These losses not only reduce grain quantity but also degrade quality, increase production costs and compromise food security.

Nonetheless, growing complications of weed management are some of the exchanges resulting from conservation practices that have spawned concerns. Generally, NT fields without the use of chemicals for stubble treatments harbour more crop diseases and pests (Buhler et al., 1994; Koger and Reddy, 2005; San Martín et al., 2018). In a study by Aderolu et al. (2018) maize related insects and nematodes were effectively decreased by plough and harrow soil tillage, thus improving pest control in maize cultivation. Similarly, Jasrotia et al. (2021) reported that different effects of NT, RT, and CT on the quantity of main insects and their predators under wheat. Additionally, they observed the lowest numbers of leaf aphids and termites in the ZT protected system. In contrast, Snizhok and Shevchenko (2022) reported an increase in destructive organisms, such as weeds due to soil tillage, with the greatest quantity observed under deep soil tillage relative to soil loosening. Ridge soil tillage in temperate regions promotes early germination of crops, this enhances crops competitive growth robustness and development to weeds thus decreasing yield losses (Alagbo et al., 2022). Moreover, NT provides conducive soil conditions for germination during moisture deficit, however, this also benefits the weed seeds stored in the soil (Winkler et al., 2022). Due to the robust physiological behaviour of most weeds, these hinders crop yields (Campiglia et al., 2015). Gandía et al. (2021) reported higher density of weeds under NT relative to MT and CT and the benefit was even more pronounced in drier seasons. Furthermore, the yield under NT was lower but compared to MT however, higher relative to CT, this decline in yield could be plausibly attributed to the high weed density observed under NT.

Ploughing flips the top layer of soil along with its residues, breaking up soil aggregates and exposing the protected soil organic matter (SOM) to oxygen, which makes organisms susceptible to predators. Conversely, reduced soil tillage (RT) or no-till (NT) methods preserve continuous surface residues and increase the abundance of microbial communities (Guo et al., 2016; Mathew et al., 2012) and diversity (Habig and Swanepoel, 2015; Sheibani and Ahangar, 2013), whereas mixing them into the soil spreads residues across different depths. This action causes temporary increases in microbial respiration but often results in greater carbon loss (Briones and Schmidt, 2017; Nkonge et al., 2022), while incorporating them into the soil distributes residues at various depths. This triggers brief spikes in microbial respiration but often leads to increased carbon loss (Mohamed et al., 2024). Furthermore, soil tillage influences infiltration, bulk density, and evaporation, with biological activity swiftly adjusting to shifts in moisture and temperature. For instance, keeping residues affects soil temperature and moisture, fostering steady microbial activity and the survival of mycorrhizae.

In conclusion, soil tillage alone can be effective in reducing the weed and pest pressure, however, these comes at an expense of disrupting other important soil processes. Hence, integrated management practices are introduced to help maintaining sustainability without compromising soil health and crop returns.

2.12. Combined impacts of weather, soil tillage, soil properties on crop yield

2.12.1. Soil penetration resistance and compaction

Agriculture commodities output, particularly crops, are affected by intrinsic factors, such as soil physical, chemical, and biological factors. Intrinsic factors make it difficult to determine a single factor that causes the decline or increase of crop yield. For example, SPR, degree of compacted soil and its water content (Bogunovic et al., 2018; Chen et al., 2014a; Gao et al., 2016), while yield is associated with root growth. Canarache (1991) suggested that soils with SPR greater than 2.5 MPa impedes normal root growth. Moreover, soil tillage plays a vital role regarding soil compaction while the soil type and weather determine the duration. Several findings have highlighted SPR under NT practice is greater than soil tillage practices (Bogunovic et al., 2018; Dekemati et al., 2019b; Pletsch et al., 2024). This is due to fact that soil tillage operations cause soil disturbance ultimately destroying soil aggregates and resulting in reduced SPR (Salem et al., 2015; Tormena et al., 2017). Birkás et al. (2010) studied soil compaction on a clay loam Chernozem under different soil tillage methods. In their study they reported that NT resulted in 40% soil settling relative to loosening. This consequently poses low risk to crops in wet periods, intermediate in periods of normal precipitation and high in dry periods. Ampoorter et al. (2010) presented an SPR increase of 60–70% and 150% in coarse and fine textured soil respectively and these values increased moisture content in the soil. After harvesting the maize crop, Khan et al. (2017) found that the plots treated with minimum soil tillage had the highest soil BD values (1.48 Mg m^{-3}), followed by DT treatment. On the other hand, the lowest BD (1.40 Mg m^{-3}) was recorded in the plots treated with conventional soil tillage. This resulted in CT treatment showing an increase in BD of up to 5.40% compared to minimum soil tillage treatment.

2.12.2. Soil biota

Earthworms are considered a vital component of soil due to their substantial production of cast, which plays a crucial role in aggregate formation (Wu et al., 2016). Recently, Fonte et al. (2023) stated that earthworms contribute 6.5% to worldwide crop yields. Moreover, the contribution was divided into aboveground biomass and harvested crop yield which Van Groenigen et al. (2014) reported 23% and 25%, respectively. Dekemati et al. (2020) assessed the impact of ploughing on earthworm quantity and crumb ratio in Hungary in the dry and rainy, rainy-dry, and dry rainy season. They reported high earthworm abundance under NT in dry season and in rainy season, and the highest was obtained under tine soil tillage and NT. The combination of seasons showed even higher earthworms in rainy-dry under NT compared to other soil tillage practices. Similarly in dry-rainy season, higher earthworms were obtained under NT. The causes of the increase in yield were associated with various pathways, such as: (i) managing pests and diseases through biological methods; (ii) stimulating microbial plant symbionts; (iii) producing substances that regulate plant growth; (iv) modifying soil structure; and (v) improving nutrient availability. The last two pathways were frequently discussed in early literature (Holt-White, 1901). Additionally, Van Groenigen et al. (2014) discovered that earthworms primarily promote plant growth by increasing the amount of nitrogen (N) in the soil. This finding could also be supported by Dekemati et al. (2019b) in a different environment. They studied soil tillage impacts on soil physical, chemical, biological properties, and yield in Hungary. In their study they observed higher SOC in the topsoil, earthworm abundance, and SMC under NT which suggested greater expected crop yields. However, the crop yield under NT was lower compared to other soil tillage treatments and this was attributed to higher SPR resulting from periodical atmospheric drought.

2.12.3. Soil aggregation

The stability of soil refers to the resilience of soil to structure disintegration when exposed to different extreme climate impacts, such erosive effect of rain or wetting (Le Bissonnais, 1996). Commonly, water and soil aggregate stability have an inverse relationship, as stability heightens with drying (Caron et al., 1992; Rasiah et al., 1992). During adverse rainfall events cropping fields under the management of CT methods, such as ploughing exposes soil aggregates to the effect of falling raindrops due to lack of surface cover. Upon encountering the soil, these rainfall drops are disintegrating the soil structure into smaller soil particles. The resulting particles are susceptible to transportation, carrying nutrients and carbon, and forming surface crusts. This process can rapidly and persistently decrease productivity by diminishing accessible water and nutrients, depleting SOC, and impeding air and water circulation (Nouri et al., 2021).

Aggregate stability is one of the factors affected by freeze-thaw (FT) (Dagesse, 2013; Oztas and Fayetorbay, 2003; Skvortsova et al., 2018). Thus, the potential of FT to alter soil mechanical properties can influence various biogeochemical processes, including organic matter turnover and stabilization, and carbon and nitrogen mineralization (Song et al., 2017). Theoretically, the increase on the number of FT cycles aggravates destructions caused by CT soil tillage methods on soil aggregates fraction and stability. Soil response to FT cycles is important and depends on various factors, such as soil texture, SOC content, moisture content at freezing moment and cropping practices (Kochiieru et al., 2020). The latter cited authors reported greater water stable aggregates near full water saturation (WSA_{NS}) content at 0−10 cm soil depth on a Cambisol as opposed to Retisol. However, from 0-40 cm soil depth NT showed greater WSA_{NS} on Cambisol and between the 0−25 cm soil depth on Retisol.

2.12.4. Soil moisture content

Water conservation and stubble retention is crucial for provision by NT and, which greatly influence yield increases, especially in dryland areas with limited water resources (Rusinamhodzi et al., 2011; Scott et al., 2013; Thierfelder et al., 2013). Subsoil moisture reserves permit early planting and underpin growth after flowering when grain filling is susceptible to water shortage (Kirkegaard and Hunt, 2010; Sadras et al., 2012). However, the function of NT and stubble retention is impacted by elements including rainfall pattern, evaporative demand, stubble retention, and soil type (Dai et al., 2021; Kirkegaard, 1995; Kirkegaard and Hunt, 2010; Monzon et al., 2006; Verburg et al., 2012). Šíp et al. (2013) conducted a study from 2006-2009 in Czech Republic at two sites Chrášťany and Ruzyně with an Orthic Luvisol and a Cambisol, respectively. They reported that unpleasant weather and soil properties negatively affected grain yield. Additionally, the negative effects on grain yield were more pronounced under NT compared to CT. Differences in yield were attributed to poor soil water storage under unfavourable weather (in 2007), water holding capacity and dry soil conditions at Chrášťany. Dai et al. (2021) studied different soil and crop properties as impacted by soil tillage and mulch techniques on a dark loessial soil in Shaanxi Province, China. In their study they observed no differences between NT and CT on SMC and soil water storage. This was attributed to a well distributed rainfall which classified the cropping season as a wet year. Kitonyo et al. (2018) observed a decline of 40 mm (10%) in water storage under NT without straw retention relative to CT in 2015/2016 short rains.

2.13. Influence of soil physical properties on crop yield in varying weather conditions

2.13.1. Soil penetration resistance (under dry conditions)

Crop production in hot and dry weather conditions is influenced by a several variables, including environmental factors, cultivation practices, and soil characteristics. These factors can have a negative impact on crop yields, particularly under prolonged hot and dry conditions, which can lead to significant reductions in yield. The effects of these factors are particularly pronounced in regions that experience extreme weather conditions (Bekele and Chemeda, 2022). Yield losses estimated at 25% result from soil (Bakken et al., 1987), and when there is a link between compaction and water stress yield losses estimation increase to 50–75% (Hoque and Kobata, 2000). Rising temperatures and declining precipitation amount have an impact on soil processes, which can lead to crucial changes on the physical, chemical, and biological properties of the soil. Water scarcity is a primary constraint on crop growth in arid and semi-arid regions that rely on rainfed agriculture (Debaeke and Aboudrare, 2004; Zhang et al., 2014). Moreover, it is one of the factors that plays a major role in soil densification consequently affecting crop root growth. For instance, Dexter et al. (2007) observed large variation of SPR under soil water dynamics in severe seasons which impacted soil physical state and crop growth. In addition, Massah and Noorolahi (2011) stressed that temperature and relative humidity can affect SPR, with higher temperatures and lower relative humidity leading to higher SPR values. On the other hand, Tuba et al. (2021) observed higher SPR values between 2017 and 2018, they attributed that to greater SMC resulting from more positive weather conditions, contrary to the extremely high SPR values recorded for the dry season of 2018.

According to Souza et al. (2021) environments where water is regulated are influenced by unpredictable rainfall patterns. This phenomenon further increases density of sandy soil and impedes root proliferation. Furthermore, they explained that less water retention is enhanced due to soil texture of sandy soil, shortening the drying period for sandy soils relative to clay soils (Figure 4). Concurrently, the dynamics of relative soil water content are affected by all the other processes related to it, and this influences the growth of plant root systems. Therefore, the two conditions that limit plant root growth are: (i) low water content in the soil a few days after rainfall events, and (ii) a rapid increase in soil water potential, which makes it challenging for plant roots to access deep soil layers.

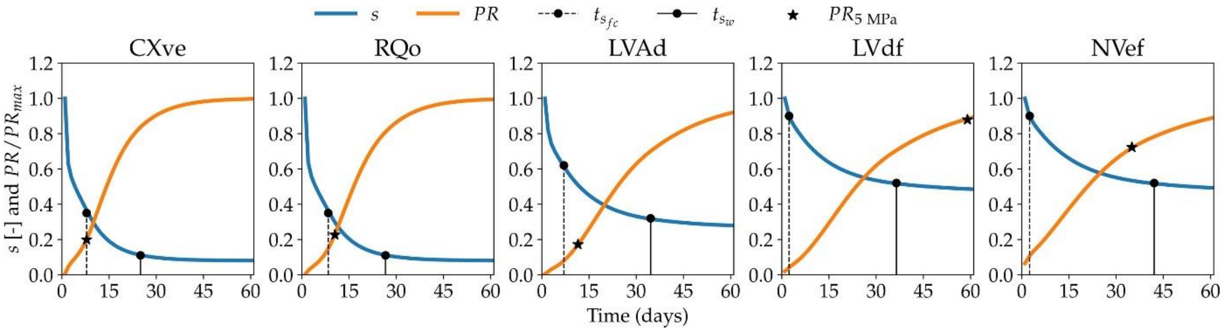

Figure 4. “Dynamics of relative soil water content (s) and soil penetration resistance (PR) during a dry down . The PR_{max} for the CXve, RQo, LVAd, LVdf, and NVef soils are 25.1, 22.1, 29.1, 5.7, 6.9 MPa, respectively. A black star indicates PR at 5.0 MPa”. Adopted from Souza et al. (2021).

2.13.2. Soil penetration resistance (under wet conditions)

In a research study on an Endocalcic Chernozem, the researchers compared two years effect of six soil tillage treatments on SPR, it was found that higher SMC resulting from more favourable weather conditions in 2017 was associated with lower SPR values (Dekemati et al., 2019b). In contrast, Nawaz et al. (2013) highlighted that, soils with greater clay quantity and moisture experience high soil compaction resulting from the of tractor field trips. According to Capobiango et al. (2023), soil compaction led to an increase in soil bulk density and mechanical resistance, which had varying effects on soybean varieties based on rainfall patterns. Compaction resulted in improved seedling emergence and vegetative growth. However, it reduced the relative growth rate, pods quantity, and the grain yield. The researchers attributed the rapid growth at the commencement of the plants' life cycle to moderate soil compaction (2.09 MPa), which collided with ideal weather conditions in December 2020 period. This period was characterized by heavy rain and shade caused by clouds, which allowed for intense growth during the vegetative phase of soybeans. The mean SPR values varied between 0.5–2.2 MPa. The year 2005 was the wettest year among the examined three years, receiving a total rainfall of 702.1 mm, that is 20–23% greater compared to the other two years. The observed advantageous SPR values can be attributed to performing soil tillage operations under ideal moisture conditions and in optimum quality (Földesi and Gyuricza, 2011).

2.13.3. Porosity

Soil porosity is a crucial factor in regulating essential processes, such as nutrient supply, water retention, infiltration, and gas exchange. Compaction can have a negative impact on soil pore structure, leading to reduced saturated hydraulic conductivity (Ksat) and air movement in soil, as well as limited water infiltration and increased surface runoff (Lipiec and Hatano, 2003). Wetter seasons bring about higher quantities of rainfall; it can be scattered. High soil porosity plays a vital role during these periods since it favors water infiltration. In compacted soil regions, winter barley exhibited reduced plant establishment and root dry weight. This was attributed to oxygen-deficient conditions resulting from the reduced size of soil pore spaces (Millington et al., 2017). Contrastingly, a decrease in soil porosity promotes soil erosion. This phenomenon is governed by antecedent soil moisture among other factors (Holz et al., 2015). It has been reported that soil with SMC greater than 30% is vulnerable to aggregate breakage and development of sealing (i.e., soil state whereby surface sealing or compaction decreases soil porosity) more rapidly relative to soil with 30% less SMC, particularly during fast wetting (Le Bissonnais et al., 1989; Luk, 1985). These indicate that soil under areas that experience excessive or frequent rainfall, and with low porosity and low aggregate stability are more prone to erode, thus removing the nutrient rich topsoil. Consequently, this gives rise to reduced crop growth and diminished yields. Meta-analysis by Zhang et al. (2021) found that yield declines with decreasing A horizon below 25 cm and when the decline was less than 25 cm, there was no significant yield decline. Waterlogging can occur in areas with heavy rainfall, particularly in soils that have a low water adsorption capacity or inadequate drainage due to decreased pore space. This excess water accumulation can negatively impact crop yields (Jensen et al., 2003). These intense rainfall events under low infiltration and runoff fields cause conditions such as hypoxia. This leads to a decreased amount of major nutrients, such as nitrogen through denitrification by soil bacteria (Pais et al., 2022). Moreover, hypoxia damages root gaseous exchange and nutrient absorption, specifically nitrogen (de Castro et al., 2022; Herzog et al., 2016) which plays a vital role in yield quantity and quality.

2.13.4. Soil aggregates

Soil aggregates share a complex link to soil quality; whereby ideal soil quality requires a combination of both befitting size and essential quantity of bulky soil aggregates. This arrangement safeguards the soil to hold a positive pore structure, suitable for growing and developing crops (Zhao and Hu, 2022). Admittedly, Rieke et al. (2022) reported sensitivity of all the aggregate stability indicators to intrinsic soil properties, climatic factors or both to a certain measure. This implies that soil aggregate stability has a positive relationship with precipitation. Despite the majority of studies conducted in single regions, it was discovered that areas that receive higher rainfall are associated with greater aggregate stability (Büchi et al., 2022; Cerdà, 2000; Rieke et al., 2022). Wet-dry cycles may have a disrupting effect on soil aggregation, particularly on soil high in clay mineralogy. This occurs due to the swelling of clay particles thus detaching and decreasing aggregate stability (Singer et al., 1992). For instance, studies by Sinoga et al. (2012) reported that soil aggregate stability at low productivity gleyed paddy soils was the lowest level, suggesting a strong soil ability to be degraded. This may be related to the more serious destabilization of soil aggregates resulting from the long-term waterlogging (Gong et al., 1990).

2.14. Implications/suggestions of soil tillage on sustainable crop production practices

Conservation soil tillage (CA) practices have shown significant benefits for soil health and structure compared to conventional soil tillage (CT) methods. Research indicates that reduced soil tillage, especially when combined with cover crops, can enhance soil porosity while decreasing soil density and strength. However, the effects on soil penetration resistance can vary based on soil type, crop rotation, and management practices. One of the key advantages of CA is improved moisture storage, which is particularly crucial in dry years. No-till systems, although they may take time to show results, can significantly reduce evaporation rates and increase water retention capacity.

Conventional soil tillage, on the other hand, can negatively impact soil moisture retention and structure due to its disruptive effects on soil composition and organic matter. It often leads to increased exposure of SOC to decomposition, resulting in a loss of SOM. Additionally, CT can cause soil sealing and reduced moisture infiltration, while also removing valuable crop residues that protect the soil surface. The benefits of CA, particularly NT practices, often become more pronounced over time. Long-term implementation can lead to improvements in soil structural components, such as porosity, BD, and water holding capacity. However, it is important to note that the effectiveness of different soil tillage systems can be influenced by meteorological conditions during crop development periods. No-till systems may be especially beneficial in regions prone to drought or with limited water resources. The impact of soil tillage practices on soil properties and crop production can vary depending on site-specific factors. Therefore, it is crucial to consider local conditions, soil types, soil texture and climate when choosing the most appropriate soil tillage method for a particular agricultural system.

2.15. Conceptual framework

The conceptual framework (Figure 5) delineated in the document elucidates the principal factors influencing soil tillage methods, with particular emphasis on techniques such NT, subsoiling (SS), shallow soil tillage (ST), minimum soil tillage (MT), etc. It underscores the significance of management practices, study duration, soil type, climatic conditions, and soil tillage equipment in determining soil properties and agricultural outcomes. The framework posits that soil tillage methods exert influence on soil friability, SMC retention, and soil compaction, which subsequently impact crop yield and overall soil health. Through the incorporation of these variables, the framework conceptualizes conservation soil tillage as a complex system wherein environmental factors, equipment selection, and soil conditions interact to influence agricultural productivity and sustainability.

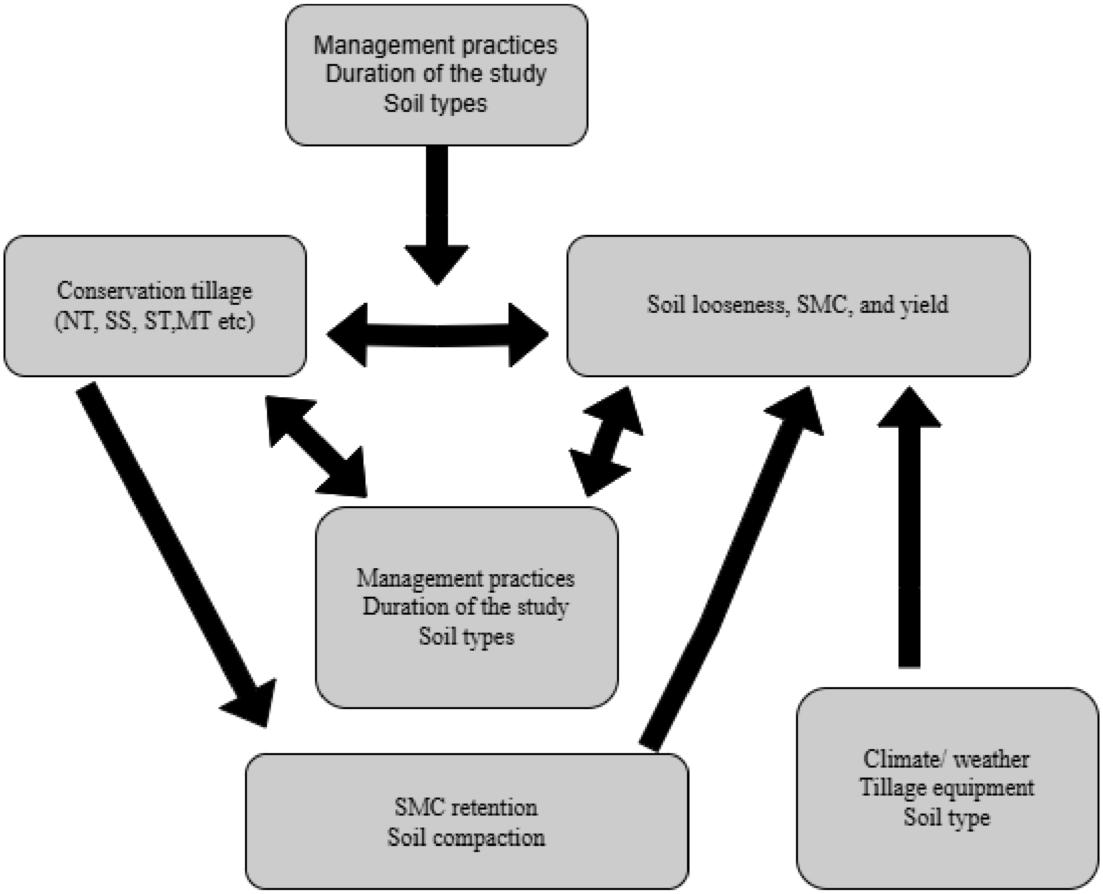

Figure 5. Visual representation of conceptualized conservation soil tillage methods . NT-no-till, SS-subsoiling, ST-shallow soil tillage, SMC-soil moisture content. Source: author

3. MATERIALS AND METHODS

3.1. Study Location

The study was conducted at the Józsefmajor Experimental and Training Farm (JM) of the Hungarian University of Agriculture and Life Sciences near Hatvan (47°41′30.6″ latitude N, 19°36′46.1″ longitude E; 110 m above sea level), established in 2002.

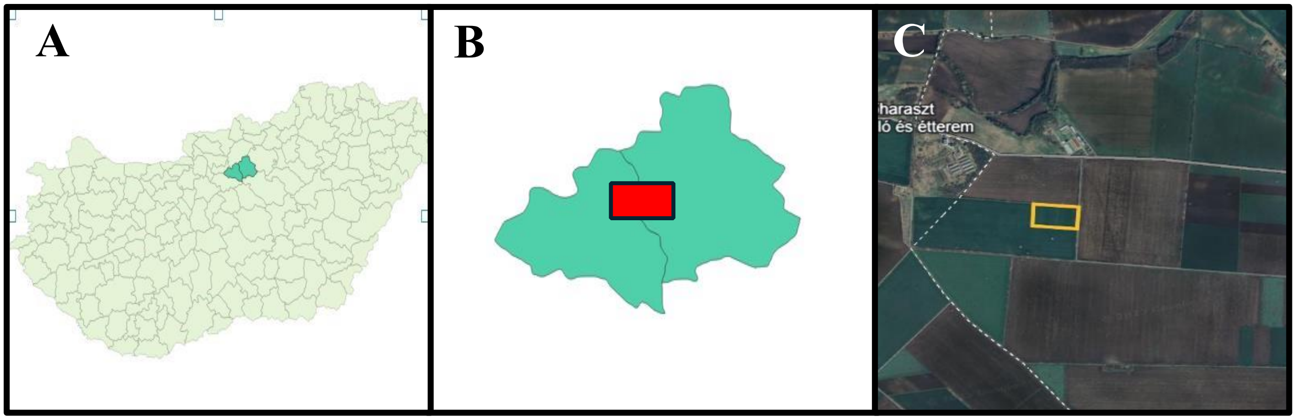

Figure 6. Displays the location of the study area . A – Map of Hungary; B – Position of the study field at regional (at the border separating Pest and Heves county); C – Topographic picture of the experimental field highlighted in yellow color. (Source: Author).

The research area covers 5.05 hectares. The topography is level, with a clay loam texture, classified as Endocalcic Chernozems (IUSS Working Group WRB, 2022). The soil contained a humus content of 3.12% in the top 20 cm layer, with corresponding sand, silt, and clay contents of 36%, 27%, and 37%, respectively (Mohamed et al., 2024). As described by Ács et al. (2015), the climate in Hungary consists of warm, dry summers followed by dry, wet winters, referred to as a continental climate. The weather conditions are classified as continental, with annual temperatures ranging between 10.3 and 15°C during growing periods (New et al., 2002). The mean annual rainfall period from 2018 to 2021 ranged between 500.98 and 643.36 mm (Figure 7). During the duration of the study, the annual rainfall was 117.55, 43.72, and 95.24 mm lower in 2018, 2020, and 2021, respectively, when compared to the average long-term rainfall (1991–2020). Whereas in 2019, the study area received 24.33 mm more rainfall compared to the long-term average (1991–2020).

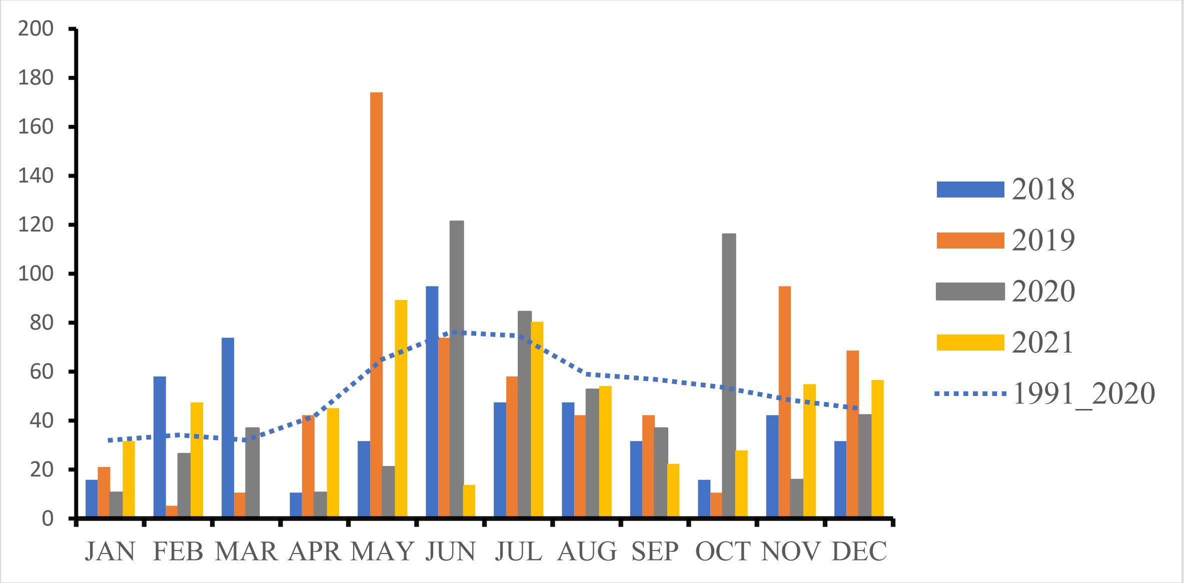

Figure 7. Monthly average rainfall received between 2018 to 2021 and the long-term monthly average rainfall between 1991 and 2020 . Source: NASA's MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2)

3.2. Experimental design

The research area (Figure 8) consists of six soil tillage treatments that are arranged in a completely randomized block design with four replications, and each treatment area has a size of 2340 m^2 (13 m × 180 m).

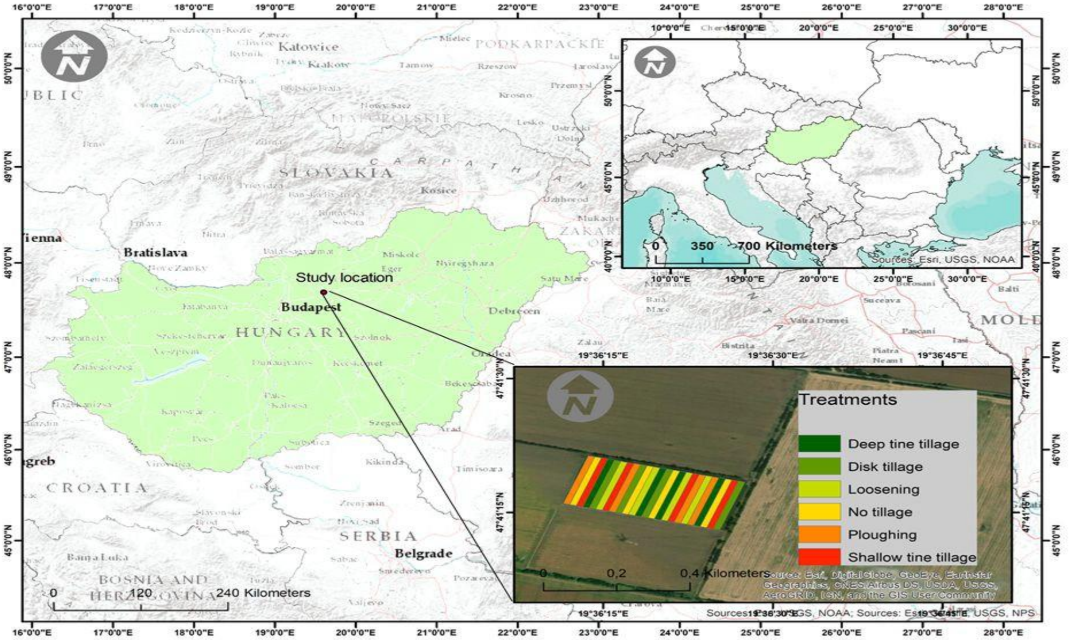

Figure 8. Displays the study design with treatments differentiated by various colors . Source (Dekemati et al., 2020)

The soil tillage treatments were disking (D, 12-16 cm), shallow cultivation (SC, 18-20 cm), no-tilling (NT), deep cultivation (DC, 28-32 cm), loosening (L, 40-45 cm), and ploughing (P, 28-32 cm) (**Table 1)**. Primary soil tillage was performed in correspondence with soil workability.

Table 1. Soil tillage treatments at Józsefmajor Experimental Farm, depth of soil disturbance, and soil tillage equipment employed.

Soil tillage method	**Depth of soil disturbance (cm)**	**Equipment**
Disking (D)	12-14	Väderstad Carrier 500
Shallow cultivation (SC)	18-20	Kverneland CLC Pro
No-soil tillage (NT)	4-6 (depth of sowing)	Väderstad Rapid 300C / Kuhn Maxima 6
Deep cultivation (DC)	22-25	Kverneland CLC Pro
Ploughing (P)	28-30	Kverneland LM100 + packomat
Loosening (L)	40-45	Vogel and Noot TerraDig XS

3.3. Soil moisture content measurement

Soil moisture content (SMC) was measured from 0 to 60 cm depth at 5 cm increments in four replications per treatment, and the data were aggregated to 0–10, 10–20, 20–30, 40–50, and 50–60 cm depths. Measurements were performed in 30-day intervals between March and November of the 2018–2019 and 2020–2021 cropping seasons. A PT-I type gauge (Kapacitiv Kft, Budapest, Hungary), which is based on a time domain reflectometry (TDR) principle, was used to determine SMC (Figure 9). The SMC was shown on the LCD of the instrument as water by weight, %, m/m% (Dekemati et al., 2021). The specified soil is classified as dry, humid, or wet when its moisture content ranges between 14.8–18.9, 19.0–23.9, and >24.0 m/m% SMC, respectively (Csorba et al., 2011).

Figure 9. Soil moisture meter, a PT-I type gauge (Kapacitiv Kft, Budapest, Hungary) .
Source: Dekemati (2020)

3.4. Soil penetration resistance

Soil penetration resistance (SPR) was measured at 5 cm intervals from the surface to a depth of 50 cm, with four replicates per treatment. The collected data were subsequently consolidated into depth ranges of 0–10, 10–20, 20–30, 40–50, and 50–60 cm. Measurements were conducted at 30-day intervals from March to November during the 2018–2019 and 2020–2021 growing seasons. A Szarvas handheld type penetrometer (Mobitech, Hungary) and an Eijkelkamp penetrologger instruments were utilized for SPR measurement (Figure 10). The device employed a conical point with a 1 cm^2 area and a 60° angle.

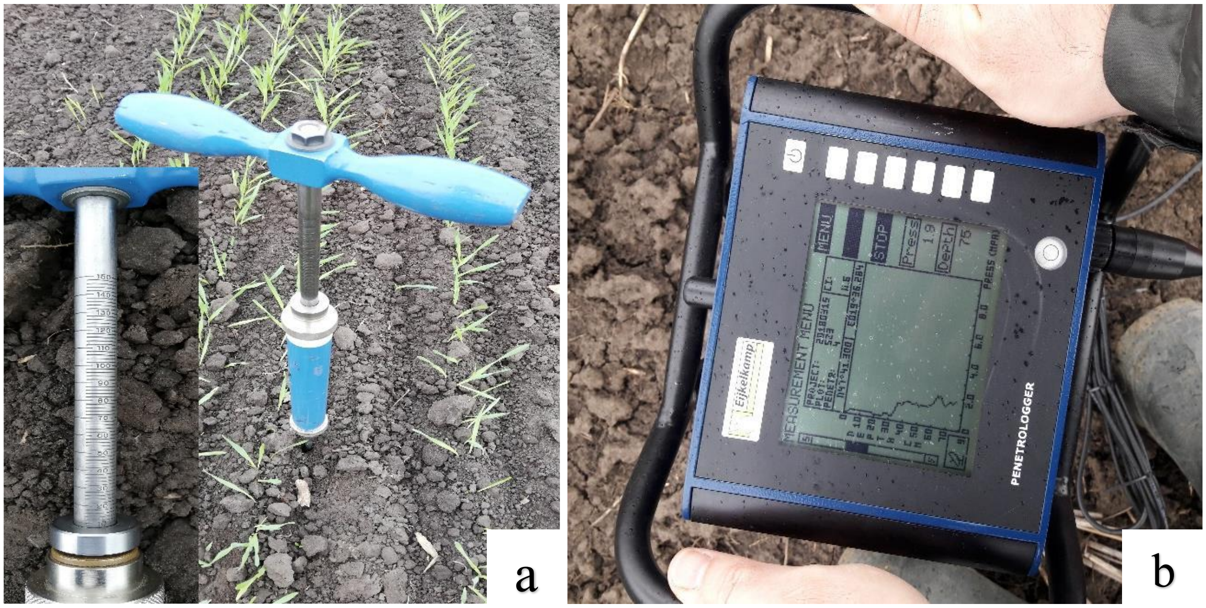

Figure 10. Szarvas-handheld type (a) and Eijkelkamp (b) penetrometers . Photos by Igor Dekemati

3.5. Measured crop parameters

To obtain the fresh root weight, three sunflower plant roots per treatment were randomly selected, collected, then washed, and measured using a digital scale, and the resulting weight was converted to t ha^{-1}. A similar procedure was followed to collect wheat roots with an auger. After collecting, they were washed and weighed with a scale. A 12-row combine harvester was used to harvest sunflower heads. Similarly, wheat was harvested with a 6.6 m width combine, equipped with a straw chopper (Table 2).

The grains were ground for chemical composition of protein determination using the near-infrared (NIR) spectroscopy Product Analyzer (INSTALAB 600). The protein content was expressed as percentage. To determine the thousand kernel weight (TKW), 1000- grains per crop were counted and a weighing balance was used to measure their weight. The HLW was measured determined using a chondrometer. This was done by measuring the weight of the empty chondrometer followed by filling it with winter wheat and winter oat grain to the brim and the weight of the full chondrometer with grain was taken down for each sample, which equals 1 litre of grain. For this measurement each crop's HLW was determined separately. All seed samples were analysed at the Crop Production Laboratory at the MATE Institute of Agronomy. The number of spikes square meter was determined in the field by randomly selecting and measuring the area then followed by enumerating the number of spikes within the selected area in four replications.

Table 2. Summary and dates of the activities done during sunflower cropping season

Winter Wheat cropping activities		
Activity	**Description**	**Date**
Fertilization	NPK (20, 100, 60 kg ha^{-1})	2018.10.10
Soil tillage	Ploughing, cultivation with cultivators	2018.10.10
Soil tillage	Loosening, disking, ploughing and processing with a disc	2018.10.11
Sowing:	258 kg ha^{-1} (winter wheat)	2018.10.26
Germination and cultivation	Wheat emergence and shallow ploughing	2018.11.10-12.23
Fertilization	1st Top dressing	2019.02.11
Spraying		2019.04.09.
Harvesting	John Deere W650	2019.07.18.
Winter Oat cropping period activities		
Spraying	Fozat 480 3 l (a.i. *glyphosate*)	2019.07.25
Fertilization	NPK: 6:24:12, 300 kg. power/ha^{-1}	2019.10.02
Soil tillage	All treatments	2019.10.02
Sowing	Rapid 300, 175 kg/ha^{-1}, Mv Hópehely	2019.10.09.
Fertilization	1st Top Dressing Nitrosol, 60 kg ha^{-1} *(a.i. 30% Nitrogen)*	2020.02.20.
Spraying	Sekator OD, 0.15 L ha^{-1}, *(a.i. Amidosulfuron, Iodosulfuron-methyl-sodium, and Mefenpyr-diethyl).*	2020.04.10
Spraying	Tango Star 1 L ha^{-1}, (a.i. *fenpropimorph* and *epoxiconazole*) (JD4830)	2020.04.10

Spraying	Decis Mega, 0.15 l ha^{-1}	2020.05.16, 05.27
Harvest	John Deere W650	2020.07.15
	Sunflower cropping period activities	
Spraying	Fozát 480, 3 L ha^{-1}	2020.09.10
Soil tillage	P, L, D, DC, and SC	2020.10.16.
Fertilization	120 kg ha^{-1} 27% CAN" $NH_4 + NO_3$ + dolomite	2021.03.31
Spraying	Fozát 480, 6 L ha^{-1}	2021.03.31
Seedbed preparation	Appropriate land preparation with Metalwolf 3.8/4.2 combiner	2021.04.23
Sowing	56000 seed ha^{-1}, Syngenta SY Onestar CLP planted with KUHN Maxima 6 sowing machine	2021.04.23
Spraying	Pulsar 40SL *(a.i. imazamox)*, 1.2 L ha^{-1} + Silwet Star 0.1 L ha^{-1} *(a.i. 80 % heptamethyl trisiloxane + 20 % allyloxy polyethylene glycol).*	2021.06.01.
Spraying	Pulsar 40SL *(a.i. imazamox)*, 1.2 L ha^{-1} + Silwet Star 0.1 L ha^{-1} *(a.i. 80 % heptamethyl trisiloxane + 20 % allyloxy polyethylene glycol).*	2021.06.01.
Spraying (desiccation)	Dessicash 20SL (a. i.*diquat dibromide, 240 g per liter*,), 1.6 L ha^{-1}	2021.08.30
Harvest	Claas Lexion 660	2021.09.12

a.i: active ingredient(s)

3.6. Statistical Analysis

Data collected was recorded in excel sheet followed by data curation. The final curated data was subjected to R-software version 4.3.1 for statistical analysis. Firstly, before data analysis, the skewness of the data was checked by computing the Kolmogorov– Smirnov test and the Shapiro–Wilk test (Shapiro and Wilk, 1965; Massey Jr, 1951). The results indicated that the following assessed parameters SPR, SMC, hectoliter weight (HLW) (for both wheat and oat), wheat grain yield (GY) and root weight (RW) data were not normally distributed ($p<0.05$). Hence, to assess the relationship of tillage on SPR and SMC a generalized mixed effect model was employed to account for random effects, including depth and season. While for hectoliter weight (HLW), wheat grain yield, and (RW) data wer subjected to square root transformation and means were separated using analysis of variance at 5% level of significance. Mean separation was done with Tukey HSD post-hoc test at p = 0.05. The correlation relationships of the parameters assessed were calculated based on skewness of the data. For instance, the normally distributed parameters were subjected to Pearson correlation while a Spearman's rank test was employed for non-parametric parameters.

4. RESULTS AND DISCUSSION

The following results and discussion will address the specific objectives and research questions that were listed in Chapter 1. The following study assesses the response of SPR, SMC, crop yield and yield components of sunflower, oats, and wheat under various soil tillage practices. The results of this study will provide insights into which soil tillage practice(s) provide better climate resiliency and still maintain or improve the soil's ability to provide ecosystem services, good quantity and quality crop returns.

4.1. The effect of soil tillage on soil moisture content

The analysis of the current study's field measurements was subjected to a generalized linear mixed models in R for statistical analysis. As mentioned by Soucémarianadin et al. (2018) and Stockmann et al. (2013) that physical and chemical parameters differ in response to extenal factors (environemnant and anthropogenic). Similar to the current study's results, the measured results of the 0-50 cm depth presented by Table 4, A2. Figure 26-A2. Figure 28, and the ANOVA results (Table 3) confirmed the variation of soil tillage on SMC. Soil moisture content response to soil tillage substantial variation was observed between winter wheat, winter oat, and sunflower (Table 4) at 0-50 cm depth. During winter wheat NT substantially differed from L, while in winter oat growing season substancial differences were observed between NT and P with NT proving more superior in enhancing SMC. This could be attributed to the soil disturbance by the loosening implement and the availability of higher SOM, earthworm activities and improved soil structure under NT. While in sunflower cropping period P significantly reduced SMC compared to other soil tillage variants. Consistent ploughing without variation of the ploughing depth, encourages the development of plough pan just below the ploughing depth. This reduces the soil porosity and destroys their continuity thus negatively affecting soil moisture infiltration. In contrast the depth of loosening is much deeper that ploughing. By loosening, this breaks any natural or anthropogenic soil impedence and creates deeper grooves. Thus, providing deeper easy moisture infiltration and storage. This ultimately increases the SMC of the L treatment (Zhou et al., 2017). Although SPR in the current study did not vary between the two soil tillage treatments, it can be hypothesized that the SMC difference is due to depth of loosened layer storing greater moisture in L treatment than P.

Table 3. ANOVA table for soil moisture content at 0-50 cm

	Df	Sum Sq	Mean Sq	F value	Pr(>F)

Treatments	5	295	59.034	2.5686	0.02534 *
Replication	3	2	0.553	0.0241	0.99495
Residuals	1431	32888	22.983		

*Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 4. Soil moisture content measured from 0-50 cm under different soil tillage treatments for winter wheat, oat and sunflower cropping seasons.

Treatments	**Winter Wheat**	**Winter Oat**	**Sunflower**
	Mean ± SD		
Disking	26.24±4.80ab	24.95±4.82ab	25.29±4.21b
Shallow Cultivation	25.84±4.92ab	24.70±4.85ab	25.16±4.31b
No-Till	26.42±4.40b	25.33±4.50b	25.51±4.08b
Deep Cultivation	25.60±4.59ab	24.46±5.25ab	24.97±4.61b
Ploughing	26.08±4.37ab	23.48±5.07a	23.51±6.03a
Loosening	25.27±4.93a	24.42±4.94ab	24.88±4.36b

Means ± SD with same lower-case letters between soil tillage treatments indicate statistical similarity at 5% level of significance.

The results under winter wheat growing season at various soil depths showed that both soil tillage and depth significantly influenced SMC (Table 5). At 10–20 cm during winter wheat cropping period, SMC was significantly higher under D (26.36 m/m%) compared to L treatment. Additionally, SMC at NT treatment was also significantly different to L.

At 20–30 cm, SMC was significantly lower under L and DC compared to D and NT. Furthermore, no statistically significant differences were detected among P, SC, NT, and D. At 30–40 cm, significantly higher SMC was observed at P (29.16 m/m%) compared to the lowest at L (28.16 m/m%). At 40–50 cm, significantly higher SMC was observed at P relative to L. In all assessed treatments, SMC significantly increased with depth.

Table 5. Winter wheat **-** Soil moisture content measured at various soil depths

Winter Wheat (2018-2019)						
Depth (cm)	**Disking**	**Shallow Cultivation**	**No-Till**	**Deep Cultivation**	**Ploughing**	**Loosening**
0-10	18.21±3.38aA	17.75±3.42aA	18.99±2.31aA	18.25±3.73aA	18.83±2.44aA	17.69±3.49aA
10-20	26.36±2.64bB	25.45±2.49abB	26.19±2.64bB	25.28±2.34abB	25.26±1.95abB	24.81±3.14aB
20-30	28.12±2.13bC	27.97±2.04abC	28.18±1.82bC	26.93±2.22aC	27.28±1.86abC	26.84±2.75a
30-40	29.06±1.84 abCD	28.97±2.08 abC	29.12±1.62 abCD	28.35±2.06abD	29.16±1.36bD	28.16±2.37aCD
40-50	29.44±1.66abD	29.09±2.04abC	29.62±1.47abD	29.21±1.73abD	29.80±1.30bD	28.84±2.26aD

Means ± SD followed by the same lower-case letters between soil tillage treatments and the same upper-case letters between depths indicate statistical similarity at the 5% significance level.

The SMC results under winter oat crop showed significant differences from soil tillage treatments and depth (**Table 6**). At 0-10 cm, SMC was significantly higher under NT compared to P. At 40-50 cm, disking (D) significantly increased SMC compared to loosening (L). Regarding depth, SMC increased with increasing depth in soil tillage treatments. Meanwhile, SMC P and L at 20-30 differed significantly to 30-40 and 40-50 cm. Treatments NT, D, SC, and DC had significantly greater SMC compared to L.

Table 6. Winter oat - soil moisture content measured at various sampling periods under different soil tillage treatments.

Winter Oat (2019-2020)						
Depth (cm)	**Disking**	**Shallow Cultivation**	**No-Till**	**Deep Cultivation**	**Ploughing**	**Loosening**
0-10	16.43±2.23abA	16.43±2.26abA	17.51±1.85bA	15.72±2.81abA	15.20±3.07aA	16.28±2.73abA
10-20	25.27±2.38aB	24.38±2.65aB	25.39±2.34aB	24.26±3.14aB	24.17±2.61aB	24.42±3.18aB
20-30	27.17±2.28aC	26.85±2.61aC	27.33±2.37aC	26.61±3.08aC	25.85±2.67aAB	26.37±2.92aAB
30-40	27.74±1.69aC	27.72±1.73aC	27.96±1.73aC	27.61±2.03aC	26.48±2.11aC	27.22±2.04aC
40-50	28.15±1.31bC	28.13±1.23bC	28.47±1.32bC	28.12±1.47bC	26.83±1.41aC	27.83±1.60abC

Means ± SD followed by the same lower-case letters between soil tillage treatments and the same upper-case letters between depths indicate statistical similarity at the 5% significance level.

Sunflower SMC results were measured in the 2020/21 cropping season (Table 7). Based on the meteorological data the growing period received insufficient, particularly the second period of the growing season in 2021 (Figure 7). At 0–10 cm, a significant SMC increase of 13% and 17% was observed at D and NT, respectively, relative to P. However, at 10–20 cm, NT significantly increased SMC by 66% similar to D. Meanwhile, at 20–30 cm, 30–40 cm, and 40–50 cm, P was significantly lower by 3%, 2%, and 16%, respectively, relative to NT.

Table 7. Sunflower **-** Soil moisture content measured at various sampling periods under different soil tillage treatments.

Sunflower (2020-2021)						
Depth (cm)	**Disking**	**Shallow Cultivation**	**No-Till**	**Deep Cultivation**	**Ploughing**	**Loosening**
0-10	17.48±1.38bcA	17.33±1.80bcA	18.10±1.72cA	16.59±2.02bA	15.52±2.16aA	16.99±1.81bA
10-20	25.70±1.57bB	25.32±1.86bB	25.73±1.63bB	24.92±1.72bB	24.76±2.03aB	24.91±1.61bB
20-30	27.07±1.30bcC	27.02±1.43bcC	27.15±1.41cC	26.89±1.32abcB	26.26±1.27aBC	26.40±1.38abC
30-40	27.90±1.10abD	27.96±1.19abD	28.08±1.16bD	27.98±1.10abD	27.47±1.12aCD	27.75±1.10abD
40-50	28.32±0.89bD	28.20±0.91bD	28.49±0.94bD	28.47±0.87bD	24.56±9.21aD	28.36±0.89bD

Means ± SD followed by the same lower-case letters between soil tillage treatments and the same upper-case letters between depths indicate statistical similarity at the 5% significance level.

In this study no-till (NT) conserved higher SMC in all the cropping seasons (Table 4). This may be due to greater soil micro-aggregate concentration in the top layer (0–10 cm) compared to conventional soil tillage. This promoted higher SMC storage at this depth. Although these differences were not statistically significant, they are consistent with the findings of Dekemati et al. (2019b), who also observed the impact of stubble retention on SMC levels in the same study area. Adequate stubble retention with at least a 30% soil cover ratio in NT treatment plots protects the soil from harsh weather conditions, consequently reducing evaporation. However, it is important to note that SMC was occasionally higher in CT than the conservation soil tillage practices (SC and NT) at various depths (Table 5). This can be explained by the amount of precipitation that occurred during the cropping period. Precipitation was fairly distributed throughout the year, with May receiving 174.02 mm downpours (Figure 7). The current work's results are consistent with various (Budu et al., 2022; Kühling et al., 2017; Ramos et al., 2019) studies that reported higher SMC under conservation soil tillage than under conventional soil tillage.

Particularly notable was the significant difference in SMC between P and NT at the depth of 20–30 cm which highlights the contrasting impacts of CT versus conservation soil tillage practices (Table 7). Our findings underscore the continued positive influence of conservation soil tillage methods on soil moisture conservation.

The substantial differences in SMC between SC, D, and NT at the depth of 40–50 cm compared to ploughing were noteworthy, with respective differences of 3.64 m/m%, 3.76 m/m%, and 3.93 m/m%. Generally, findings in this study underscore the efficacy of conservation soil tillage practices, such as NT, in maintaining higher soil moisture levels at deeper soil depths compared to traditional ploughing methods. Such differences hold significant implications for agricultural management strategies. We posit that improved conservation soil tillage methods hold the potential to mitigate soil moisture deficits and enhance overall soil health and productivity.

Regarding the sampling time, substantial differences were observed during the study period (Table 8**).** In March, a significantly higher SMC was observed at P (24.06 m/m%) followed by NT (23.88 m/m%) compared to L (20.53 m/m%) in winter wheat crop. No significant differences were observed between soil tillage treatments in April, June 28, and August. However, on June 3, SMC was significantly lower at L treatment compared to D. Considering the differences between sampling dates, the SMC increased with time in all treatments.

Table 8. Winter wheat **-** Soil moisture content measured at various sampling periods under different soil tillage treatments.

Winter Wheat (2018-2019)						
Measuring Date	**Disking**	**Shallow Cultivation**	**No-Till**	**Deep Cultivation**	**Ploughing**	**Loosening**

14 Mar	22.76±4.88abA	21.72±4.99abA	23.88±4.38bA	21.78±4.49abA	24.06±4.65bA	20.53±4.85aA
11 Apr	25.19±3.72aB	25.94±3.54aB	25.19±3.47aAB	26.27±2.58aB	25.23±2.85aAB	25.45±3.25aB
3 Jun	27.96±3.18bC	26.50±4.48abB	26.83±4.12abBC	25.81±3.98aB	26.41±4.38abBC	25.38±3.72aB
28 Jun	27.09±5.87aBC	27.05±5.53aB	27.92±5.01aC	26.48±5.63aB	26.73±5.12aBC	27.04±5.35aBC
15 Aug	28.18±3.68aC	28.01±3.23aB	28.29±3.21aC	26.68±3.45aB	27.94±3.58aC	27.93±3.61aC

Means ± SD followed by the same lower-case letters between soil tillage treatments and the same upper-case letters between depths indicate statistical similarity at the 5% significance level.

Soil moisture during the winter oat cropping period was measured only two times (March and September) (Table 9). In the first measurement, there were significant differences observed between treatments. Despite the lack of significant differences, NT had the highest SMC values compared to all the other treatments, while the lowest SMC value was measured under P. Similar to the first measurement, there were no significant differences in the second measurement between treatments. However, the highest SMC value was observed under NT and the lowest under P. The differences between measuring time/date showed significant differences in all treatments. Soil moisture content in all treatment plots increased significantly with time.

Table 9. Winter oat - Soil moisture content measured at various sampling periods under different soil tillage treatments.

Winter Oat (2019-2020)						
Measuring Date	**Disking**	**Shallow Cultivation**	**No-Till**	**Deep Cultivation**	**Ploughing**	**Loosening**
19 Mar 20	23.12±4.65aA	22.75±4.66aA	23.51±4.20aA	22.09 ± 4.98aA	21.64 ± 4.996aA	22.10±4.60aA
19 Sep 20	26.78±4.30aB	26.65±4.24aB	27.09±4.11aB	26.83 ± 4.40aB	25.62±4.30aB	26.75±4.13aB

Means ± SD followed by the same lower-case letters between soil tillage treatments and the same upper-case letters between depths indicate statistical similarity at the 5% significance level.

In 2021, soil moisture difference between treatments were observed in the first measurement under sunflower crop (Table 10). In October, November, and March, NT showed a 7%, 5%, and 4%, respectively, higher SMC relative to P. In September, a significantly higher SMC was observed at D, SC, NT, DC, and L than at P. SMC differences between the sampling dates showed that at P and L, there were no significant differences among sampling dates. Soil moisture content showed a monthly fluctuation (increasing and decreasing).

Table 10. Sunflower - Soil moisture content measured at various sampling periods under different soil tillage treatments.

Sunflower (2020-2021)

Measuring Date	Disking	Shallow Cultivation	No-Till	Deep Cultivation	Ploughing	Loosening
9 Sep 2020	26.65±4.23bB	26.43±4.13bB	26.90±4.01bB	26.68±4.32bB	22.37±9.25aA	26.60±4.05bB
23 Oct 2020	26.15±3.91aB	25.93±4.16aB	25.87±4.04aB	24.94±4.97aAB	24.13±4.95aA	25.03±4.56aAB
17 Nov 2020	25.32±4.09aAB	25.85±3.86aB	25.52±3.76aB	24.79±4.57aAB	24.32±4.90aA	24.84±4.23aAB
16 Mar 2021	23.62±4.44aA	22.97±4.74aA	23.28±4.38aA	23.16±4.84aA	22.43±5.65aA	23.19±4.71aA
24 Apr 2021	24.73±3.79aAB	24.65±3.85aAB	25.97±3.34aB	25.29±3.66ABa	24.24±4.00aA	24.74±3.60aAB

Means ± SD followed by the same lower-case letters between soil tillage treatments and the same upper-case letters between depths indicate statistical similarity at the 5% significance level.

The results of the study suggest that there is a complex relationship between soil tillage practices and soil moisture levels, which cannot be simply generalized. Specifically, during the sampling periods in April and June, the highest SMC was observed when loosening was practiced, while in August, no-soil tillage practices were associated with higher moisture levels. This pattern can be attributed to the impact of soil tillage techniques on soil structure and moisture dynamics. Deep soil tillage methods, such as loosening, can extend the loosened layer in the soil and increase moisture infiltration rates. In contrast, the presence of a protective mulch layer in NT may mitigate evaporation rates and sustain higher soil moisture levels. These findings emphasize the importance of considering multiple factors in agricultural management decisions, as the interaction between soil tillage practices, soil structure, and moisture retention is complex and nuanced. Our results are in line with those of Jin et al. (2007), who observed significantly greater SMC of 18.9 and 20.8% relative to P in May 2005 at 20–40 and 40–60 cm depths under loosening. Fu et al. (2003) reported that half of summer rainfall in arid wheat fields was obtained under subsoiling. Moreover, subsoiling enhanced soil water storage capacity by 76.2 mm in 0–2 m depth prior to planting. The highest SMC obtained on the 3rd of June under D is attributed to the high rainfall (174.02 mm) received in May. Plausibly, the increased density of soil that results from an annual disking application is more pronounced in humid soils, which could lead to higher SMC in the rhizosphere. Lukacs et al. (2008) pointed out that in wet seasons high soil density in the rhizosphere leads to relative water abundance in a rainy period.

4.2. The effect of soil tillage on soil penetration resistance

The SPR result at 0-50 cm under different soil tillage treatments for wheat, oat and sunflower can be shown by Table 11, A2. Figure 30, A2, Figure 31, and A2. Figure. 32. Soil tillage significantly affected SPR in all cropping (winter wheat and sunflower) seasons $p < 0.05$. Considering all cropping seasons and the 0-50 cm depth, significantly greater SPR was observed in D and NT compared to L treatments which had the lowest SPR. This finding agrees with other authors, for instance, Bogunovic et al. (2014) in Croatia found greater compaction in NT and shallow soil tillage systems compared to traditional soil tillage. Another study conducted under the current study's soil and climatic conditions also reported higher SPR under NT and D treatments (Dekemati et al., 2019b). Variation of SPR under different soil tillage treatments in 0-50 cm depth could be reduced and absence of soil disturbance. Other assessed treatments DC, P, and L were disturbed to deeper depths than NT and D. Hence this reduced soil density in the top layers, however NT and D treatments begin to experience compaction in the topsoil layer. Moreover, disking is detrimental on the soil this is worsened by the type of texture. Birkás et al. (2002) mentioned that soil with clay texture and high SMC usually experience compaction when repeatedly tilled with a disk implement. This occurs due to slipping of the disc plates, thus compacting the soil below the depth of disking (Birkás, 1987; Spoor, 1991).

Similar, SPR trends were observed in winter oat and sunflower cropping seasons despite the variations in annual rainfall amounts received per season. Treatment D *(*2.21 MPa*)* in winter oat and sunflower exhibited significantly greater SPR relative to SC, DC and L (Table 11). Birkás et al. (2004) observed a disk-pan formation after three years, with critical SPR values of 3.75 MPa after five years and 4.6 MPa between years 7–10 resulting from disking. They also elucidated that the use of heavy-duty cultivator minimizes some of the negative impacts of a disk and subsoiler. As shown by the results of this study (Table 11), throughout the three experimental seasons SPR remained consistently lower under L treatment compared to D. This could be attributed to the crumb ratio, although not measured in this study, however, reports from Dekemati et al. (2021) in Croatia on a Stagnosols highlights that DC and SC produced better agronomic structure consisting of greater crumb ratio as compared to P. This reduced dust formation, increased earthworm abundance ultimately positively regulating SPR. Bogunovic et al. (2019) also reported lower soil crumb ratio of 31.5% on average on a Chernozem soil under P and D treatments compared to shallow soil tillage (ST), deep cultivation (T), loosening (L) and direct drilling (DD).

Soil penetration resistance was significantly greater in NT *(2.03 MPa)* than SC *(1.71 MPa)*, DC *(1.63 MPa)*, P *(1.40 MPa)*, and L *(1.45 MPa)*. This finding corroborates with both local and international studies (Bogunovic et al., 2019, 2015; Dekemati et al., 2019b). In crop production various studies point out that NT is associated with greater SPR. This occurs due to continuous traffic when agronomical practices, such as planting, and fertilizer application are executed. The implements used tire pressure compresses the soil particles thus resulting in higher soil density.

Interestingly, DC showed significantly greater SPR compared to P *(1.40 MPa)* and L *(1.45 MPa)*. Similarly, SC *(1.71 MPa)* had significantly higher SPR relative to P *(1.40 MPa)* and L *(1.45 MPa)*. This finding is disagreement with the finding of Dekemati et al. (2021), who observed lower SPR in DC treatments compared to P. from 2016-2018. However, in 2017 they observed greater SPR compared to P and DC which is agreement with the finding of this study. Higher SPR under P is a norm due to the force exerted by the plough. Moreover, when ploughing is done usually the one side of the tractor wheel drives in the furrow thus the weight of the machine further compacts the soil. In earlier studies in northern Europe, Keller (2004) pointed out that in general plastic strain was noticed above 50 KPa. This shows that normally employed modern agricultural wheel loads irrespective of the tire size and air pressure likely cause deeper permanent compaction that cannot be fixed naturally (Håkansson and Reeder, 1994).

Table 11. Winter wheat, winter oat and sunflower SPR measured at 0-50 cm under different soil tillage treatments.

Treatments	**Wheat**	**Oat**	**Sunflower**
		Mean ± SD	
Disking	3.02± 1.83c	2.21±0.61c	1.75±0.57c
Shallow Cultivation	2.49± 1.68ab	1.71±0.53b	1.40±0.74b
No-till	2.88± 1.85bc	2.03±0.49c	1.75±0.60c
Deep Cultivation	2.50±1.73ab	1.69±0.55b	1.36±0.69b
Ploughing	2.49± 1.70ab	1.40±0.57a	1.06±0.65a
Loosening	2.42±1.60a	1.45±0.54a	1.07±0.61a

Means ± SD with same lower-case letters across soil tillage treatments indicate statistical similarity at 5% level of significance.

Regarding the spatial differences, during winter wheat cropping season at 0–10 cm, soil tillage significantly increased SPR at D (55% higher) compared to L. This was followed by NT, which was 52% and 47% higher compared to L and P, respectively (Figure 11A). Furthermore, SPR at D and NT were significantly higher than in SC by 34% and 31%, respectively. At 10–20 cm, SPR increased above the 2.00 MPa in D and NT treatments (Figure 11B). Moreover, D was significantly higher compared to P and L by 54% and 46%, respectively, while NT was significantly greater than P and L by 41% and 34%. The SPR in DC was also significantly higher relative to D and NT (Figure 11B). At 20–30 cm, a similar trend to the latter depth was observed (Figure 11C), while at 30–40 cm, the highest SPR among all the treatments was observed at D, while the lowest was recorded at L (Figure 11D). Similarly, at the 40–50 cm depth, the highest SPR was observed at D, and the lowest was found at SC.

The SPR differences between depths showed an increasing trend with an increase in depth across all the treatments investigated soil tillage.

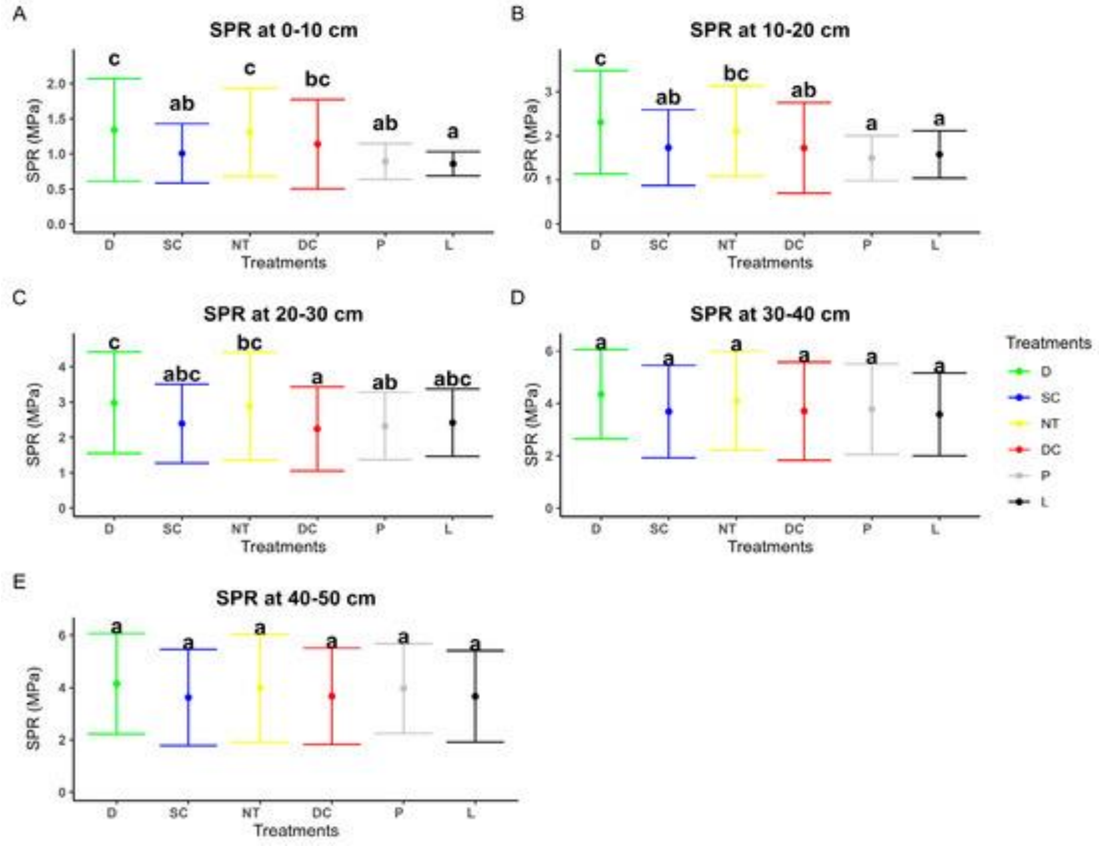

Figure 11. Spatial SPR variations for wheat cropping season at various depths . *(A) 0—10 cm, (B) 10—20 cm, (C) 20—30 cm, (D) 30—40 cm, and (E) 40—50 cm. D—disking, SC—shallow tine cultivation, NT—no-till, DC—deep tine cultivation, L—loosening, P—plowing. SPR mean values with the same lowercase letter indicate no significant difference at p > 0.05. Error bars show the standard deviation of the mean.*

The results of spatial effect of soil tillage on SPR during oat cropping period. During winter oat growing period at 0-10 cm, SPR was significantly greater under D *(2.32 MPa)* compared to P *(1.60 MPa)*, which showed the lowest (**Figure 12**). Treatment L did not differ significantly from P, however, compared to D, L improved SPR. The study's treatments when considering individual values, they showed the following trend NT>DC>L>SC. At 10-20 cm, soil tillage significantly affected SPR with the greatest measured under D *(2.57 MPa)* and NT *(2.26 MPa)* compared to P *(1.71 MPa)*. At 20-30 cm, similar to the latter depth higher SPR was observed under D and NT. The overall SPR values at 20-30 cm showed the following trend D>NT>SC>DC>L>P. At 30-40 cm, treatments significantly lowest SPR was observed under P *(1.16 MPa)* and L *(1.16 MPa)*, both soil tillage treatments recorded equal values. At 40-50 cm, significantly lower SPR was observed under L treatment *(1.67 MPa)*, but statistically L only differed with treatment D which recorded the highest SPR *(1.67 MPa)*.

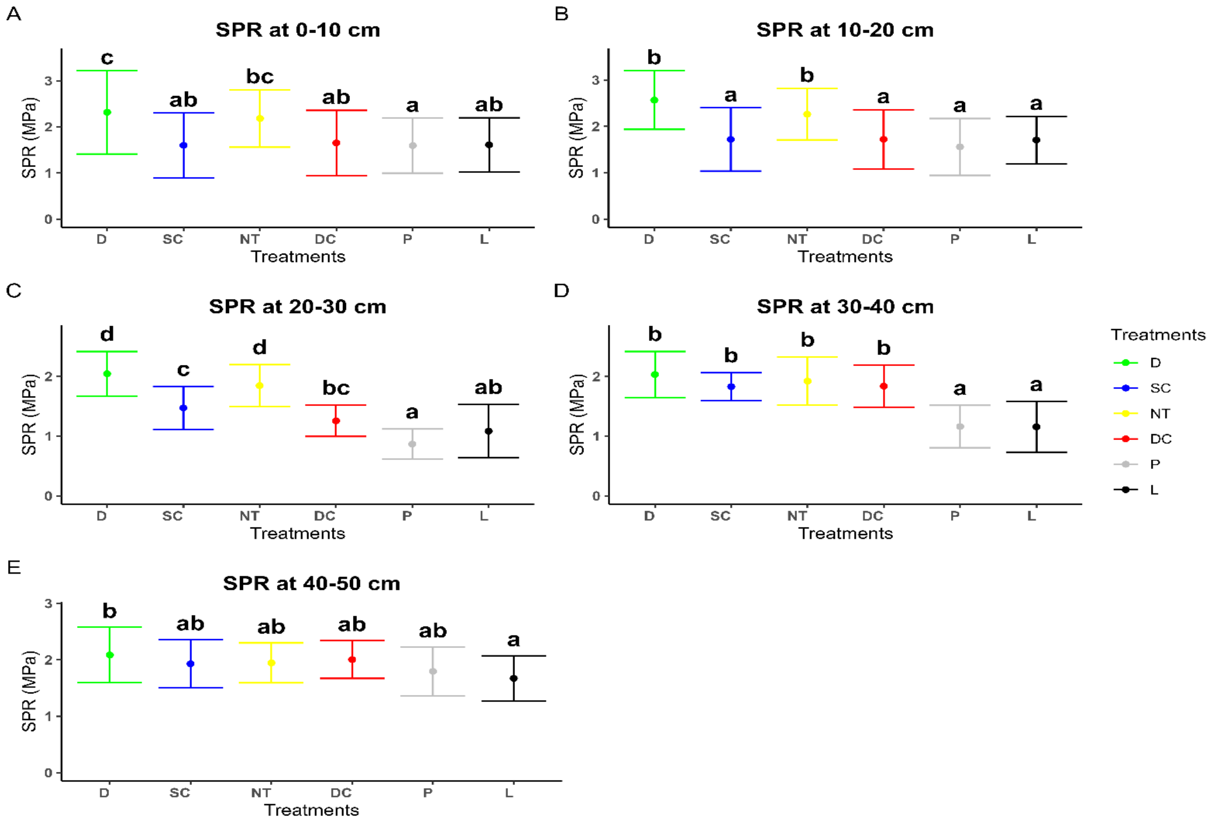

Figure 12. Average spatial SPR at various soil depths measured in 2019/20 oat cropping season at different depths. *(A) 0-10 cm, (B) 10-20 cm, (C) 20-30 cm, (D) 30-40 cm, and (E) 40-50 cm. D-disking, SC-shallow cultivation, NT-no-till, DC-deep cultivation, L-loosening, P-ploughing. SPR mean values with the same lowercase letter indicate no significant difference at p > 0.05. Error bars show the standard deviation of the mean.*

Regarding depth, at 0–10 cm, D and NT soil tillage methods significantly increased the average SPR (Figure 13). The greatest mean SPR measured at NT was 98% higher compared to P and L. While SPR at D was 82% higher compared to P and L; however, compared to NT, the difference was not significant.

At 10–20 cm, SPR was significantly 163%, 134%, and 91% higher at D *(1.90 MPa)*, L *(0.81 MPa)*, and DC *(0.96 MPa)*, respectively, compared to P *(0.72 MPa)*. Due to limited soil disturbance, SPR was highest under D *(1.90 MPa)*, followed by NT *(1.82 MPa)* and SC *(0.99 MPa)*, reflecting the accumulation of compacted layers over time. While soil tillage methods characterized by greater soil disturbance (P and L) showed lower SPR values. The nature of deep cultivation enables deeper soil loosening compared to SC however, there was a lack of significant difference observed between the two soil tillage methods. At 20–30 cm, the mean SPR values for D *(1.96 MPa)* and NT *(1.96 MPa)* were statistically similar. The average SPR values between soil tillage treatments showed the following trend: D = NT < SC = DC < L < P. The lowest SPR was observed at P, while the highest values were observed at both NT and D. The SPR at D and NT was 133% and 87% higher compared to P and L, respectively. At 30–40 cm, SPR was significantly greater at D *(1.94 MPa)* and lowest at L *(1.22 MPa)*. The average SPR measured among treatments showed the following trend: D < NT < DC < SC < P < L. At 40–50 cm, significant differences among soil tillage treatments were observed between SC and L. The SPR under SC was 20% higher compared to L.

Regarding differences between depths, SPR increased with increasing depth in all treatments. Moreover, SPR exceeded 2.00 MPa at 40–50 cm at SC and DC. With respect to the sampling period, SPR in September 2019 was 55% significantly greater at NT compared to L. There were no significant differences at D, SC, and NT. However, overall, SPR values showed the following order: NT < D < SC. In October 2019, D soil tillage treatment *(1.64 MPa)* increased SPR by 85% *(0.84 MPa)*, 85% *(0.84 MPa)*, 56% *(1.05 MPa)*, and 43% *(1.15 MPa)* compared to L, P, DC, and SC, respectively.

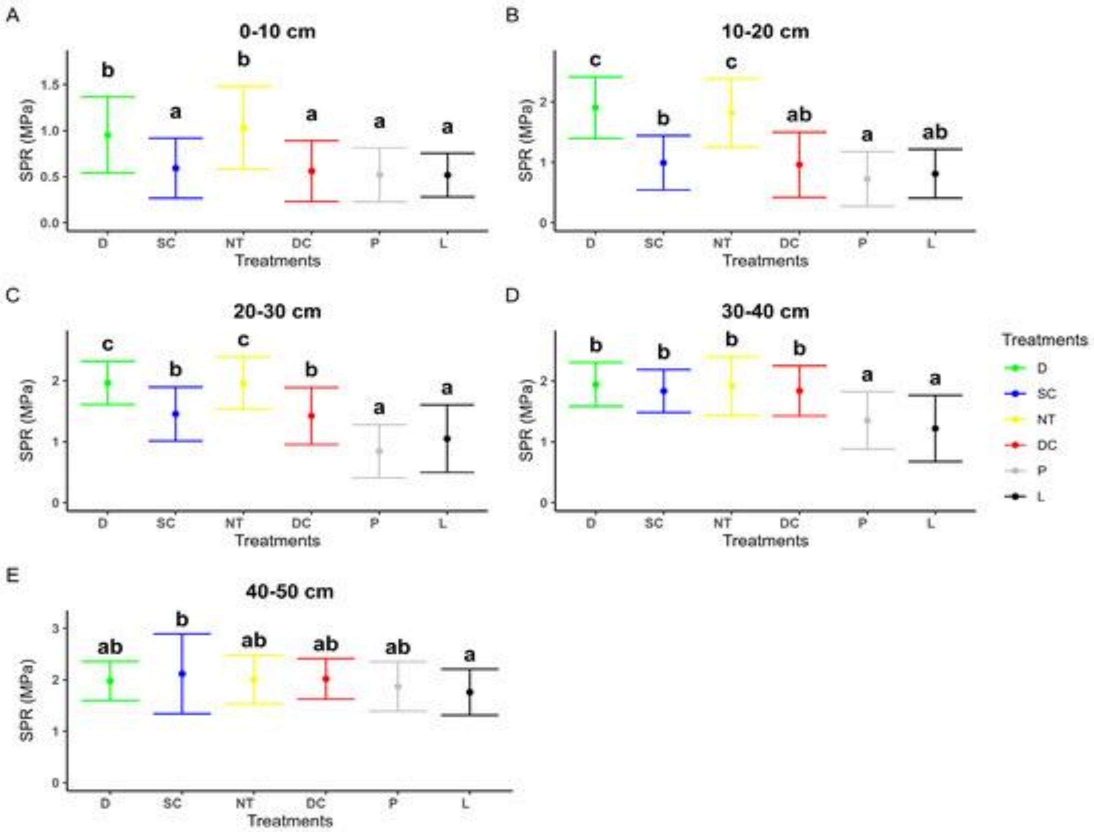

Figure 13. Spatial average SPR at various soil depths measured in 2020/21 sunflower cropping season at different depths . *(A) 0-10 cm, (B) 10-20 cm, (C) 20-30 cm, (D) 30-40 cm, and (E) 40-50 cm. D-disking, SC-shallow cultivation, NT-no-till, DC-deep cultivation, L-loosening, P-ploughing. SPR mean values with the same lowercase letter indicate no significant difference at p > 0.05. Error bars show the standard deviation of the mean.*

The greatest SPR at 0-10 and 10-20 cm under D throughout the experimental period, relative to the lowest observed under P proved the beneficial effect of ploughing in reducing soil density. These findings align with Dekemati et al. (2019b) who reported higher SPR under NT and D soil tillage treatments at 10 and 20 cm depths. Similarly, Bogunovic et al. (2014) found greater compaction in NT and shallow soil tillage systems compared to traditional soil tillage. Wang et al. (2022) reported greater SPR under plough soil tillage and precision seeder sowing relative to no-soil tillage and no-soil tillage seeder sowing. Chen et al. (2013) reported increased SPR in both NT and RT row positions compared to MP. They attributed their findings to cumulative soil consolidation over time under NT and RT and to the fall and spring soil tillage compaction in the case of MP. The highest SPR was observed in D, while L and P significantly reduced SPR.

The higher SPR observed in annually disked plots can be attributed to several factors. Disking, a shallow soil tillage operation (12–16 cm in our case) can lead to soil tillage-induced soil compaction below the disked layer due to repeated operations at the same depth. The compressive force exerted by heavy disking implements compresses soil particles and reduces pore space. Additionally, SPR is influenced by soil moisture content (SMC), decreasing as SMC increases (Celik et al., 2010). Soil organic matter (SOM) enhances water-holding capacity and improves soil structure. Mechanized soils often have thinner topsoil with low SOM, which results in reduced water-holding capacity, increased nitrate loss, and soil densification (Malecka et al., 2012). Furthermore, high SPR under D can be explained by the disruption of soil aggregates, decreasing the weighted mean ped diameter and adversely affecting soil stability (Madden et al., 2009). This process leads to the formation of dust that seals soil pores during water percolation, gradually forming a pan layer as the practice is repeated. The effect is exacerbated when soil tillage coincides with higher rainfall. The aforementioned impacts were manifested on crop yields and RW as shown in Figures 20 and 17.

The higher density observed at 0–10 cm under NT can be attributed to farm machinery traffic, consistent with findings from various authors (Ampoorter et al., 2010; Cambi et al., 2016; Sakai et al., 2008). Our results align with studies conducted elsewhere, such as Malecka et al. (2012), who observed significantly greater SPR under NT on Albic Luvisols at the topsoil layer. A study by De

Moraes et al. (2016) examined the effects of no-soil tillage (NT) practices on soil bulk density (BD) in Brazil. They observed that, after 11 and 24 years of NT, the top 10 cm depth of clay soil showed increased BD compared to conventional soil tillage methods. In agricultural settings, soil compaction is primarily caused by the use of heavy machinery. Cárceles Rodríguez et al. (2022) noted that the extent of compaction is influenced by the frequency and intensity of soil tillage operations, as well as soil moisture conditions during these activities.

In contrast, loosening practices produced lower SPR values in most recorded soil depths. This was particularly beneficial during Europe's dry year in 2021, when precipitation was 20% below the long-term average. Loosening to a depth of 45 cm proved advantageous compared to other soil tillage methods at various soil depths. This is supported by SMC results study. They reported higher sunflower yield under the L treatment, proving that loosening provided better growing conditions by extending the depth of root exploration, as well as improving water and nutrient storage. Furthermore, the relationship between sunflower yield and SPR showed that yield decreased with increasing SPR further highlighting the substantial effect of soil loosening on enhancing yield.

Figure 14 shows winter wheat SPR results as affected by treatment and sampling time. In the first measured month (March), soil tillage treatments significantly affected SPR ($p< 0.05$). Moreover, at D, SPR was significantly higher compared to SC, DC, P, and L (Figure 14A). Similar significant differences were observed at NT compared to SC, DC, P, and L. In July 2019, soil tillage treatments significantly affected SPR, with the greatest SPR observed at P compared to DC (Figure 14D). Differences between the monthly measured SPR revealed that SPR increased significantly with time, except for a few occasions where decreases were observed (Figure 14).

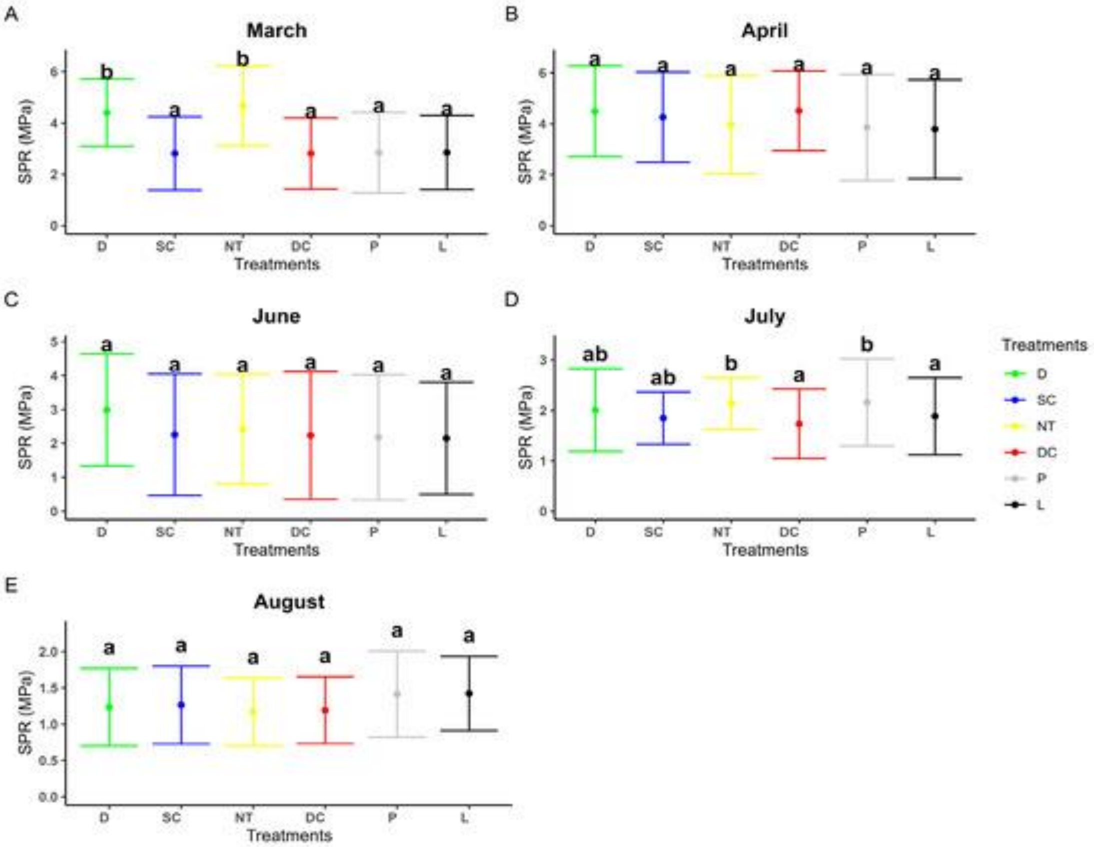

Figure 14. Average temporal SPR variations measured in 2019; winter wheat cropping season from March to August *. (A) March, (B) April, (C) June, (D) July, and (E) August. D-disking, SC-shallow cultivation, NT-no-till, DC-deep cultivation, L-loosening, P-ploughing. SPR mean values with the same lowercase letter indicate no significant difference at p > 0.05. Error bars show the standard deviation of the mean.*

Temporal effects of soil tillage on soil penetration resistance under winter oat cropping period are shown by Figure 15. Soil penetration resistance was measured only twice during the oat growing period; however, the results show that soil tillage significantly affected SPR. On the 19th of March 2020, SPR was significantly reduced under L treatment (MPa) compared to DC *(1.94 MPa)*, NT *(2.31 MPa)*, SC *(1.97 MPa)* and D *(2.60 MPa)*. The greatest SPR was recorded under D *(2.60 MPa)*, followed by NT *(2.31 MPa)*. Moreover, D and NT were both significantly higher than P *(1.59 MPa)*.

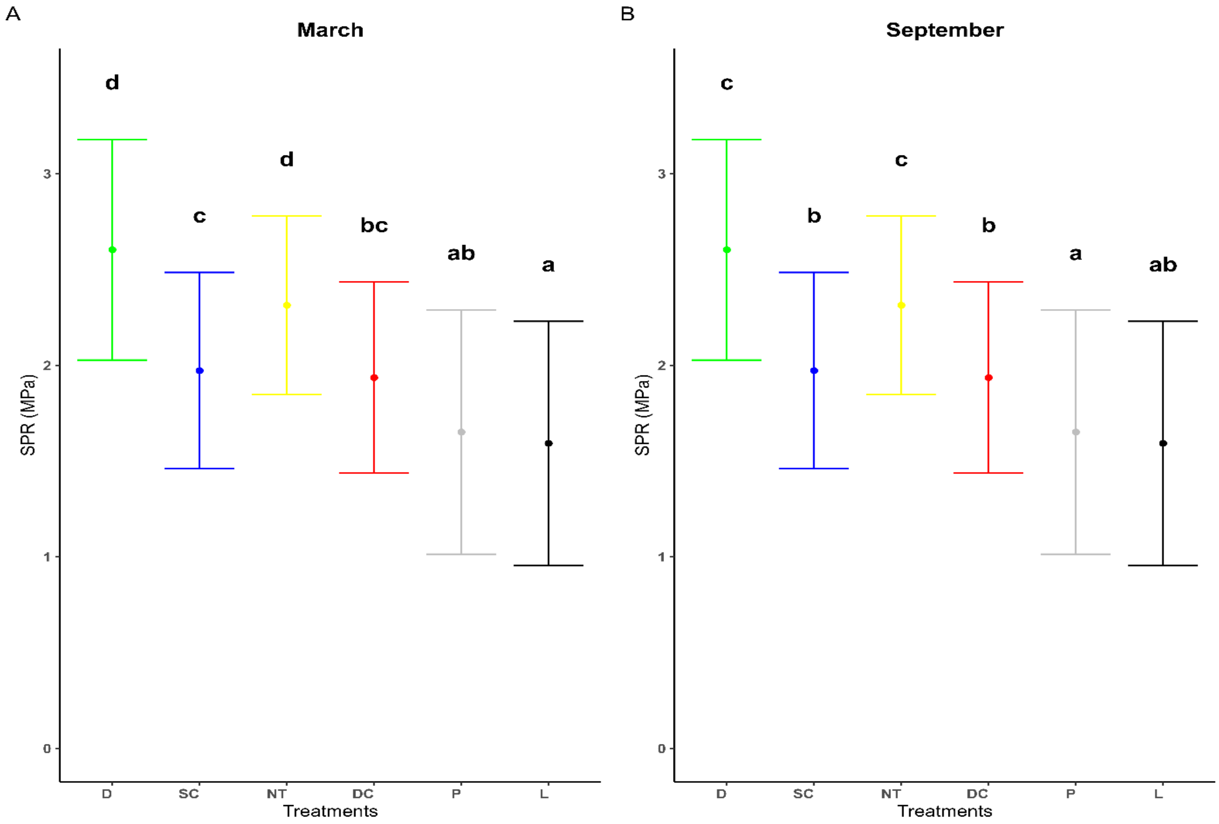

Figure 15. Temporal average SPR variations measured in 2019: oat cropping season in March and September . *(A) March, (B) September. D-disking, SC-shallow cultivation, NT-no-till, DC-deep cultivation, L-loosening, P-ploughing. SPR mean values with the same lowercase letter indicate no significant difference at p > 0.05. Error bars show the standard deviation of the mean.*

Figure 16 shows the temporal effect of soil tillage on SPR during the sunflower cropping period. In November 2019, a similar trend to October was observed, with the exception that the greatest SPR *(1.61 MPa)* was measured at NT in October. Furthermore, between soil tillage treatments SPR at NT was 5% *(1.53 MPa)*, 33% *(1.21 MPa)*, 50% *(1.07 MPa)*, 94% *(0.83 MPa)*, and 101% *(0.80 MPa)* higher compared to D, SC, DC, P, and L. However, the difference between NT and D was not significant. Similarly, in March 2021, SPR was greatest under NT but statistically similar compared to D. Furthermore, DC significantly differed from P and L, while NT and D differed significantly from SC and DC. The overall SPR measured in March showed the following trend: D = NT < SC = DC < P = L.

In April 2021, SPR showed the following trend: D < NT < DC < SC. Notably, pronounced SPR differences were observed when D is compared to P and L. In March 2021, soil tillage treatment D had significantly higher SPR compared to September 2020, October 2020, and April 2021. Soil penetration resistance under SC was significantly higher in March compared to October and November being about 29% and 35%, respectively. At NT, a significantly higher SPR *(2.28 MPa)* was measured in March 2021, followed by September 2020 *(1.77 MPa)* and October 2020 *(1.46 MPa)* (Figure 16). Under DC treatment, SPR values fluctuated with time, with the highest values measured in March 2021 *(1.60 MPa)*, September 2020 *(1.54 MPa)*, and April 2021 *(1.54 MPa)*. The latter months mentioned differed significantly from October *(1.05 MPa)* and November *(1.07 MPa)* 2020 (Figure 16). The SPR at P was significantly 53% *(0.84 MPa)* and 49% *(1.27MPa)* lower in November 2020 compared to September and April 2021. A similar trend to DC was observed at L; however, the highest SPR was observed in April 2021 *(65% higher;1.32 MPa)* compared to the lowest observed in November 2020 *(0.80 MPa)*. According to the 95% level of significance, the average SPR between months showed the following trend: April 2021 = March 2021 = September 2021 < October 2020 = November 2021.

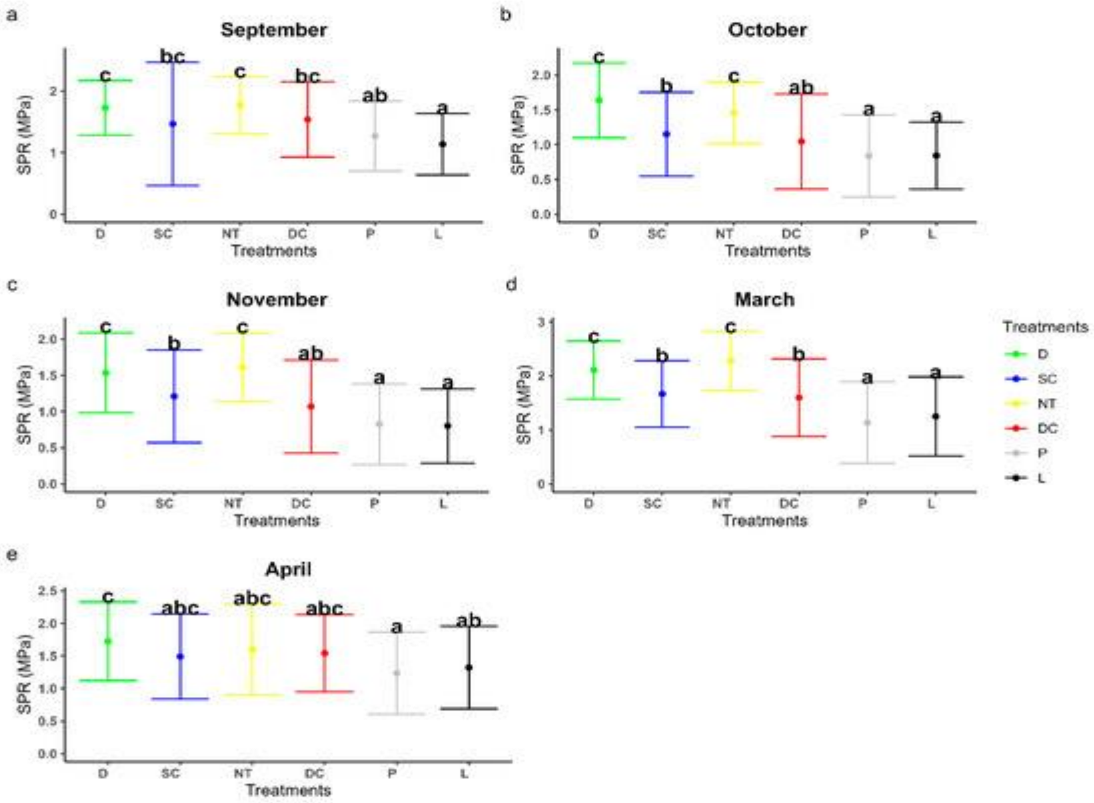

Figure 16. Temporal average SPR variations measured in 2020/21 sunflower cropping season between September 2020 and April 2021 . *(a) September, (b) October, (c) November, (d) March, and (e) April. D-disking, SC-shallow cultivation, NT-no-till, DC-deep cultivation, L-loosening, P-ploughing. SPR values with the same lowercase letter indicate no significant difference at p > 0.05. Error bars show the standard deviation of the mean.*

Temporal SPR variations play a significant role in soil and plant processes, as evidenced throughout the study. Various studies have shown monthly temporal effects on SPR under different soil tillage methods (Bogunovic et al., 2018; Dekemati et al., 2019b). Chemura et al. (2022) emphasized the importance of noting both short and long-term soil tillage effects considering anticipated more intense future weather.

The current study revealed complex relationships between SPR, SMC, and soil tillage practices. For instance, in March 2019, the highest SPR values (>4 MPa) were observed under NT and D, despite humid soil moisture conditions highlighting the complex interactions between soil tillage, compaction, and climatic factors. This suggests that below-average rainfall from January to March 2019 was inadequate to mitigate higher SPR in these treatments. Throughout the study period, various factors influenced SPR, including rainfall patterns, SMC, and temperature. For example, despite average rainfall in April 2019, a sudden SPR surge was observed across all treatments, possibly due to lower SMC and elevated temperatures increasing soil drying rates.

Generally loosening treatment is employed to break the compact layer, thus providing a deeper loosened layer. However, the current study yielded higher SPR under L relative to DC on the 28th of June 2019 but in the absence of significant differences. On the same period, statistically similar SPR between NT and P was recorded. Despite ploughing disturbing the soil to a certain depth (30 cm for this study), there was no temporal difference among the soil tillage treatments. This suggests that the soil type of the study area is not immune to consolidation which occurs after soil tillage, thus reverting the soil structure to its natural state. Moreover, ploughing is associated with deterioration of aggregates by accelerating SOM decomposition and SOM is the primary binding agent of soil aggregates and plays a pivotal role in soil aggregation (Bhattacharyya et al., 2009; Tripathi et al., 2014). Additionally, ploughing promotes dust formation which may further exacerbate compaction as the dust leaches during rainfall blocking the soil pores ultimately increasing SPR (Blanco-Moure et al., 2012; Huang et al., 2015).

The study also highlighted the importance of soil tillage depth and frequency. Deep cultivation (22–25 cm) did not provide an adequate loosened depth compared to loosening between 40 and 45 cm. This suggests that for extended loosened depth, soil tillage methods, such as ploughing or loosening are preferable, as they guarantee deeper loosened depth and alleviation of compaction layers. However, variation of ploughing depth should be mandatory to prevent the development of a plough pan.

4.3. The effect of soil tillage on winter wheat, winter oat, and sunflower growth, yield and yield quality parameters

Winter wheat grain was harvested on 19 July 2018, at 10.2% moisture content (Table 1). Each treatment was harvested, and yield was measured in t ha^{-1}. In 2018, soil tillage treatments had a significant effect on wheat grain yield ($p < 0.05$) (Figure 17). Winter wheat grain yield was similar ($p > 0.05$) in DC, L, and SC. However, the latter three soil tillage practices had greater wheat yield compared to NT, P, and D as the lowest wheat grain yield producers. In contrast, the wheat grain yield in the NT and P fields was not significant ($p > 0.05$).

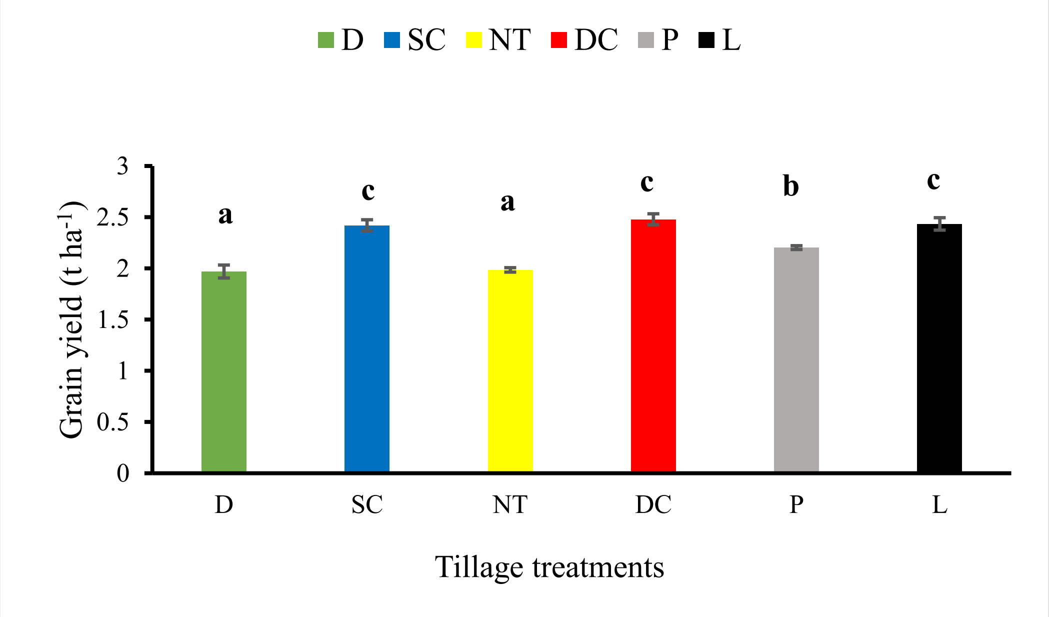

Figure 17. Wheat grain yield for the 2018 cropping season. *(D–disking, SC–shallow cultivation, NT–no-till, DC–deep cultivation, L–loosening, P–ploughing). Bars with similar lower-case letters indicate similarities according to ANOVA and the Tukey post-hoc test at p < 0.05. Hanging bars indicate the standard deviation.*

The oat yield in 2019 was significantly affected by soil tillage (Figure 18). Ploughing significantly decreased oat yield compared to SC, DC, and L. The differences in oat yield followed the following order L>DC>SC>P.

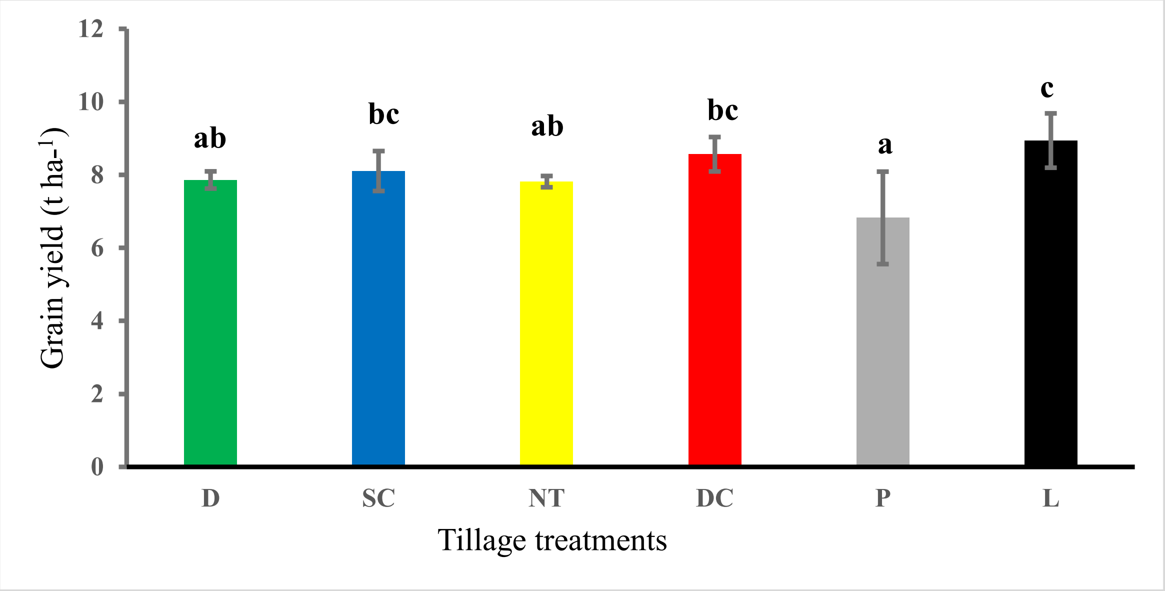

Figure 18. Oat grain yield for the 2019 cropping season . *(D–disking, SC–shallow cultivation, NT–no-till, DC–deep cultivation, L–loosening, P–ploughing). Bars with similar lower-case letters indicate similarities according to ANOVA and the Tukey post-hoc test at $p < 0.05$. Hanging bars indicate the standard deviation.*

In 2021, the sunflower seed yield is illustrated in Figure 19, revealing that soil tillage had a substantial effect on seed yield, which was considered statistically significant ($p < 0.05$). The highest seed yield was observed at L (3.86 t ha^{-1}); however, it was not different from SC (3.47 t ha^{-1}) and P (3.45 t ha^{-1}). In comparison, the sunflower seed yield in the NT treatment was 34% lower than the yield observed in the L treatment.

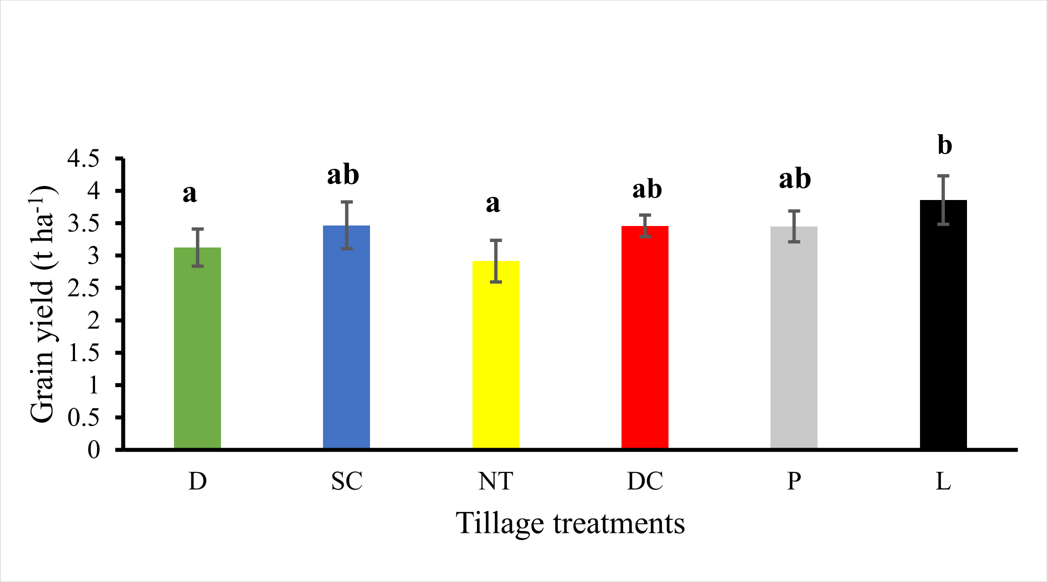

Figure 19. Sunflower seed yield for 2021 cropping season . *(D–disking, SC–shallow cultivation, NT–no-till, DC–deep cultivation, L–loosening, P–ploughing). Bars with similar lower-case letters indicate similarities according to ANOVA and the Tukey post-hoc test at $p < 0.05$. Hanging bars indicate the standard deviation.*

The root weight (RW) of winter wheat, winter oat and sunflower results are presented in Figures 21-23, respectively. Soil tillage significantly affected root weight ($p < 0.05$) in both cropping seasons. The winter wheat RW under DC was 22% greater relative to the lowest obtained at D. The wheat root weight was in the following order: DC > L = P > SC > NT > D when considering all treatments.

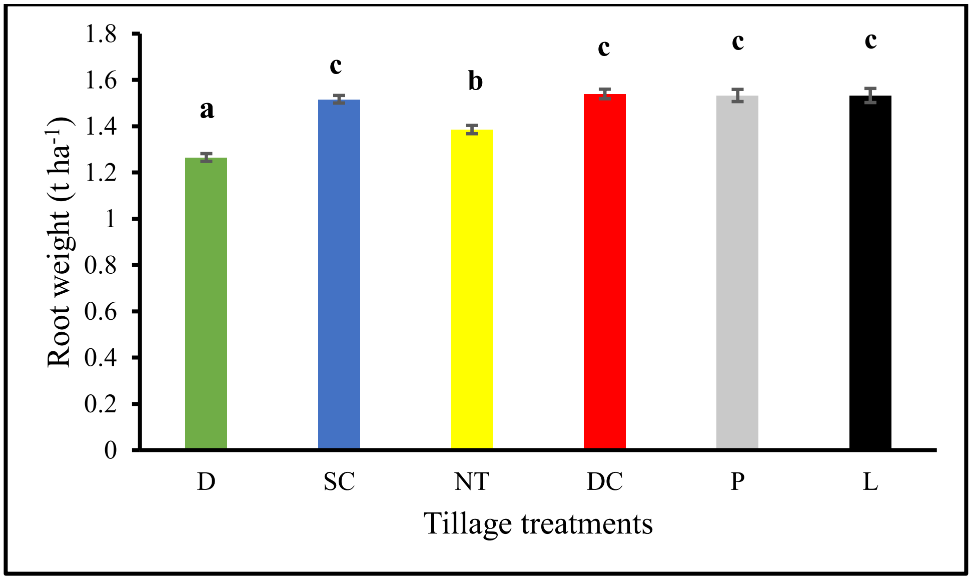

Figure 20. Wheat root weight for the 2018 cropping season . *(D–disking, SC–shallow cultivation, NT–no-till, DC–deep cultivation, L–loosening, P–ploughing). Bars with similar lower-case letters indicate similarities according to ANOVA and the Tukey post-hoc test at $p < 0.05$. Hanging bars indicate the standard deviation.*

In 2019, soil tillage significantly affected winter oat RW with greatest observed under L treatment. The winter oat RW was significantly reduced under P treatment compared to all the other treatments investigated. Deep soil tillage DC and L increased the RW more effectively compared to P.

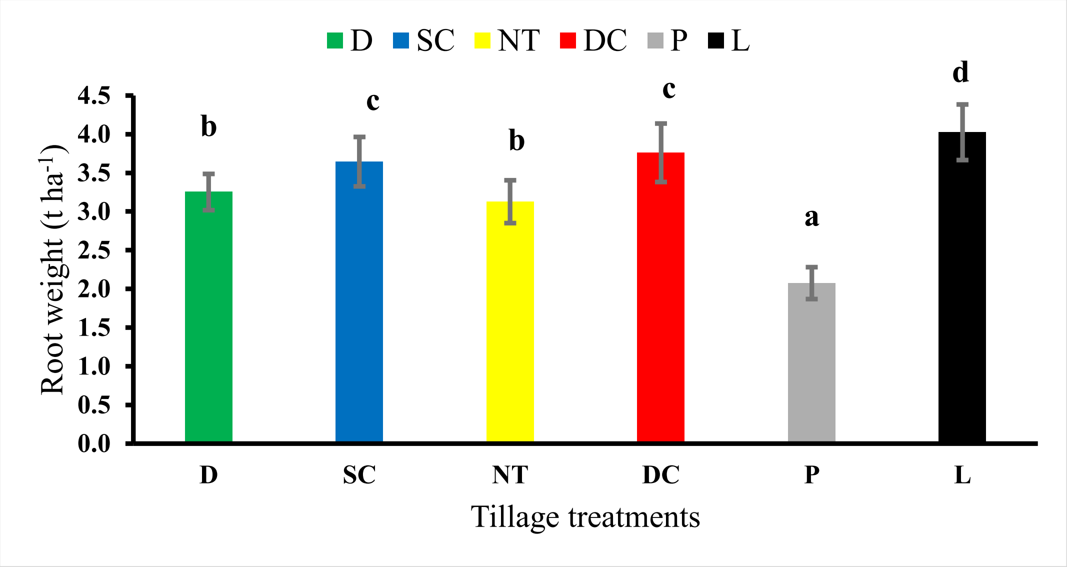

Figure 21. Oat root weight for the 2019 cropping season. *(D–disking, SC–shallow cultivation, NT–no-till, DC–deep cultivation, L–loosening, P–ploughing). Bars with similar lower-case letters indicate similarities according to ANOVA and the Tukey post-hoc test at $p < 0.05$. Hanging bars indicate the standard deviation.*

In 2021, the soil tillage significantly affected sunflower RW ($p> 0.05$). The sunflower root weight under L (3.89 t ha^{-1}) was 22% higher compared to the lowest at D (3.18 t ha^{-1}). Significant differences were observed between P (3.52 t ha^{-1}) and L (3.89 t ha^{-1}) with greater RW measured at L. Moreover, L was significantly greater than NT (3.31 t ha^{-1}) and SC (3.49 t ha^{-1}). Treatment DC (3.71 t ha^{-1}) produced significantly higher RW than SC (3.49 t ha^{-1}), NT (3.31 t ha^{-1}), and D (3.18 t ha^{-1}).

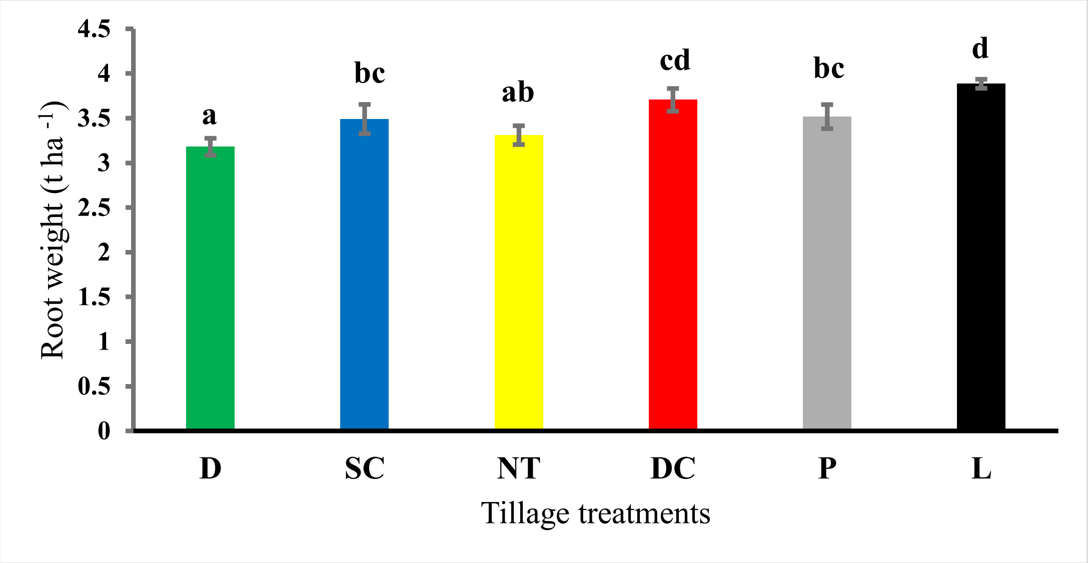

Figure 22. Sunflower root weight for the 2021 cropping season. *(D–disking, SC–shallow cultivation, NT–no-till, DC–deep cultivation, L–loosening, P–ploughing). Bars with similar lower-case letters indicate similarities according to ANOVA and the Tukey post-hoc test at $p < 0.05$. Hanging bars indicate the standard deviation.*

The outcomes obtained in 2018 regarding wheat grain yield under NT conditions as compared to P align with the findings of Afzalinia and Zabihi (2014). They reported diminished maize grain yield and yield components following short-term NT studies when compared with CT practices. These researchers attributed the observed results to the increased soil compaction associated with NT. The similarity between the results obtained in our study and those of Afzalinia and Zabihi (2014) suggests that soil compaction may indeed contribute to reduced yields under minimum soil tillage practices. Moreover, the study's correlation coefficient suggests that crops may have sacrificed grain yield for a more developed root system under NT (see Figure 23). These outcomes may have been caused by compaction, as roots require more energy to grow in compacted soil. Additionally, low wheat yield was observed at D, in oat under P, and in sunflower at D and NT treatments relative to all other treatments. This may be attributed to the compaction (as indicated by the root weight results in Figures 20-22) resulting from the annual disking of the soil. Therefore, we emphasize the importance of implementing specialized conventional soil tillage management strategies, such as loosening, to optimize agricultural productivity. It is important to note that ploughing and disking (particularly in wet soil) should not be encouraged for agricultural productivity due to their adverse effects on soil structure, moisture retention, and overall soil health.

In 2019, the season lacked clear trends in terms of which treatment obtained greatest yields. Higher yields were observed in SC, DC, and L (Figure 18). This finding is not in line with Dekemati et al. (2021), who reported zero yields differences over from 2016-2018 under DC, SC and P.

In 2021, the greatest sunflower yield was obtained at L. This showed that loosening provided suitable growing conditions (depth of the loosened layer). According to records, loosening of the soil is believed to improve the soil's physical condition by alleviating the compact layer. This allows the roots to increase in depth and weight and extend deeper into the soil to absorb water and nutrients accumulated in the subsoil (Xue et al., 2019). Consequently, loosening improves dry biomass accumulation, and ultimately attaining greater grain yield and profitable benefits (Feng et al., 2018; Shah et al., 2017).

Zhang et al. (2009) outlined a significant correlation between root biomass and shoot biomass which leads to greater yields and water use efficiency. Considerable differences regarding sunflower yield at D were noted. These findings can be explained by several reasons. One of the reasons is assuming the presence of a compact layer created by annual disking. Birkás et al. (2002) reported that annual disking causes more harm than ploughing, particularly in humid light-textured soils. Consequently, hindering normal root growth (Ren et al., 2018) thus prohibiting the absorption of water and nutrients and accelerating aging.

The effects of soil tillage on wheat and oat quality parameters are presented in Tables 12 and 13. Soil tillage significantly affected wheat protein percentage (P%), thousand kernel weight (TKW), Zeleny number (ZN), straw weight (SW), and hectoliter weight (HLW) (Table 12). Protein percentage was significantly improved under P (14.42%) and D (14.45%) treatments compared to other soil tillage variants. Significantly lower protein percentage was observed under L (12.85%) treatments. Meanwhile at SC (13.58%) and DC (14.08%) treatments it was moderately high, however, yet significantly lower than in P and D treatments. Significantly higher protein percentage was noted under NT (13.36%) compared to L (12.85%) however compared to DC (14.08%), NT showed significantly lower protein percentage. Significantly greater TKW found at L (46.81g) treatment and the lowest at P (39.82g). Treatments D, SC, NT, DC, and L, all showed significantly greater TKW compared to P. The following trend was observed from the greatest to lowest L>DC=NT>SC=D>P. While the greatest ZN was measured at NT (43.71) treatments whereas significantly lowest was observed at treatment L (34.10). Treatment NT (43.71) significantly increased ZN compared to D

(41.49), SC (38.95), DC (36.30), and P (39.55). While ZN at treatment P (39.55) was significantly greater than L (34.10) and SC (38.95). The greatest SW was measured at P (3.91 t ha^{-1}) treatment, while comparisons between SC (3.64 t ha^{-1}) and NT (3.31 t ha^{-1}) showed that NT produced significantly lower SW. The greatest hectoliter weight (HLW) was measured at SC (72.64 kg/HL) and the lowest significantly HLW was measured at P (67.80 kg/HL). Treatment D (70.0 kg/HL) was significantly lower than SC (72.64 kg/HL) but significantly greater than treatment P (67.80 kg/HL).

Table 12. Wheat yield components under different soil tillage treatments.

Treatments	**Protein (%)**	**TKW (g)**	**ZN**	**SW (t ha^{-1})**	**HLW (kg/HL)**
Disking	14.45±0.20d	41.52±0.46b	41.49+0.47d	3.26+0.05a	**(70.0)**8.37±0.00b
Shallow Cultivation	13.58±0.11b	41.55±0.07b	38.95+1.29c	3.64+0.07b	**(72.64)**8.52±0.03d
No-Till	13.36±0.18b	43.81±0.18c	43.71+0.15e	3.31+0.14a	**(71.53)**8.46±0.02c
Deep Cultivation	14.08±0.05c	44.53±0.26c	36.30+0.80b	3.71+0.06bc	**(71.00)**8.43±0.00c
Ploughing	14.42±0.04d	39.82±0.31a	39.55+1.63c	3.91+0.11c	**(67.80)**8.23±0.00a
Loosening	12.85±0.16a	46.81±0.48d	34.10+1.66a	3.82+0.04bc	**(72.59)**8.51±0.02d

Means ± standard deviation with same lower-case letters across soil tillage treatments indicate statistical similarity at 5% level of significance. TKW–Thousand kernel weight, HLW–Hectoliter weight, ZN– Zeleny number, SW–Straw weight. Bold values in brackets are original values and next to them are transformed values.

There was no observed soil tillage effect on protein %, TKW and HLW throughout the oat cropping period. However, the greatest protein value was observed under DC (16.08 %) and the lowest under NT (15.08 %). The overall protein% value showed the following trend P>DC>L>SC>D>NT from the greatest to the lowest. While the measured TKW values differed with the greatest observed under D and the lowest under SC. Moreover, D treatment continued to be superior with higher HLW values while the lowest was observed under P. Soil tillage significantly affected straw weight with significantly greater straw weight observed under L and the lowest observed under P which is statistically similar to SC. Straw weight showed the following trend L=DC, DC=SC, P>SC, P>D, SC=D=P. Plant density/m^2 (PD /m^2) was significantly higher under L treatment. However, while significantly least plant density was measured under D treatment.

Table 13. Winter oat yield components under different soil tillage treatments.

Treatments	**P (%)**	**TKW (g)**	**PD /m^2**	**SW (t ha^{-1})**	**HLW (kg/HL)**

Disking	15.23±0.73a	39.13±0.91a	328.50±28.83a	2.25±0.10a	**(40,87)**6.39±0.03a
Shallow Cultivation	15.58±0.46a	36.83±0.41a	379.50±33.64abc	2.78±0.13b	**(38,99)**6.24±0.10a
No-Till	15.08±1.07a	37.90±2.13a	367.75±32.42ab	2.38±0.11a	**(39,74)**6.30±0.13a
Deep Cultivation	15.90±0.22a	37.45±1.37a	406.75±35.85bc	3.04±0.15bc	**(39,62)**6.23±0.15a
Ploughing	16.08±0.62a	37.60±0.92a	355.25±13.74ab	2.21±0.19a	**(38,14)**6.17±0.14a
Loosening	15.63±0.64a	36.85±0.24a	430.25±38.21c	3.15±0.31c	**(39,51)**6.28±0.09a

Means ± standard deviation with same lower-case letters across soil tillage treatments indicate statistical similarity at 5% level of significance. P %– protein percentage, HLW–hectoliter weight, TKW–Thousand kernel weight, PD /m^2*– plant density per m*^{2}*, SW–Straw weight. Bold values in brackets are original values and next to them are transformed values.*

4.3. The effect of soil tillage on wheat, oat and sunflower growth parameters and quality traits

The effect of soil tillage on wheat growth and yield quality parameters

Protein content, Zeleny sedimentation (Gabriela and Sala, 2021) test and Hagberg falling number are tools utilized to evaluate the standard of winter wheat flours (De Vita et al., 2007; Mares and Mrva, 2008). The quality of winter wheat grain, particularly the makeup of endosperm proteins, can be influenced by environmental conditions, such as water availability (Ames et al., 1999), nitrogen levels (Luo et al., 2000), and the application of herbicides (Manthey et al., 2004). In this current study, soil tillage significantly affected grain quality traits. The significant increase of protein percentage under D and P is in line with Ahmadi et al. (2024). In their study they found that higher protein percentage is associated with CT treatment. Moreover, they did not observe statistical differences between minimum soil tillage (MT) and NT. Similar to our finding's soil tillage treatments with minimal soil disturbance (SC) were statistically similar to NT. A classical study conducted under mediterranean climate by López-Bellido et al. (1998) reported that soil tillage had an effect on wheat protein content. The NT system resulted in significantly lower grain protein content compared to the conventional soil tillage method. Lestingi et al. (2010) also discovered that reducing soil tillage intensity affected the crop's nitrogen supply due to alterations in nitrogen dynamics, yield potential, and grain quality. In contrast Grigoras et al. (2012) reported higher protein percentage under conservation soil tillage (NT). Moreover, other authors highlighted that there seems to be a slight relationship between grain protein content and the soil tillage methods (Baenziger et al., 1985; Carr et al., 2003; Gürsoy et al., 2010; Rieger et al., 2008), however, CT methods normally provide greater protein content (De Vita et al., 2007; López-Bellido et al., 2001, 1998).

Surprisingly, L treatment is more intensive than D and P, yet the protein% was the lowest compared to all treatments. López-Bellido et al. (2001) highlighted that protein percentage is closely associated with nitrogen availability, thus it is affected by N management. Under loosening the soil is worked to a depth of 45 cm (in our case), thus breaking any present compact layer. The depth of the loosened layer could be a driver of nutrient loss during heavy rains which were received in 2019 (Figure 9). However, the results of present study also showed significantly higher protein% under DC relative to SC and NT. This could plausibly be that wheat planted on our experimental site preferred soil tillage methods that involve mixing of the soil with stubble residues such as D and P for higher protein synthesis. Conversely, non-inversion shallow soil tillage methods, such as SC and NT provided less conducive environment for protein synthesis. The lowest protein percentage observed under L treatment could be a loss of nutrients particularly N through leaching.

The improved TKW observed under L compared to P. Conversely, a similar response of statistical similarity was observed between NT and DC. Despite this mixed response, there was a trend observed whereby considering all the treatment plots, TKW decreased with soil tillage intensity except under L. Our results corroborate the study of Liu et al. (2021), who reported significantly higher TKW under sub-soiling soil tillage as compared to NT and CT. They attributed their results to conservation soil tillage treatment's ability to improve soil chemical and physical conditions for greater and stable crop yields. However, Guan et al. (2014) reported substantially higher TKW under plough soil tillage relative to NT. The current study showed a substantial difference of TKW between NT and P. Various authors reported that increased intensity of N mineralization resulting from higher soil tillage intensity could be a reason for enhanced levels of TKW in some studies (López-Bellido et al., 2001; Šíp et al., 2013). In this current study that was not the case, although the N mineralization was not measured, it assumed that plausible SOM mineralization under P could the reason for the lower TKW. Other studies also have higher loss of SOM with ploughing which can be used to justify the observed results. Moreover, earlier research conducted by Dekemati et al. (2019b) in the same experimental area as this current study reported greater SOC under NT (2.3%) compared to the lowest observed under P (1.8%)

at 10 cm depth. Similarly, Mohamed et al. (2024) in the same experimental site later also reported greater SOC under NT followed by SC while the lowest was observed under P.

Significantly greater ZN observed under NT compared to L is in contrary with the results obtained by Ahmadi et al. (2024). Alizadeh et al. (2021) identified a direct correlation between the amount of zinc sediment and the concentrations of wet protein and gluten. Furthermore, Ahmadi et al. (2024) found a strong association between Zeleny sedimentation and the percentage of protein. Similarly, in the current study a positive strong correlation between protein% and ZN was observed (Figure 26). Superior gluten quality and a higher gluten concentration are typically associated with reduced sedimentation rates and increased Zeleny number values (Hrušková and Faměra, 2003). Although this current study was limited to the protein% only, hence it is plausible that the greater ZN observed under NT is related to a lower gluten content. However, further studies are required to confirm the assumption. Studies elsewhere reported contrary results, for example, Colecchia et al. (2015) in NT conditions, a lower percentage of wet gluten and wheat protein was also noted compared to other soil tillage methods. Woźniak. (2009) supported the notion that reduced soil tillage leads to decreased wet gluten and protein levels, as well as a lower grain weight test for spring wheat.

Ploughing significantly improved winter wheat SW, however, the statistical difference was comparable to DC and L, yet significantly greater than SC > NT = D. Taner et al. (2015) reported no significant difference on wheat biomass yield under CT, RT and NT, however, higher yield was observed in NT treatment. Contrary to this study, the lowest ST was recorded under D, with no statistical difference to NT. Treatments subjected to soil tillage practice with soil disturbance greater than 16 cm depth proved to be better in enhancing SW. In this study, the overall (0-50 cm) SPR was highest under D treatment followed by NT (Table 11), this observation supports the latter reasons of the observed low ST.

The HLW is regarded as the most crucial physical characteristic for evaluating grain quality, as well as for its storage, transportation, and milling processes (Bódi and Pepó, 2007). Brezinščak and Bogunovic (2021) did not observe significant changes of HLW under CT, MT and RT without straw retention. Similarly, Taner et al. (2015) did not observe significant differences of HLW, whereas Jug et al. (2011) reported significantly lower hectoliter mass under NT compared to other soil tillage practices. The latter author reported winter wheat hectoliter mass values that is slightly higher under CT (79.4 kg) compared to NT (79.3 kg). Wozniak (2013) observed that the hectoliter mass (HM) was notably influenced by the year, while soil tillage treatment had no significant impact. The HM recorded values were 75.6 kg for CT, 75.2 kg for RT, and 75.2 kg for herbicide soil tillage. Similarly, research by Troccoli and Di Fonzo (1999) and De Vita et al (2007) indicated that soil tillage treatments had a lesser effect compared to weather conditions, particularly concerning the impact of climatic conditions during the grain-filling phase on the shape and size of the grain.

In this study SC and L treatments enhanced the wheat HLW equally compared to P. Moreover, NT and DC proved to be better than D in relation to improving HLW of wheat. Previous studies have highlighted that soil tillage generally does not affect HLW, however, since HLW is affected by moisture, soil tillage can have an indirect effect by disrupting hydrological status of the soil (Janusauskaite and Kadziene, 2022; Moraes et al., 2017; Tshuma et al., 2024; Wozniak, 2013). The assumptions on the lower HLW observed at P, are the fact that ploughing results in stirring of the soil, thus allowing the locked moisture to escape. Moreover, by turning the soil, the residues that serve as cover to conserve moisture are buried thus leaving the soil bare and exposed to high solar radiation.

The outcomes obtained in 2018 regarding wheat grain yield under NT conditions as compared to P align with the findings of Afzalinia and Zabihi (2014), who reported diminished maize grain yield and yield components following short-term NT studies when compared with CT practices. These researchers attributed the observed results to the increased soil compaction associated with NT. The similarity between the results obtained in our study and those of Afzalinia and Zabihi (2014) suggested that soil compaction may indeed contribute to reduced yields under minimum soil tillage practices. These outcomes may have been caused by compaction, as roots require more energy to grow in compacted soil. Additionally, low wheat yield was observed at D relative to all other treatments. This may be attributed to the depth of the loosened layer (as indicated by the root weight results in Figure 20) resulting from the annual disking of the soil. Therefore, we emphasize the importance of implementing specialized soil tillage management strategies, such as loosening, to optimize agricultural productivity. It is important to note that ploughing and disking (particularly in wet soil) should not be encouraged for agricultural productivity due to their adverse effects on soil structure, moisture retention, and overall soil health.

Despite the lack of substantial differences for protein%, the lowest value observed under NT is in line with other studies mentioned previously but with significant differences (Ali et al., 2019).

Moreover, the lowest P% might suggest that undisturbed soil surface as in NT arable lands might affect N availability for protein synthesis ultimately resulting in lower wheat protein concentration.

TKW values obtained greater values under D soil tillage treatment compared to the lowest under SC suggesting that oat crop preferred soil conditions provided by disking. This could stem from the mixing of stubble residues which has the potential to invert topsoil nutrients into the root zone. Moreover, it is important to note that TKW ranged between 37.45-37.60 g in P and DC soil tillage practices, whereas under SC and P the TKW was below 37.00 g. This might suggest that a shallower disturbance or ploughing are soil management methods that provide unsuitable conditions to improve winter oat yield.

Results from the oat growing period showed that soil tillage practice substantially affected PD/m^2 and straw weight. Disking soil tillage had the lowest PD/m^2, the assumption is that the nature of D soil tillage encouraged moisture depletion that affected oat seed germination. In addition, seedbed preparation plays a pivotal role in enhancing germination. Disking might produce a seedbed with bigger clods that prevents proper contact with the soil and the ultimately affecting germination rate. Similar observations were reported by Amer and Muter (2023), with a vertical disc soil tillage, which provided similar agroclimatic conditions compared to a heavy disc harrow. Aquah and Chen (2022) observed higher canola plant population per square meter under spring tine soil tillage relative to disc and no-till.

The HLW was lowest under P without significant differences, this is similar to the wheat cropping period. This suggests that higher SPR observed under D and NT did not have an effect on oat HLW since they are the two that produced higher HLW values compared to other treatments. Some authors reported higher soil compaction is not always negative to crop growth and yield (Raper, 2005).

The ST during the oat growing period showed lower yields under soil tillage practices associated with higher soil compaction. Based on the results of SPR we can confirm that higher SPR under D and NT could have been the reason for diminished crop biomass. The SMC results can support our lower ST observation under P. The SMC results were lower but without some significant difference with some soil tillage treatments at 0-10 and 40-50 cm depth. Moisture is very important in the growth and enhancement of biomass of crops. Inadequate SMC in soil may affect normal crops physiological process, thus diminishing growth. Moreover, nutrients in the soil move through soil; to nourish the crop particularly N, it is very important for vegetative growth of the plants. Hence, drought conditions will decrease N absorption, and this might result in stunted growth.

In 2021, the greatest sunflower yield was obtained at L. This showed that loosening provided suitable growing conditions (depth of the loosened layer). According to records, loosening of the soil is believed to improve the soil's physical condition by alleviating the compact layer. This allows the roots to increase in depth and weight and extend deeper into the soil to absorb water and nutrients accumulated in the subsoil Xue et al. (2019). Consequently, loosening improves dry biomass accumulation and ultimately attaining greater grain yield and profitable benefits (Feng et al., 2018; Shah et al., 2017).

Zhang et al. (2009) outlined a significant correlation between root biomass and shoot biomass which leads to greater yields and water use efficiency. Considerable differences regarding sunflower yield at D were noted. These findings can be explained by several reasons. One of the reasons is assuming the presence of a compact layer created by annual disking. Birkás et al. (2002) reported that annual disking causes more harm than ploughing, particularly in humid light-textured soils. Consequently, hindering normal root growth Ren et al. (2018) thus prohibiting the absorption of water and nutrients and accelerating aging.

Soil tillage significantly affected GY during winter oat growing period. The lowest observed under P, could be low moisture availability, which may have also affected diffusion of nutrients, thus preventing root growth. Among the soil tillage practices, L treatment enhanced GY better than P investigated soil tillage practices, however GY was statistically similar to treatments D, NT, and DC. The increase of yield under L could be associated with higher moisture conditions created by deeper by the loosening. Dekemati et al. (2019b) conducted a study from the same experimental site and found out that winter oat yield was higher in L (5.87 Mg ha^{-1}), P (5.68 Mg ha^{-1}), DC (5.68 Mg ha^{-1}) compared to SC, NT, and D. Further supporting our assumption that deeper soil tillage conserves moisture which enhances crop yield. In relation to NT, De Vita et al. (2007) showed grain yield advantages only during the period of less than annual 300 mm rainfall compared to CT. In this study, the annual rainfall was higher than 300 mm, this shows the lack of advantages of NT system in areas receiving adequate rainfall. However, generally P treatment is associated with more soil degrading factors. In light of this, hence for an overall sustainable crop production and soil conservation treatments such as SC, NT, DC, and L are recommended compared to D and P.

By contrast to study by Muñoz-Romero et al. (2010), soil tillage significantly affected RW of oat. The lower RW observed under P treatments could be a result of multiple reasons. Ploughing could disrupt water infiltration, because unlike NT, P treatment removes the previous crop's roots and also breaks the formed biological soil channels that root can inhabit to explore the horizon in-depth. The latter mentioned thus prevents proper moisture infiltration which may lead to poor aeration affecting proper root growth. Moreover, the disruption of bio channels affects access to water and nutrients stored in the subsoil. Strong root growth is associated with yield increase, our low RW observed could be confirmed by depreciated GY observed under D and NT (Figure 22) which also recorded higher SPR indicating the presence of compaction. It is important to note that SC provided similar condition that favoured root growth, hence since deep soil tillage can be expensive an SC can be used as an alternative with similar positive effects. In conclusion P treatment significantly reduced root growth, so for better root growth, L treatment is recommended. Moreover, loosening also contributes to soil conservation by not removing residues that protect the soil from extreme temperatures. The soil residues when they decompose, they add SOM to the soil, further improving soil structure and increasing SOC sequestration.

4.4. Winter wheat and winter oat relationships between soil penetration resistance, root weight, and yield under high intensity soil tillage practices

The relationship of parameters under wheat low intensity soil tillage (NT, D, and SC) methods were computed, to observe if soil tillage has effect on the relationship of soil, crop growth, yield, and quality parameters (Figure 23). Soil tillage practices were selected based on the working depth as outlined in Chapter 3. According to the results, winter wheat GY negatively correlated with SPR in both D (r = - 0.86) and SC (r = - 0.82), while under NT there was a positive correlation of 20%. Similarly, the correlation between SMC and winter wheat GY was negative, under D and SC. However, under SC the correlation was weak (r = 0.35) while under NT treatments a positive correlation of r = 0.27 was observed.

Wheat Zeleny number is an important quality trait, that provides insight into the baking quality of the wheat flour. It has been reported that wheat quality is affected by genetic factors and environmental factors. Soil tillage plays a crucial role in determining the quantity and quality of grain. By altering the physical, chemical, and biological characteristics of the soil, it directly influences the growth and development of crops (Chetan et al., 2017; De Vita et al., 2007; Giannitsopoulos et al., 2019; Heidari et al., 2016). In our study, the correlation results between GY and Zeleny sedimentation

(ZS) showed that under D and NT the correlation was less than 30%. Both treatments showed negative correlations of r = - 0.26 and r = - 0.21 respectively, while SC treatment correlation was r = - 0.58.

In relation to the HLW, the wheat GY had a strong negative correlation under NT (r = - 0.90) treatment, followed by D (r = - 0.26) while SC (r = - 0.03) treatment had the weak correlation. The root weight correlated with GY under NT and D compared to SC. Similarly, under NT and D a strong negative correlation, whereas under SC a positive correlation was observed. The results indicate that under NT and D there exists a great trade-off between GY and straw weight (SW). While under SC, despite the weak correlation value, this shows that SC treatment there are no trade-offs between yield and crop biomass. An increase in GY will negatively affect SW. A strong inverse relationship between TKW and GY was observed under SC (r = - 0.74) relative to D and NT. In contrast, the relationship between GY and protein percentage was strongly correlated under SC and NT, while under D treatment there was a positive medium correlation of r = 0.49.

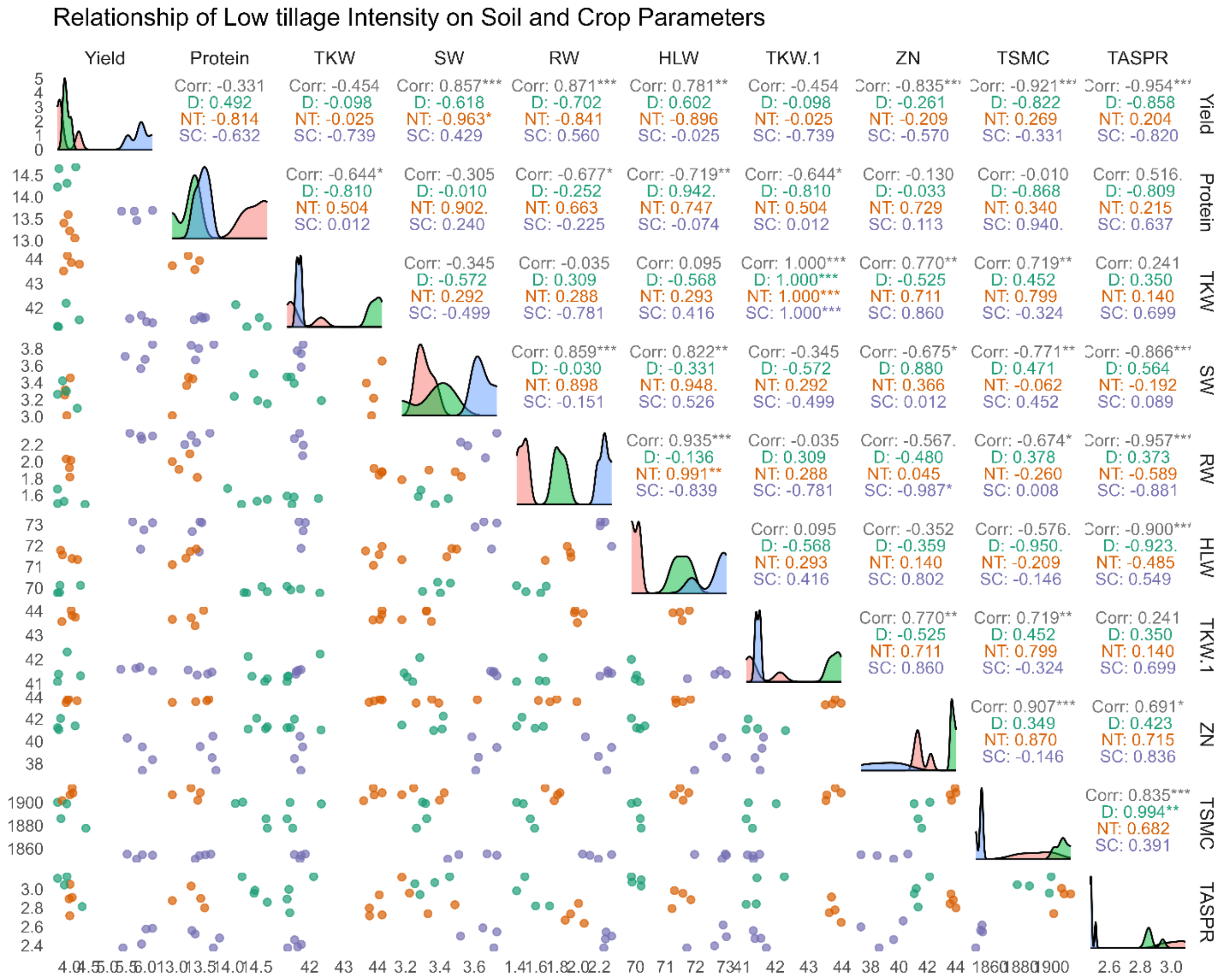

Figure 23. Winter wheat relationships under low intensity soil tillage methods . *Corr – the correlation p-value and the * indicate significance difference (p > 0.05). NT – No-till, D – disking, SC – Shallow cultivation. NA– indicate parameters where correlation could not be computed.*

The relationship between GY and SPR under high intensity soil tillage treatments (DC, P, and L) was positively strongest under DC (r = 0.83), moderately negatively strong under P (r = - 0.48) and weakest under L (r = 0.10). The relationship with SMC showed overall weaker correlations in all the soil tillage treatments. The strongest correlation among the treatments was observed under DC (r = - 0.37) followed by P (r = 0.31) and the weakest among treatments was observed under L (r = 0.12). The relationship with RW showed the overall strongest correlations in all soil tillage treatments. The strongest correlation was observed under L (r = 0.99*) followed by DC (r = 0.96**) while the weakest among the treatments was observed under P (r = 0.82) (Figure 24). The relationship with SW was strong under L (r = 0.88) and P (r = 0.82) whereas the weakest among treatments was observed under DC (r = 0.30).

The TKW and GY correlations were also strong in all treatments, however, between treatments the strongest observed under DC (r = - 0.10**), followed by L (r = - 0.92), and the lowest among treatments was observed under P (r = 0.88). The strongest correlation between HLW and GY was observed under P (r = 0.86), while under DC (r = 0.70) there was a moderate correlation and L (r = 0.44) treatments had a moderate correlation. However, the relationship between GY and protein percentage was strongest under DC (r = 0.91), while P (r = 0.45) had a moderate correlation, and the weakest correlation was observed under L (r = 0.20). The relationship between GY and number of spikes/m^2 (NOS/m^2) showed an overall of strong correlations in all treatments. However, between treatments the strongest correlation was observed under DC (r = 0.10**) followed by L (r = 0.99*) while the lowest among treatments was observed under P (r = - 0.94).

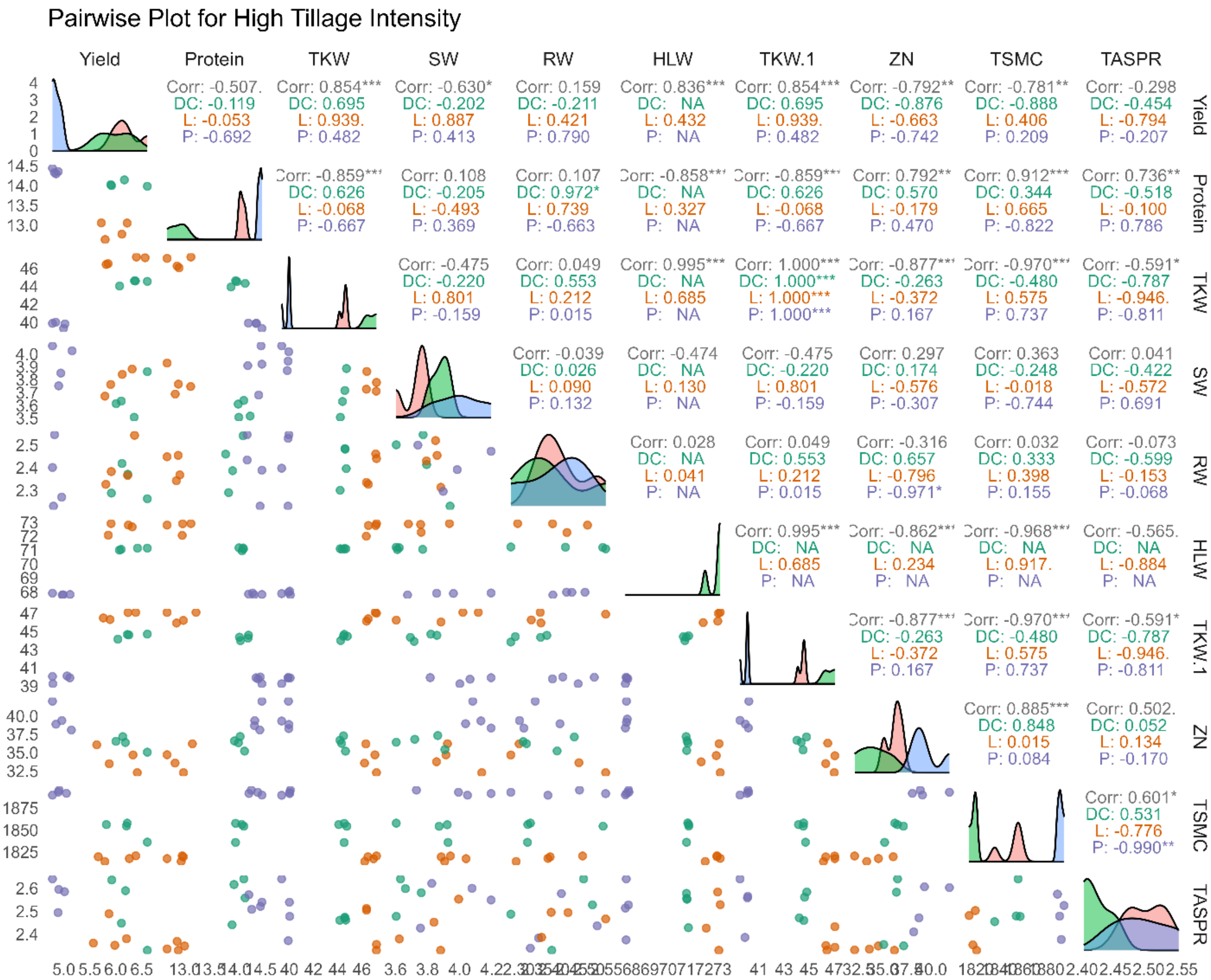

Figure 24. Winter wheat relationships under high intensity soil tillage methods. *Corr – the correlation p-value and the * indicate significance difference ($p > 0.05$). NT – No-till, D – disking, SC – Shallow cultivation. NA– indicate parameters where correlation could not be computed.*

Disking (D) soil tillage treatment showed the strongest negative correlation between GY and SPR. This indicates that when one increases in quantity the other decreases. This could be due to the fact that SPR is characterized by hardening of the soil in the sense that when this process occurs it affects a number of processes that are significant to the normal functioning of crops to complete their life cycle. These processes include chemical, biological and physical processes, however, other scholars reported more on the physical deterioration of soil. For instance, Birkás et al. (2002) reported a winter wheat yield loss of 13 and 15% (w/w) under disking soil tillage. They further suggested that the reason could be that annual disking to the same depth resulted in the compaction of soil which prevents root proliferation.

Furthermore, similar correlation trend was observed under SC. In contrast, under NT there was a weak positive correlation observed, suggesting a linear relationship between the two indices. However, due to the magnitude of the correlation, plausibly NT contribution was minimal to cause a significant change. Generally, an increase of SPR has a negative contribution to root development and ultimately yield. However, the nature of NT practices that integrate all conservation agriculture concepts, retain crop residue which helps reduce soil compaction.

The roots of the previous crop create bio pores in the soil that can be used by the next crop roots for deeper moisture and nutrient search. Residue retention and minimal soil disturbance create a conducive environment for earthworms that loosen the soil through burrowing and bioturbation. Additionally, their cast adds organic matter which is also reported to reduce soil compaction. Reports by Acir et al. (2022) and Salem et al. (2015) also highlighted that reducing soil stirring had positively enhanced soil BD and other physical properties. This leads to increased stimulation and buildup of soil microbial biomass, along with enhanced carbon sequestration, when using conservation soil tillage methods.

The relationship between GY and SMC under the same treatment was also negatively strong (r = - 0.82). Soil moisture content is an integral part of crop production. According to Lin et al. (2015) higher water in 0-10 cm depth is adventitious to enhance winter wheat GY. However, disking (D) can cause soil compaction as reported by Birkás et al. (2002). Compaction in the soil prevents roots from accessing oxygen, moreover, compaction can cause ponding in some fields, thus, inducing root hypoxia. Furthermore, waterlogging stress prevents root development and physiological metabolism, consequently leading to wheat yield depletion (Feng et al., 2022). Similarly, the relationship under SC was negative, but the strength was weak (r = - 0.33), indicating a plausible zero effect on the trade-offs between the two indices under this soil tillage method. However, NT showed a positive relationship, suggesting that under this soil tillage method more SMC will enhance GY.

Thousand kernel weight is reported to be the greatest constant yield parameter, that is minimally or not affected by abiotic factors (Svečnjak et al., 2004). However, based on our findings despite the lack of significant differences, the soil tillage practices affected TKW. The wheat quality traits (Zeleny sedimentation and HLW) under D were weakly negatively correlated (r = - 0.26) with grain yield. This suggests that for wheat crop disking creates unsuitable growing environment, such as compaction which can induce drought. Drought prevents N assimilation and protein synthesis, thus leading to grains with poor ZS values and HLW. Drawing from our results during wheat cropping period despite the lack of significant differences disking soil tillage produced the higher SPR relative to SC and NT (Table 11). This observation supports the study's hypothesis that disking soil tillage practice disintegrates soil physical structure ultimately affecting wheat quality.

The relationship between GY and RW under D and NT treatments was negatively strong ($r = -0.70$ and $r = -0.84$), these results explain the growth actions in the soil due to presence of compaction. As explained in the previous chapter that compaction detrimentally affects root growth due to its prevention of root proliferation, nutrient access and induced drought or root hypoxia due to water stagnation. In contrast SC treatment showed a positive correlation between the two indices and these suggests that higher root biomass promotes enhance grain yield.

The relationship between SW and GY was negatively strongly correlated under D and NT, moreover the relationship under NT was significant ($p < 0.05$, Figure 23). The strong negative correlation confirms the tradeoff between resources for vegetative growth and reproductive growth. Typically, these two indices exhibit an inverse relationship because the allocation of more resources to enhance plant biomass (vegetative growth) results in a deficiency for grain production. Contrastingly, SC showed a moderate positive correlation, suggesting the lack of competition between the two indices. The research conducted by Virk and Anand (1970) demonstrated a positive correlation between wheat grain yield and factors, such as spike length, biomass yield per plot, and TKW weight. Similarly, studies by Belay et al. (1993) and Aycecik and Yildirim (2006) identified a positive correlation between grain yield and the number of grains per spike, plant height, and TKW grain weight, thereby corroborating the findings of the present study.

There is generally a positive correlation between GY and TKW, as the weight of the kernels contributes to the overall yield. Hasegawa (2003) reported linear correlation of rice TKW and GY with lack of significant differences. Similarly, Chau and Bhargava (1993) stated an insignificant relationship between TKW and grain yield in rice. Contrary to expectations, the present study showed negative weak correlations between TKW and GY under D and NT. Some authors stressed that negative relationships between GY and TKW could be due to environmental differences.

Interestingly, Dudley and Lambert (1992), outlined a converted relationship between GY and protein concentration. They observed a significant ($P < 0.001$) negative correlation ($r = -0.885$) in their study as mentioned by Cociu and Alionte (2011) and meticulously elucidated by Mason and

D'croz-Mason (2002). Similar results were observed in this current study, NT and SC showed strong negative correlations but without significant differences. Findings elsewhere reported that environmental conditions could affect the relationship between crop indices. Hence a plausible explanation of the inverse relationship between GY and protein percentage could be that these soil tillage practices created a conducive environment that favoured robust biomass growth and that led to the dilution effect ultimately decreasing protein percentage. However, the GY and protein content were positively correlated under D treatment. The positive medium relationship between GY and protein content suggests that under this soil tillage practice will affect both indices similarly.

In general, for positive yield outcomes, the correlation between GY and SPR should be negative. This was clearly highlighted by results under these high intensity soil tillage treatments DC and P. These soil tillage treatments are associated with the formation of hardpans when repeatedly employed to the same depth particularly P. In contrast a positive relationship observed under L suggests that an increase in SPR will enhance GY vice versa.

Similarly, the SMC had a negative relationship, but the magnitude differed. Treatment DC and L were strongly correlated, while P showed a weak correlation. As it has been thoroughly discussed that lack of adequate moisture affects GY in crops. In all soil tillage treatments, Zeleny sedimentation (ZS), was strongly negatively correlated to GY. The ZS is related to N in grain. The plausible reason for the negative correlation is that in our study these soil tillage practices enhanced GY which stimulated the dilution effect, thus causing a decline in the baking quality of wheat.

The correlation between GY and HLW under DC and P was impossible due to the raw data values. However, under L, there was a weak correlation. The RW and GY were weakly correlated under DC and L (negatively and positively respectfully). While under P there was a strong correlation. This suggests that treatment DC provides a growing environment that induced an inverse relationship. While under P the relationship was positively indicating that the high or the quantity of RW enhances GY. In contrast under L the relationship was weak, indicating that there was less effect of the soil tillage method to GY and RW relationship.

In contrast to observed SW and GY correlations. The relationship between SW and GY was weak under DC and P (negatively and positively respectfully). The L treatment was positively strongly correlated; this suggests that L treatment favoured both biomass and GY increase or decrease. The

TKW and GY linear relationship was favoured by DC and L, while P showed a weak relationship indicating insignificant changes or contributions between the two indices. The DC and L treatments relationships have no effect. However, the strong relationship under P treatment suggests that there is a trade-off between GY and protein percentage.

Low intensity soil tillage methods for oat are shown in Figure 25. The relationship between GY and SPR was weak in all treatments. The strongest among treatments was observed under NT (r = - 0.33), followed by SC (r = 0.04), and the weakest was observed under D (r = - 0.02). The GY correlation with SMC was strongest under SC (r = 0.89) and NT (r = - 0.85), while D (r = 0.33) treatment showed the weakest correlation (Figure 25). The relationship between RW and GY showed the strongest relationships under SC (r = 0.90) and D (r = 0.87), and the weakest was observed under NT (r = 0.05) treatment. The relationship between SW and GY was strongest under SC (r = 0.80) and D (r = 0.78), while NT (r = 0.22) showed the weakest correlation. The relationship between GY and TKW was strongest under NT (r = 0.94) and under D (r = - 0.40), and SC (r = - 0.49) treatments showed weak moderate correlations. The HWL and GY showed weaker positive and negative correlations under D (r = 0.33) and NT (r = - 0.13), and the strongest negative correlation was observed SC (r = - 0.89). The GY and protein percentage relationship was weaker in all the treatments. The strongest among the treatments was observed under D (r = - 0.41), followed by SC (r = - 0.35), while the weakest was observed under NT (r = 0.03). The GY with the NOS/m^2 relationship was weakest under NT (r = 0.07) and strongest under D (r = 0.86) and SC (r = 0.89).

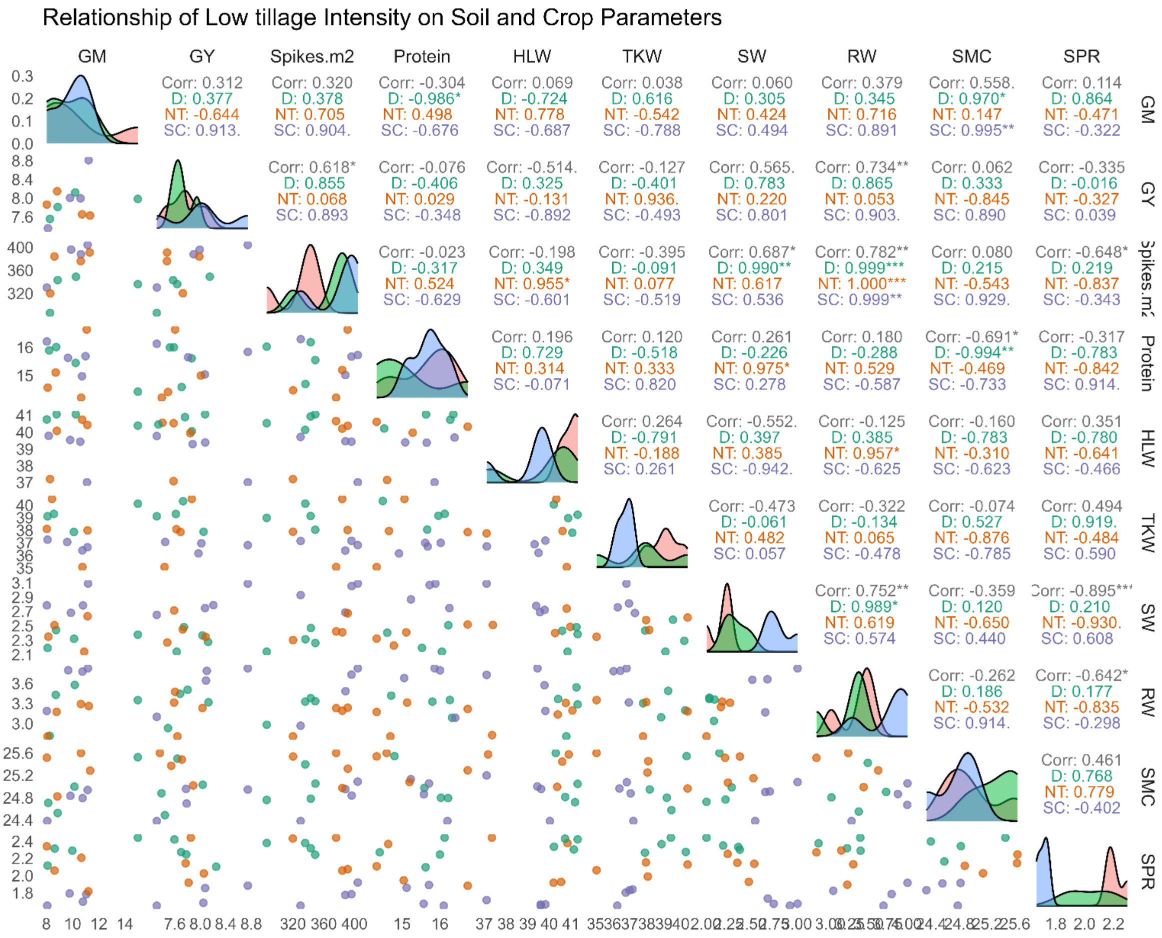

Figure 25. Winter oat relationships of soil and crop parameters under low intensity soil tillage methods *. Corr – the correlation p- value and the * indicate significance difference (p > 0.05). NT – No-till, D – disking, SC – Shallow cultivation. NA– indicate parameters where correlation could not be computed.*

The relationship between GY and SPR under high intensity soil tillage treatments was positively strongest under DC (r = 0.83), moderately negatively strong under P (r = - 0.48) and weakest under L (r = 0.10). The relationship with SMC showed weaker correlations overall in all the soil tillage treatments (Figure 26). The strongest correlation among the treatments was observed under DC (r = -0.37), followed by P (r = 0.31), and the weakest among treatments was observed under L (r = 0.12). The relationship with RW showed the overall strongest correlations in all soil tillage treatments. The strongest correlation was observed under L (r = 0.99*), followed by DC (r = 0.96**), while the weakest among the treatments was observed under P (r = 0.82). The relationship with SW was strong under L (r = 0.88) and P (r = 0.82), whereas the weakest among treatments was observed under DC (r = 0.30). The TKW and GY correlations were also strong in all treatments, however, between treatments the strongest observed under DC (r = - 0.10**), followed by L (r = - 0.92), and the lowest among treatments was observed under P (r = 0.88). The strongest correlation between HLW and GY was observed under P (r = 0.86), while under DC (r = 0.70) there was a moderate correlation, and L (r = 0.44) treatments had a moderate correlation. However, the relationship between GY and protein percentage was strongest under DC (r = 0.91), while P (r = 0.45) had a moderate correlation, and the weakest correlation was observed under L (r = 0.20). The relationship between GY and PD/m^2 showed an overall of strong correlations in all treatments. However, between treatments the strongest correlation was observed under DC (r = 0.10**) followed by L (r = 0.99*) while the lowest among treatments was observed under P (r = - 0.94).

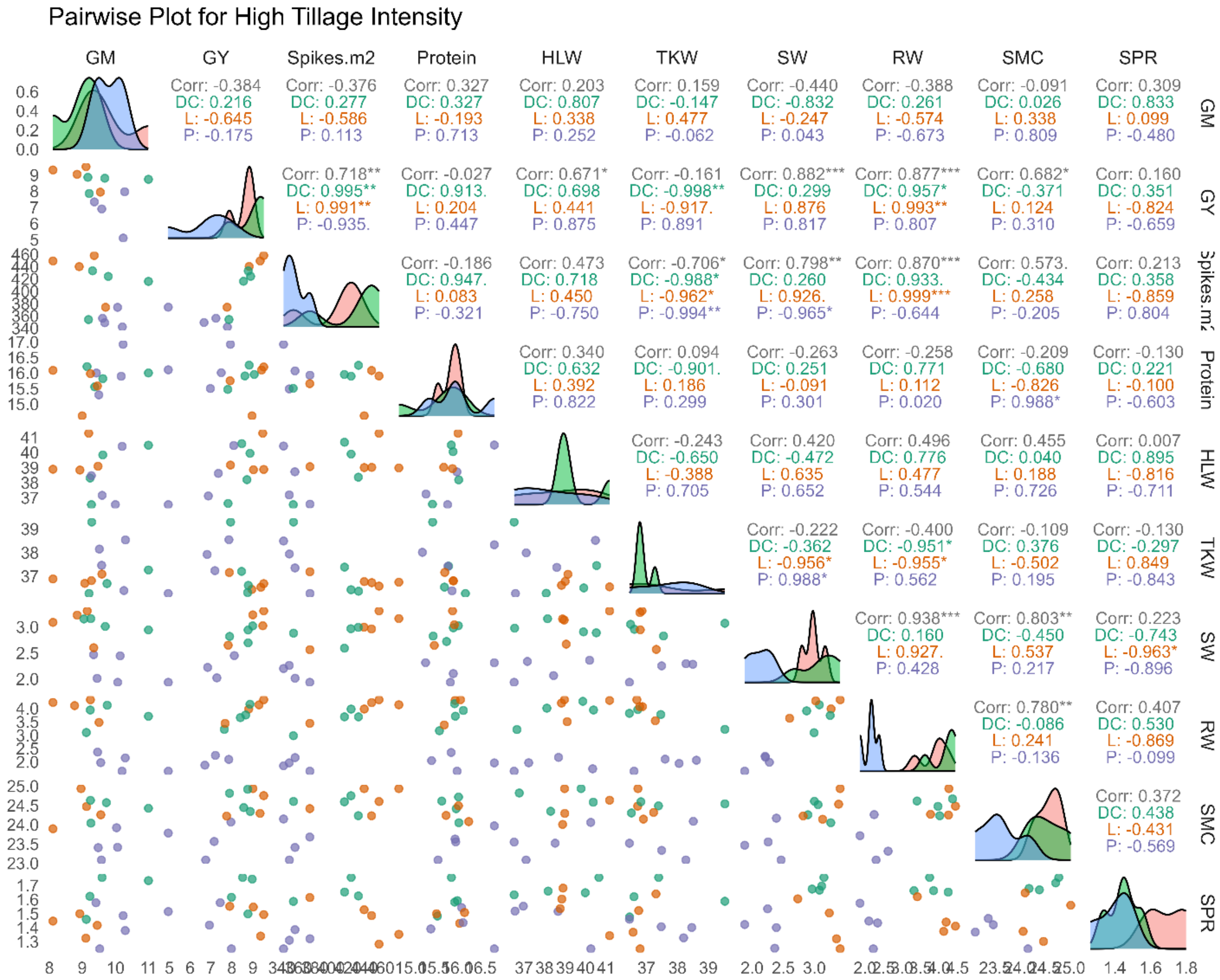

Figure 26. Winter oat relationships of soil and crop parameters under high intensity soil tillage methods . *Corr – the correlation p- value and the * indicate significance difference (p > 0.05). NT – No-till, D – disking, SC–Shallow cultivation. NA– indicate parameters where correlation could not be computed.*

All treatments showed weaker correlations between GY and SPR. GY and SMC were strongly correlated under NT and SC (negatively and positively respectfully). This indicates a contrast on the effect of the soil tillage practices. The inverse relationship under NT implies that as moisture increase negatively affect GY, whereas under SC the linear relationship indicates that an increase in SMC enhances GY. Crop roots act as a bridge between soil and above-ground canopy, and it plays a key role in grain yield formation (Zhai et al., 2021). The GY and RW relationship in the present study strongly supported the notion that RW increases, or decrease will affect GY similarly under all soil tillage treatments. In relation to the SW only L and P had positive strong correlations, suggesting similar phenomenon to the latter discussed indices. The DC and L treatments strongly support the notion that an increase or decrease of GY will result in an opposite effect on TKW. In contrast, under P thousand kernel weight was linearly related to GY. This observation was in line with Elabbadi et al. (2024), they reported a high positive correlation between GY and TKW.

The HLW and GY relationship under DC and P suggest a linear relationship. Similarly, under L but the magnitude is low so that an inference can be made. GY and protein percentage were weakly correlated in all treatments. The GY and NOS/m^2 strongly increased simultaneously/decreased under D and SC. Contradicting results between NT and SC. In NT treatments results suggest a tradeoff between GM and GY, while under SC the opposite is observed. Both correlation quantities are strong.

Oat high intensity soil tillage practices (DC, L, and P) relationships are shown in Figure 26. The concept illustrated by both NT and P practices is that there is an inverse relationship, where an increase in SPR corresponds to a decrease in GY. However, under DC, the relationship suggests the opposite, albeit with a weaker correlation that is insufficient to prompt significant change. All treatments exhibit very weak correlations, making it difficult to base any decisions on them. GY and RW strongly support the notion that an increase or decrease in RW will similarly affect GY across all soil tillage treatments. Regarding SW, only L and P showed strong positive correlations, indicating a phenomenon similar to the latter results.

Treatments DC and L strongly support the idea that an increase or decrease in GY will have the opposite effect on TKW. In contrast, under P, TKW is linearly related to GY. The relationships between HLW and GY under DC and P suggest a linear relationship, which is also observed under L, though the magnitude is too low to draw a conclusion. The relationships between GY and protein percentage strongly suggest that DC treatment favors an increase in protein percentage and GY simultaneously. A similar observation was made under L and P, but with weaker correlation values. Treatment L showed strong negative correlations between GM and GY. Our results are in contrast with Zhang et al. (2022a) who did not observe a negative correlation between GY and GM under maize cultivation in China.

5. CONCLUSION AND RECOMMENDATIONS

This chapter provides conclusion derived from the results of the study and recommendations to further enhance and cover areas that need research to contribute knowledge to the scientific world.

Soil tillage plays a significant role in crop production, by modifying the environment that crops grow, it indirectly affects crop growth and yield quality parameters. The results of this study highlight the complex interplay between soil tillage on soil penetration resistance, soil moisture content and crop production. In relation to the physical parameters of the SPR, significant differences were observed among the assessed soil tillage practices. Evidently, the study has shown that disking and no-soil tillage significantly increased soil penetration resistances under an Endocalcic chernozem soil in the Mediterranean climate of Hatvan.

Moreover, for the soil type and climatic conditions that the study was performed I observed that higher SPR resulted in lower root weight and grain yield. These findings suggest that for Endocalcic chernozem soil,periodic deep soil tillage should be considered to prevent excessive compaction when reduced soil tillage systems are employed. Deep soil tillage practices, such as L and P proved more beneficial in eradicating soil compaction. This highlighted that soil tillage depth may be a more significant factor than frequency, as observed in deep soil tillage (40–45 cm) being more effective in preventing compaction than intermediate-depth soil tillage methods (18–25 cm). However, it is equally important to note that, although ploughing can provide a substantial depth of a loosened layer, there is a possibility of plough pan formation below the working depth of the equipment. Hence, further steps should be taken in order to avoid crop yield penalties, such as annual soil condition assessment if ploughing is practiced annually. Furthermore, variation in depth of ploughing could prove beneficial in reducing the extension of a plough pan.

Seasonal changes influence soil penetration resistance trends with variations driven by climate and soil conditions, with notable increases during drier periods. Other studied soil tillage practices did not show clear impacts on soil penetration resistance; however, I observed that on a Endocalcic chernozem soil there was no difference between SC and DC despite the difference in loosening depth (18–20 and 22–25 cm, respectively) in mitigating soil penetration resistance.

To prevent crop loss due to drought in the Mediterranean, arid, and semi-arid regions, the adoption of deep soil loosening or the incorporation of periodic deep soil tillage into reduced soil tillage systems (SC, D, DC, and NT) is recommended to prevent excessive compaction particularly for the current study's soil type and climatic conditions. Moreover, future research should explore the synergy between soil physical properties, crop physiology, and climate variability to optimize soil tillage strategies for sustainable agriculture.

In this current study soil tillage had substantial influence on wheat protein%, which was enhanced by D and P treatments. With winter oat crop irrespective of absence of significant differences the protein % was higher under P, SC, L and DC. These results showed an inconsistency of the response of these quality traits and since the experiment was conducted in a single season, more research is needed to understand better the interplay between these soil tillage and protein%. Thousand kernel weight and hectoliter weight were not significantly influenced by soil tillage during oat growing season. During the growing winter wheat period, the latter were enhanced under minimum soil tillage practice than ploughing. Zeleny sedimentation measured only under winter wheat was also improved by NT. While under winter oat only the PD/m^2 also was improved by conservation agricultural practices (L, DC, NT and SC). Lastly, the straw weight was enhanced by P under wheat and L under oat, however it is important to note that the differences under wheat were not substantial. This means that L treatment can be used instead of P to enhance straw weight, thus, this further supports the notion that conservation agricultural soil tillage practices were more superior than conventional soil tillage on the investigated properties.

6. NEW SCIENTIFIC FINDINGS

1. The study confirmed that despite more than 16 years of NT practice on an Endocalcic Chernozem soil, the highest soil penetration resistance is still obtained in NT treatment compared to ploughing. This indicates that NT treatment under a Mediterranean type climate in Hatvan NT does not reduce penetration resistance irrespective of period practiced.
2. I confirmed that reduced soil tillage methods, such as no-till, shallow cultivation and disking, lack substantial differences to ploughing, loosening, and deep cultivation when climatic conditions are more humid, particularly when annual rainfall > 600 mm for thousand kernel weight and hectoliter weight for Endocalcic Chernozem soil in Hatvan.
3. Minimum soil tillage practices, such as SC and DC equally enhanced and improved SMC, crop quality similar to NT, hence they can be integrated into areas where NT practice have shortfalls or is not effective.
4. I quantified the relationships of SPR, yield and yield quality parameters. The study confirmed a strong negative correlation between grain yield and soil penetration resistance under disk soil tillage and shallow cultivation. The study further confirmed a strong negative correlation between grain yield and soil moisture content under disking; however, a weak correlation was confirmed for Zeleny sedimentation and hectoliter weight.
5. The study revealed that disking and ploughing outperformed loosening in enhancing wheat protein percentage. However, loosening improved thousand kernel weight relative to ploughing. Furthermore, the study confirmed a pattern of decreasing TKW in DC and P.
6. No-till and disking soil tillage treatments reduced wheat yield and sunflower yield, while ploughing reduced oat yield. While loosening greatly enhanced yield of all the crops for the whole three examined seasons.
7. In this study disking treatment greatly diminished root weigh for winter wheat and sunflower, whereas the root weight under winter oat substantially decreased under ploughing treatment.
8. The study revealed confirmed that no-till on an Endocalcic Chernozem does not reduce the penetration resistance even post a decade of practice as reported by other studies. Moreover, I confirmed that the higher penetration resistance under NT had an effect on crop yield as compared to tine tillage implements.

7. PUBLICATIONS

7.1. Scientific article

a. Dekemati, I., Simon, B., Bogunovic, I., Vinogradov, S., **Modiba, M.M**., Gyuricza, C. and Birkás, M., 2021. Three-year investigation of soil tillage management on the soil physical environment, earthworm populations and crop yields in Croatia. *Agronomy*, *11*(5), p.825.

b. Ibrahim, H.T.M., **Modiba, M. M**., Igor, D., Simon, B., Muktar, M., Lisanwork, N. (2022): The Role of Mixed Cropping to Climate Change in Sofi District, Harari Regional State, Ethiopia. Journal of Central European Green Innovation, 75–87. doi: 10.33038/jcegi.3564.

c. **Modiba, M. M**., Ibrahim, H.T.M., Simon, B., Igor, D. (2022): The Effect of Mulching on the Biological and Physical Properties of Soil in Maize. Journal of Central European Green Innovation, 39–49. doi: 10.33038/jcegi.3564.

d. **Modiba, M. M**., Ibrahim, H.T.M., Igor, D., Simon, B. (2023): Overview of Conservation Soil tillage Practices for Developing and Sustaining Climate Change Resilient Soils in Sub-Saharan Africa. Journal of Central European Green Innovation, 11(3), 91–104. (2023) doi: 10.33038/jcegi.4535

e. Ibrahim, H.T.M., **Modiba, M.M**., Dekemati, I., Gelybó, G., Birkás, M., Simon, B (2023): Status of Soil Health Indicators after 18 Years of Systematic Soil tillage in a Long-Term Experiment. Agronomy, 14, 278. doi:10.3390/agronomy14020278

f. Schally, G., Tóth, D., Márton, M., Bijl, H., Palatitz, P., Csányi, S., **Maimela Modiba**, M., Ibrahim, H. T. M., Simon, B. (2024). The effect of soil parameters and earthworm abundance on the finescale nocturnal habitat use of the Eurasian woodcock (Scolopax rusticola). Ecology and Evolution, 14(8). Portico. doi :10.1002/ece3.70136

g. **Modiba, M.M**., Ocansey, C.M., Ibrahim, H.T.M., Birkás, M., Dekemati, I., Simon, B (2025): Assessing 16 Years of Soil tillage Dynamics on Soil Physical Properties, Crop Root Growth and Yield in an Endocalcic Chernozem Soil in Hungary. doi:10.3390/agronomy15040801

h. Simon, B., Dekemati, I., Ibrahim, H. T. M., **Modiba, M. M**., Birkás, M., Grósz, J., Kulhanek, M., Neugschwandtner, R. W., Hofer, A., Wagner, V., Windisch, M., Hage-Ahmed, K., Butt, K.

R., Euteneuer, P (2025): Impact of soil tillage practices and soil texture on soil health and earthworms in the Pannonian region: A comparative study from Austria and Hungary. Applied Soil Ecology, 206, 105863. doi: 10.1016/j.apsoil.2025.105863

i. Ibrahim, H.T.M., **Modiba, M. M.**, Simon, B. (2023): Effects of Climate Change on Sudan's Water Resources. Journal of Central European Green Innovation, 11(3),84–90. doi: 10.33038/jcegi.4524

j. **Modiba, M. M.**, Ocansey, C. M., Ibrahim, H. T. M., Birkás, M., Dekemati, I., and Simon, B. (2024). Assessing the Impact of Soil tillage Methods on Soil Moisture Content and Crop Yield in Hungary. Agronomy, 14(8), 1606. doi:10.3390/agronomy14081606

7.2. Abstract and workshops presentation

- **Risk factor of food chains 20-22 September 2023**

Abstract title: Assessment of Soil tillage Strategies and their impact on Soil Health and sustainability on arable land

- **The 6th ISCW Conference**

Abstract title: Overview of conservation soil tillage practices for developing and sustaining climate change resilient soils in sub-Saharan Africa.

- **European Joint Programme (EJP) C-arouNd Workshop in Ghana**

Presentation title: Impacts of soil tillage on soil physical properties, crop yield and quality: Insights from a long-term experiment in Endocalcic Chernozem soil.

8. SUMMARY

Soil tillage is one of the most central parts of the agricultural sector particularly where plants are involved. Its impacts on plants have been extensively studied and in recent years due to harsh rise in awareness to conserve the terrestrial environment and cub the negative impacts of greenhouse gas emissions, soil degradation and sustainable food, fiber and fuel production. This fueled a rise interest in its effect on soil physical, chemical and biological properties. These interests varied tremendously as researchers globally were looking into elucidating various topics, such as greenhouse gas emissions, soil microbial biodiversity, and nutrients. Similar, to other researchers elsewhere, this dissertation assessed the effects of soil tillage on soil moisture content, soil penetration resistance, yield quality parameters and grain yield.

To assess the soil tillage effects on the soil and crop properties, a three-year study was conducted under rainfed field conditions at the Józsefmajor Experimental Farm near Hatvan. Three different crops were planted seasonally, namely winter wheat, winter oats, and sunflower. The findings of the study showed that soil tillage significantly affected SMC, SPR, crop growth and yield quality parameters and grain yields. Among the soil tillage treatments investigated, NT and D were more superior in increasing SPR compared to other soil tillage treatments. The winter wheat cropping season results showed greater SPR values at treatments D and NT with some occasional exceptions when considering differences at various depths and sampling time.

SMC during the three investigated seasons was significantly affected by soil tillage. The SMC measured at the whole depth (0-50 cm) was lower under L compared to NT, significantly lower under P compared to all the other soil tillage practices and lower under P and NT compared to the other soil tillage practices in wheat, sunflower and oat respectively. In the winter wheat growing season, SMC was consistently lower under L treatment for all depths measured. However, under sunflower, similar results were observed under P. There were no consistent trends in sunflower with regards to soil tillage practices. Significant differences were observed under varying soil tillage practices and depths. The temporal effects of soil tillage showed D treatment stored significantly higher moisture than L during wheat growing period in June, while in March higher moisture was obtained under P and NT. In sunflower growing season, significantly greater SMC was obtained under NT, followed by DC, while the lowest was observed under P. In the winter oat season, no significant differences were observed between soil tillage treatments, however, moisture significantly differed by sampling time.

SPR at 0-50 cm was significantly affected by soil tillage in wheat growing season, higher SPR was observed under D and the lowest under L. Similar results were observed during sunflower growing season. In winter oat growing season, under treatment D, SPR was still significantly higher, however, the lowest was observed under P. In relation to different depths D treatment, it was consistently the highest under wheat crop. At different sampling time, in March and July, NT was significantly higher than L. Similarly, under the sunflower growing period, NT and D significantly increased SPR at various depths compared to L. In October, November, March and April, significantly greater SPR was obtained under NT compared to L. While during oat growing season, higher SPR measured at different sampling times was consistently observed under D treatment compared to P and L. At the various depths differences showed similar consistency of D treatment compared to P and, however with occasional similarities.

Varied results were obtained for root weight (RW) and grain yield (GY). Wheat had significantly higher yield under L, SC and DC compared to D, NT and P, while under sunflower the seed yield was significantly improved by L treatment compared to D and NT. Similar for at, L treatment significantly increased the yield compared to P. RW during wheat season was higher in DC, P and L compared to D and NT. While sunflower RW was significantly greater under L relative to D while similar root growth response was observed between SC and P. Winter oat root growth was significant suppressed by P while L and SC favoured greater RW.

The yield quality parameters measured from winter wheat and winter oat were also significantly affected by soil tillage particularly for winter wheat. Significantly greater protein% observed under D and P for winter wheat, while under winter oat there were no significant differences observed. The thousand kernel weight (TKW) was significantly greater under L compared to P. However, for oat there were significant differences observed, similarly for Hectoliter weight (HLW) for the same crop, no significant differences were observed. While for wheat HLW was significantly greater under SC compared to P. The Zeleny number (ZN) was significantly improved under NT compared to L. PD/m^2 was significantly improved by L compared to D, moreover DC had similar planting density per square meter (PD/m^2) relative to L. The SW was significantly higher under P for winter wheat while for winter oat significantly higher straw weight (SW) was observed under L treatment.

The overall results of this study revealed that conservation soil tillage practices, such as L provided conducive conditions for plant growth simultaneously improving soil health compared to ploughing. Hence, for sustainable crop production we recommend the adoption of these practices or incorporation of these occasionally in NT system to reduce the higher SPR without reversing its benefits.

APPENDICES

A1. Bibliography

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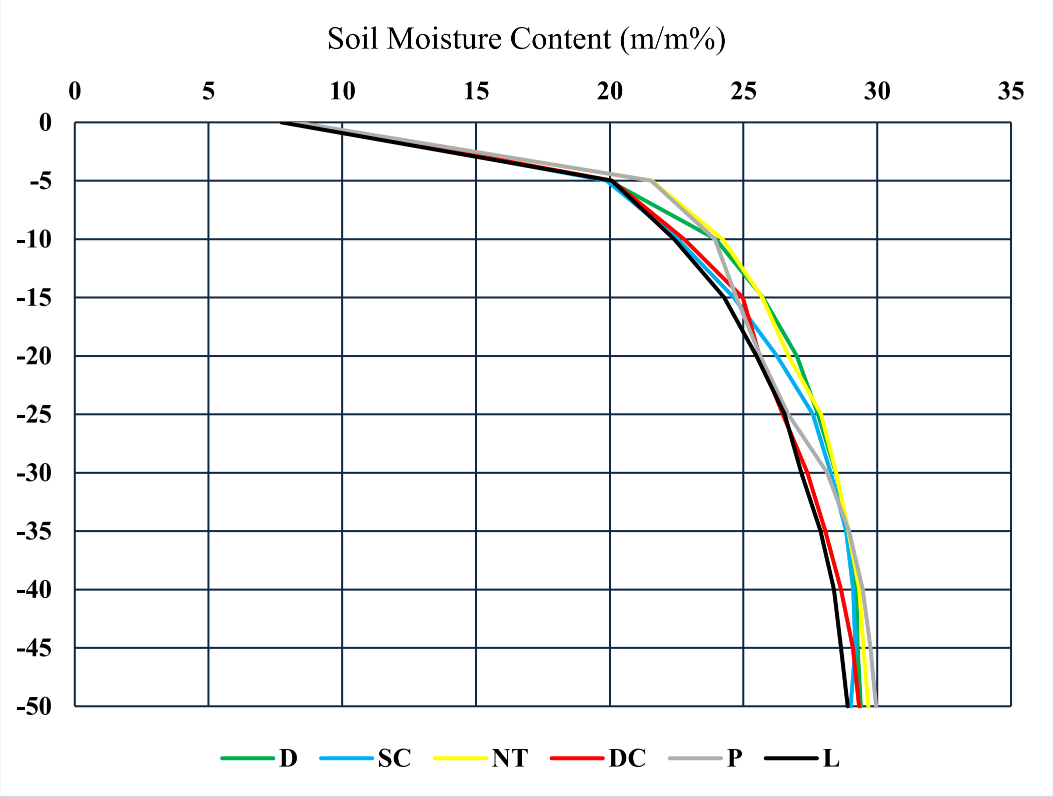
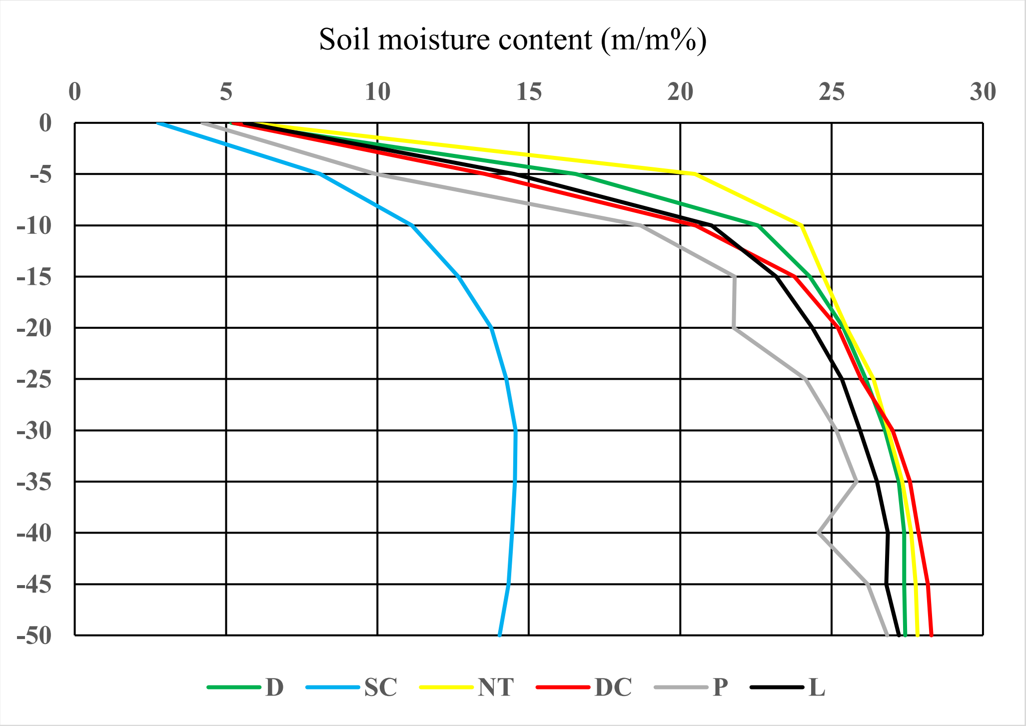
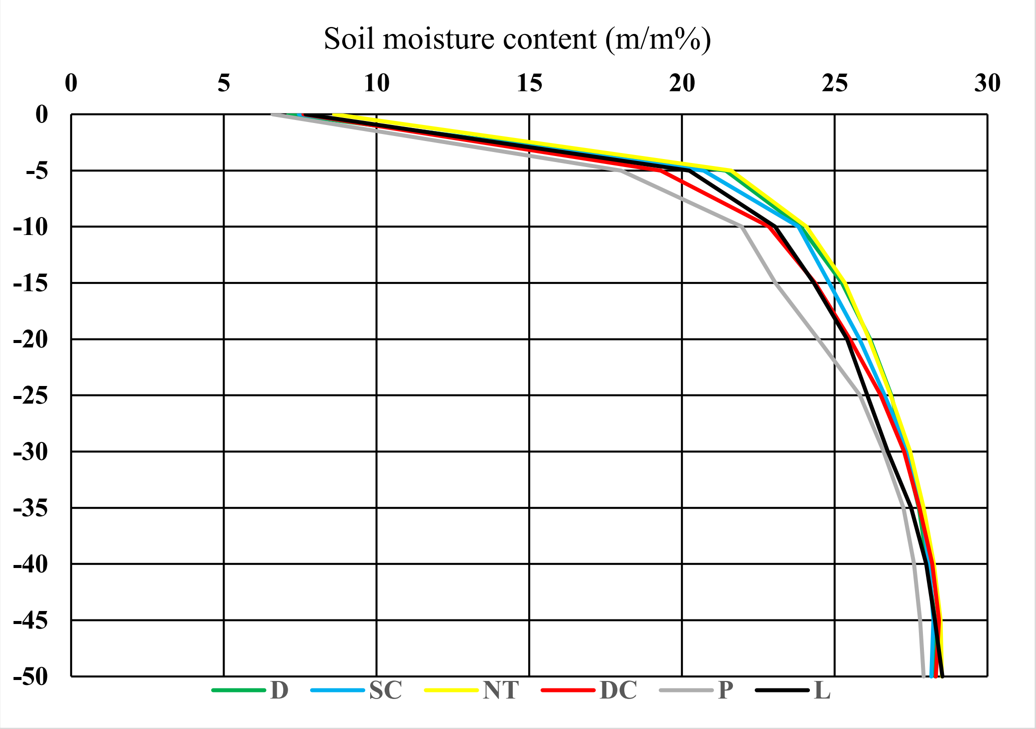
A2. Soil moisture content and soil penetration resistance graphs



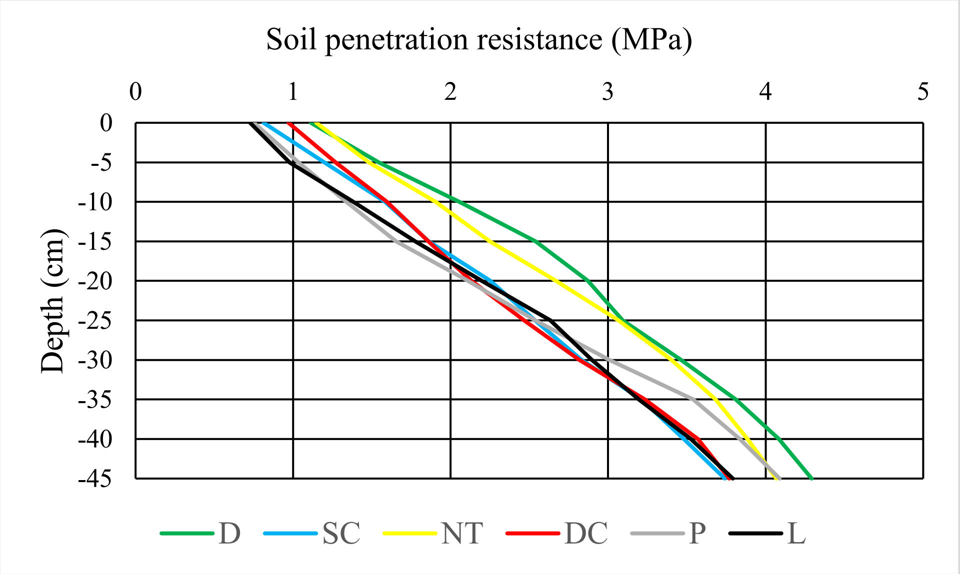
A2. Figure 28. Winter wheat soil moisture content values measured at 0-50 cm depth



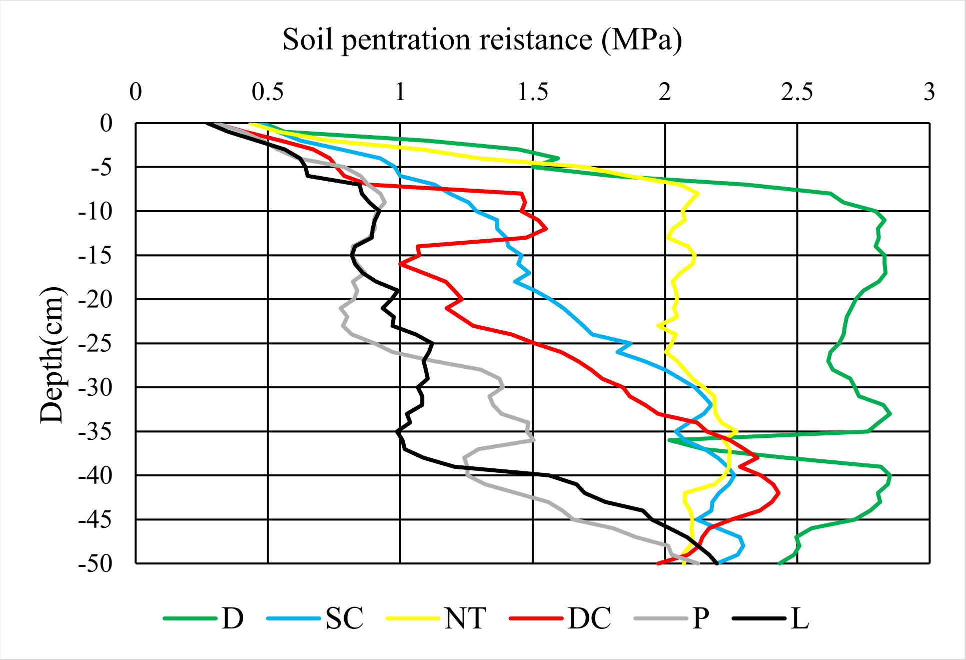
A2. Figure 29. Winter oat soil moisture content values measured at 0-50 cm depth



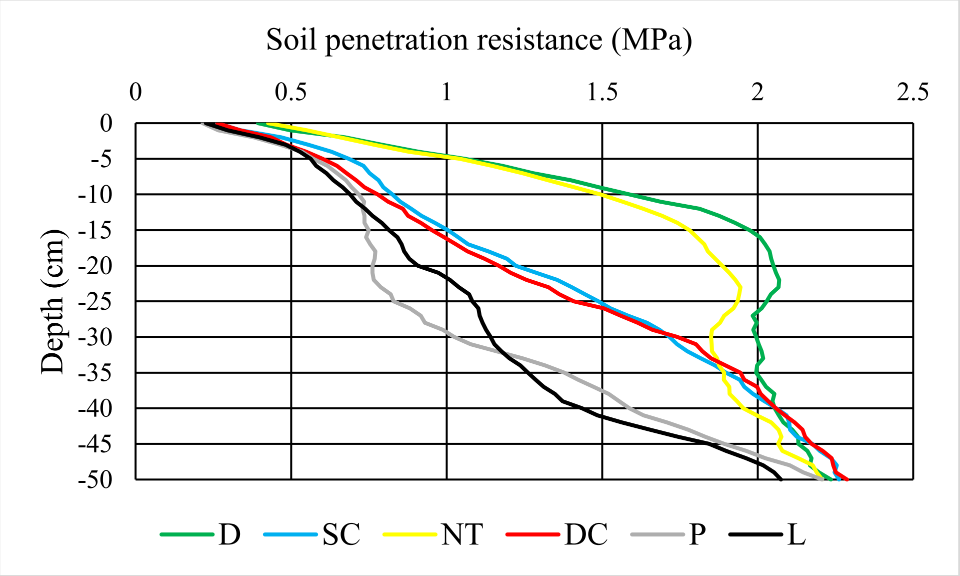
A2. Figure 30. Sunflower soil moisture content values at 0-50 cm depth



A2. Figure 31. Winter wheat soil penetration resistance values at 0-50 cm depth



A2. Figure 32. Winter oat soil penetration resistance values at 0-50 cm depth



A2. Figure 33. Sunflower soil penetration resistance values at 0-50 cm depth

A3. Experimental photos

A3. Figure 34. Soil tillage practices at Józsefmajor Experimental Farm. (a) Disk soil tillage, (b) Cultivator, (c) Loosening, (d) Moldboard ploughing, (e) No-till