EFFECT OF PRIMARY TILLAGE INTENSITY ON BOREAL CLAY SOIL TEMPERATURE BEFORE SPRING SOWING IN FINLAND

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ABSTRACT

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Tiivistelmä — Referat — Abstract

This study investigates the effect of primary tillage intensity on soil temperature dynamics in boreal clay soils during the pre-sowing period in Finland. Field data were collected from 2013 to 2016 in Jokioinen, southwestern Finland, comparing three tillage treatments: conventional ploughing (20–25 cm), stubble cultivation (10–15 cm), and zero-tillage. Spring barley (*Hordeum vulgare L.*) was cultivated and soil temperatures were monitored at a 10 cm depth using high-resolution sensors, with additional meteorological data collected to capture air temperature and snow cover effects. The results from this study showed that reduced tillage systems, particularly stubble cultivation, consistently maintained higher minimum soil temperatures and exhibited less daily variability than ploughed plots. While ploughed soils warmed fastest in early spring, this advantage was not sustained, and reduced tillage treatments often reached thermal thresholds (0, 2, and 5 °C) earlier or at similar times. Cumulative temperature sums above these thresholds indicated that stubble cultivation offered the best balance between early warming and soil temperature stability. Frost and snow cover data confirmed that zero-till plots had shallower frost depths due to greater crop residue and snow insulation. These findings suggest that intermediate tillage intensity enhances thermal conditions and field readiness in variable boreal springs, offering a practical compromise between soil conservation and early sowing potential.

Avainsanat — Nyckelord — Keywords

Boreal clay soil, soil temperature, ploughing, stubble cultivation, zero-tillage, spring sowing.

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List of abbreviations

CT: Conventional tillage

RT: Reduced tillage

ZT: Zero tillage

P: Ploughed till

S: Stubble cultivation

1. Introduction

Agriculture in the boreal region of Finland is characterized by a short growing season, cold soils in spring, and a strong dependence on soil temperature for successful early-season crop establishment (European Environment Agency, 2003). According to (Luke Statistics, 2022), spring barley (*Hordeum vulgare L*) is the most cultivated cereal crops in Finland which is about 21% of the arable land, which requires favorable soil conditions for germination and root development, making soil temperature a key determinant of early growth performance (Kleemola et al., 1995). In spring cereal cultivation, the quality of the seedbed is important to ensure rapid crop establishment by reducing evaporation and providing adequate contact between soil and seed (Känkänen et al., 2011).

Tillage practices play a critical role in shaping soil thermal dynamics by altering surface conditions, residue cover, and soil structure. Conventional tillage (CT), involving full soil inversion and residue removal, which enhances solar energy absorption by exposing darker soil surfaces, thereby promoting faster soil warming in early spring (Blanco-Canqui & Lal, 2007; Franzluebbers, 2002; Liang et al., 2025). In contrast, reduced tillage (RT) and zero-till (ZT) systems retain crop residues on the surface, which insulate the soil, retains moisture, and reflects solar radiation slowing the rate of soil warming (Unger & Vigil, 1998; Cui et al., 2024). These effects are particularly relevant in boreal clay soils, which are characterized by high water-holding capacity and low permeability, combined with cold climatic conditions, these properties contribute to slower spring soil warming (Subin et al., 2013). Surface residues in RT and ZT systems can further lower early spring soil temperatures, potentially delaying sowing and influencing crop phenology (Jessop & Stewart, 1983). By modifying soil porosity, moisture retention, and residue distribution, tillage intensity directly affects heat flow and moisture dynamics, with important implications for seedbed conditions and early crop development (Licht & Al-Kaisi, 2005).

This research focuses on the impact of primary tillage intensity on soil temperature in boreal clay soils prior to spring sowing, with spring barley as a case study by comparing moldboard ploughing, stubble cultivation, and zero-till systems. This study seeks to evaluate how tillage-induced changes in soil structure and residue cover influence the soil thermal environment.

The goal of this study is to contribute to the development of sustainable and climate-adapted tillage practices that enhance the reduction of soil erosion and long-term crop productivity. Additionally, understanding these interactions between climatic variability and the increasing emphasis on sustainable agriculture. As farming systems in the boreal region adapt to environmental constraints, optimizing tillage practices to balance soil warming with erosion control and moisture conservation becomes essential. The data for this thesis were collected as part of the TALMA project, conducted in collaboration with the University of Helsinki, Department of Agricultural Sciences, and the Natural Resources Institute Finland (Luke). The project was funded by Maa- ja vesitekniikan tuki ry. (MVTT).

2. Literature review

2.1 Factors influencing soil temperature

Various environmental and soil-related factors influence the absorption, retention, and transfer of heat in soil, which are shown in Figure 1. These factors include surface characteristics like color, the presence of crop residues, soil moisture content, incoming solar radiation, soil porosity, texture, and the tillage method used. For example, a thick layer of plant residues on the soil surface acts as an insulating layer, reducing the penetration of solar radiation and consequently slowing the transfer of heat to deeper soil layers (Azooz et al., 1997).

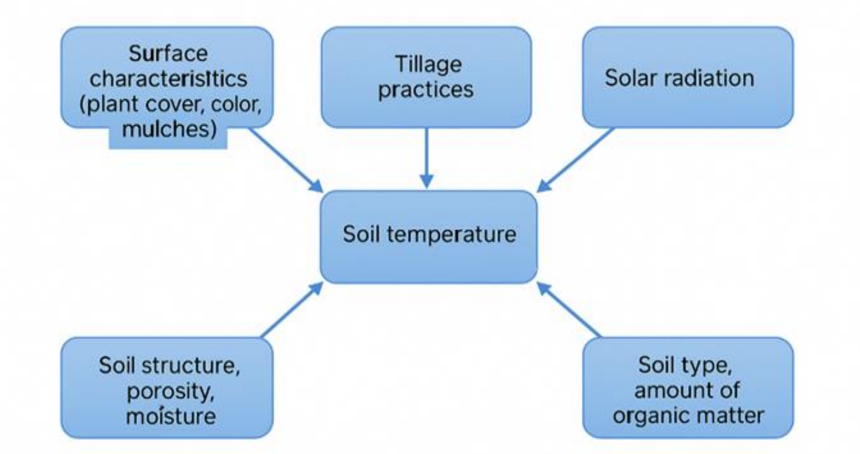

Figure 1. Factors affecting soil temperature. Adapted from (Azooz et al., 1997; Hillel, 2004; Morrow & Friedl, 1998).

Soil type is a major determinant of thermal behavior, with mineral soils generally warming more quickly than organic soils (Osman, 2013). This is largely due to their denser, less porous structure, which facilitates more efficient heat transfer. In contrast, the lightweight and porous nature of organic soils tends to slow down temperature changes (DeVries, 1963; Kung & Steenhuis, 1986). A key factor behind these differences is specific heat capacity, the amount of energy required to raise the temperature of a given mass of soil, expressed in $J \cdot K^{-1} \cdot kg^{-1}$ (c) (*SFS-Oppaat*, 2002).

2.2 Soil properties and thermal dynamics of boreal clay soils in Finland

Boreal zones, covering vast areas of the Northern Hemisphere, are characterized by long, cold winters and short, cool summers. In Finland, agricultural soils used for cereal cultivation are largely dominated by fine-textured clay soils, particularly in the southern and southwestern parts of the country. These soils often experience slower warming in spring due to their dense structure. Furthermore, their heavy texture makes them prone to compaction, which reduces air porosity and exacerbates delays in spring soil warming, especially under high moisture conditions.

The specific heat capacity of soil is influenced by both moisture content and soil structure. Since tillage alters soil porosity and water retention, it affects the soil's ability to store heat and respond to temperature changes (Lipiec & Hatano, 2003; Ochsner et al., 2001). Soil thermal properties including heat capacity, thermal conductivity, and thermal diffusivity are determined by texture, structure, moisture, and organic matter, all of which tillage can modify (Dec et al., 2009; Evgeny & Ahmed, 2016). In clay soils, high moisture content notably increases heat capacity, requiring more energy to raise the temperature, while simultaneously lowering thermal diffusivity and slowing temperature changes (Hillel, 2004; Ochsner et al., 2020). This effect is illustrated in Figure 2, which shows how thermal conductivity and diffusivity respond to increasing volume wetness in different soil types. As a result, clay soils warm up more slowly in spring compared to coarser, drier soils.

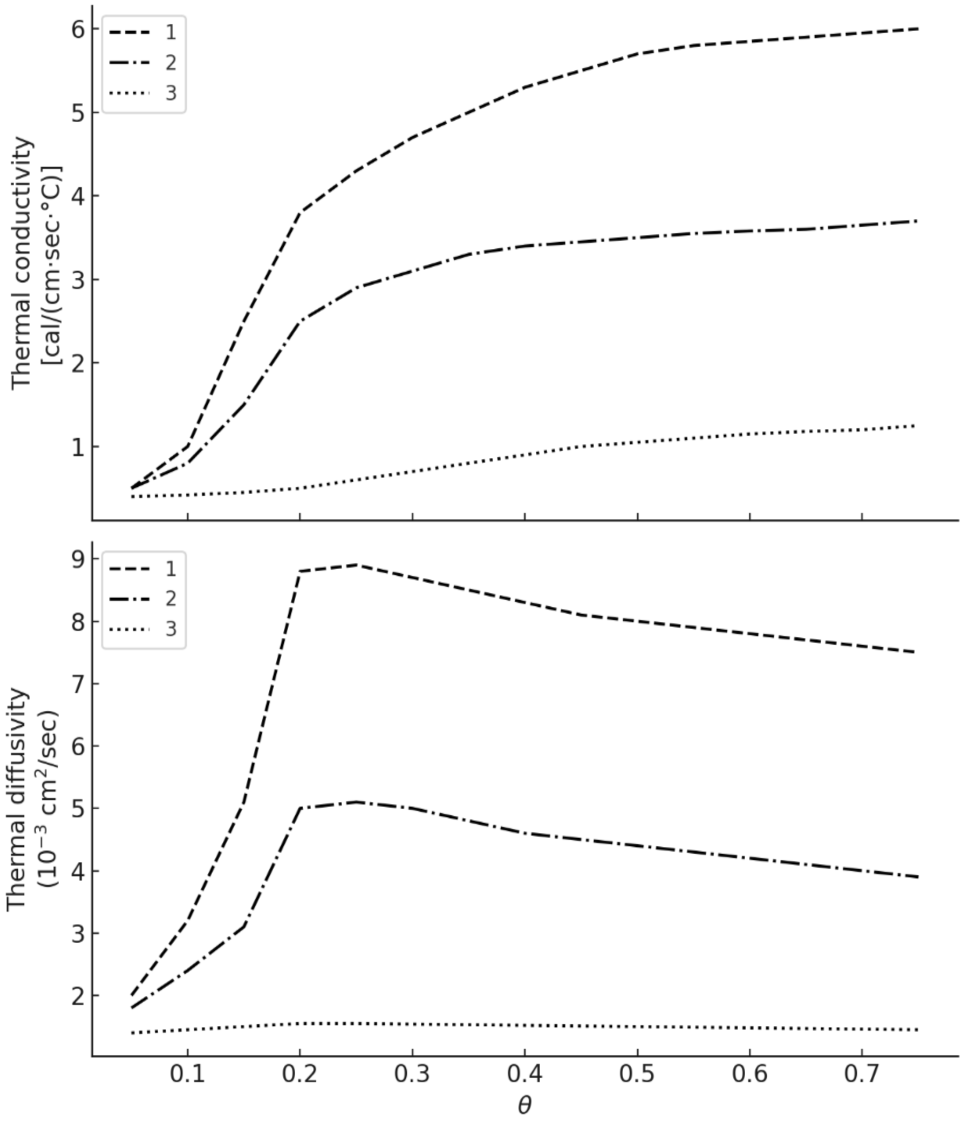

Figure 2. Thermal conductivity and diffusivity of (1) sand, (2) loam, and (3) peat soils as functions of volumetric soil moisture content (θ, cm^3 cm^{-3}). Adapted from (Hillel, 2004).

The distribution of different soil types and crop areas across Finland, and their association with regional climatic conditions, is summarized in Table 1. This classification highlights the predominance of clay soils in major cereal-growing regions, where soil thermal dynamics are especially critical for agricultural productivity (Lemola et al., 2023).

Table 1. Soil types and crop areas in Finland adapted from (Lemola et al., 2023)

Category	Share (%)	Locations
Clay soils	29	Highest shares in Southwest Finland (Varsinais-Suomi) and Uusimaa
Coarse mineral soils	62	Dominant in Central and Eastern Finland and Ostrobothnia
Organic soils	9	Mostly in Ostrobothnia and Northern Finland
Grassland crops (Nurmi)	33	Concentrated mainly in Eastern, Northern Finland and Ostrobothnia
Cereal crops (Viljat)	48	Concentrated along coastal areas
Special crops (Erikoiskasvit)	2	Mostly in some municipalities in Southwest Finland, Satakunta, Southern Ostrobothnia, and Åland

2.3 Tillage impacts on soil temperature, moisture, and crop performance in boreal regions

Table 2 compares conventionally tilled and zero-till soils, demonstrating the key differences in their physical and hydrological properties. CT tends to increase water evaporation and soil erosion while reducing the soil’s water-holding capacity (Flerchinger et al., 2003). Although these changes can accelerate soil warming in spring due to lower moisture content and a more fragmented soil structure, they also increase the risk of surface runoff and nutrient loss (Blanco-Canqui & Lal, 2008; Virto et al., 2012). Tillage also affects soil freezing dynamics, with tilled soils freezing more readily due to their looser structure and lower water content (Henry, 2013). Additionally, the extent of infiltration under both tillage systems depends heavily on soil structure, which can be enhanced or degraded depending on tillage intensity and frequency (Pires et al., 2017).

Table 2. Effects of tillage and zero-tillage on soil properties (Flerchinger et al., 2003).

Soil Property	**Tilled**	**Zero-till**
Water evaporation from soil	Increases	Decreases
Water storage capacity in soil	Decreases	Increases
Soil temperature	Warms up faster	Warms up more slowly
Soil freezing	Increases	Decreases
Infiltration	Affected by soil structure	Affected by soil structure
Erosion	Increases	Decreases

Long-term investigations on boreal clay soils in Finland have revealed that ZT practices substantially mitigate erosion through both surface runoff and subsurface drainage mechanisms (Honkanen et al., 2021). Similarly, RT and ZT systems contribute to the enhancement of topsoil structure and the accumulation of soil organic matter. Nonetheless, these conservation tillage approaches are frequently associated with reduced spring soil temperatures due to increased moisture retention and the insulating properties of retained surface residues (Gadermaier et al., 2012). Empirical data from Honkanen et al. (2021) in southern Finland indicated that ZT plots exhibited significantly higher volumetric moisture content and lower soil temperatures particularly at a depth of 5 cm relative to conventionally tilled plots. These alterations in early-season soil microclimate were found to be critical for seedling emergence and initial crop establishment. These findings corroborate earlier work by Alakukku et al. (2012), who reported delayed spring soil warming in reduced tillage systems under high-moisture conditions.

Consequently, the selection of tillage intensity in boreal agroecosystems necessitates a strategic balance between enhancing early-season soil thermal conditions and sustaining long-term soil health. Conservation tillage practices such as RT and ZT have been demonstrated to improve soil structural integrity, augment drainage efficiency, and increase water-holding capacity. These attributes contribute to the attenuation of hydrological extremes and support erosion control and carbon sequestration objectives (Liang et al., 2025). However, the agronomic advantages of such systems must be carefully weighed against their limitations under boreal climatic constraints. In particular, the thermal inertia caused by high moisture content and surface residue coverage can impede spring soil warming, delay sowing operations, and constrain early vegetative growth (Lal, 2004).

In cold-climate regions, the interaction between tillage practices and soil thermal dynamics is further modulated by antecedent winter conditions, including snow cover thickness, frost depth, and precipitation regimes. Snow cover functions as an insulating barrier that buffers the soil surface from extreme subzero temperatures, thereby limiting frost penetration and facilitating more rapid soil thaw in spring when cover exceeds approximately 20–30 cm (Durán et al., 2014; Iwata et al., 2010). Conversely, minimal or delayed snow accumulation contributes to deeper frost penetration, occasionally surpassing 100 cm, significantly delaying spring soil warming. Analogously, surface crop residues in reduced tillage systems exhibit similar insulating properties by limiting heat loss during winter and reducing frost depth (Gadermaier et al., 2012; Lal, 2004). However, in early spring, these residues inhibit soil warming by reflecting solar radiation and maintaining elevated soil moisture, thereby extending the lag phase before the soil reaches agronomically critical temperatures.

As shown in Table 3, soil under zero-till exhibited the lowest average spring temperatures (4.7 °C) and the highest volumetric water content (38.2%), reflecting slower warming (0.12 °C/day) and drying (0.20%/day) rates compared to conventional plowing, which achieved the highest soil temperatures (6.5 °C) and fastest drying rates (0.45%/day).

Table 3. Soil temperature and moisture conditions in the varying upper 0–10 cm layer under different tillage systems. Adapted from (Alghamdi et al., 2021; Blanco-Canqui & Lal, 2007; Gałęzewski et al., 2022).

Tillage System	**Soil Temperature (°C)**	**Volumetric Water Content (%)**	**Warming Speed (°C/day)**	**Drying Speed (%/day)**	**Observations**
Conventional Plowing	6.5 ± 0.3	32.1 ± 1.2	0.22	0.45	Faster early warming and drying
Shallow Cultivation	5.8 ± 0.2	34.7 ± 0.9	0.18	0.30	Moderate warming and drying
Zero-till	4.7 ± 0.4	38.2 ± 1.5	0.12	0.20	Slowest warming, highest moisture retention
Reduced Tillage (Chisel)	5.5 ± 0.3	35.5 ± 1.1	0.17	0.28	Intermediate effects

2.4 Primary tillage selection in boreal clay soils

In Finland, the choice of primary tillage method has become a balancing act. While CT boosts spring warming, it also risks erosion and compaction, especially under wet conditions (Känkänen et al., 2011). ZT offers sustainability benefits but can reduce soil temperature, yield, and nutrient availability in early years (Soane et al., 2012). Research by Känkänen et al. (2011) showed that the transition to zero-till management on clay soils in southern Finland led to a temporary decline in crop performance, with spring cereal yields being 10–20% lower compared to conventional autumn tillage during the first 3–5 years after conversion. Over time, as soil structure and biological activity improved, the yield gap gradually decreased. This yield decline was primarily attributed to lower soil temperatures and wetter seedbeds, both of which inhibited root development and early vegetative growth. Furthermore, reduced tillage may exacerbate issues related to nitrogen availability. Cooler soil slows down microbial activity and mineralization, leading to reduced nitrogen uptake and limited aboveground biomass production, especially in clay-rich fields (Soane et al., 2012). These nutrient dynamics further contribute to growth degradation, particularly during the early growth stages when nitrogen demand is high.

2.5 Soil temperature effects on germination and early growth in boreal clay soils

Soil temperature is a key environmental factor controlling the rate of seed germination, root elongation, nutrient uptake, and overall crop growth, particularly in cold boreal regions like Finland (Peltonen-Sainio et al., 2009). In boreal clay soils, spring warming is notably slow due to their thermal properties. This is further hindered by prolonged snow cover and water saturation from snowmelt, often delaying early sowing of crops like spring barley (*Hordeum vulgare* L.) and leading to uneven germination and poor plant establishment (Licht & Al-Kaisi, 2005).

Each plant species has a base (minimum), optimum, and maximum temperature range for germination. For spring barley, the base temperature is approximately 1–3°C, with optimal germination occurring between 15–20°C, and inhibition of germination typically beyond 30°C (Longo et al., 2017). If soil temperatures remain near or below the base threshold, germination is significantly delayed or may fail altogether. Low temperatures slow biochemical processes within seeds, extending the lag phase before radicle emergence (Alvarado & Bradford, 2002). For spring-sown cereals in boreal climates, suboptimal soil temperatures often cause non-uniform emergence, ultimately reducing crop yields due to poor competition and uneven early development (Qu et al., 2023; Tenhovuori, 1986).

Tillage practices significantly influence soil thermal dynamics and, by extension, the success of crop germination and establishment. The differences in soil thermal behaviour are particularly important in boreal climates, where a rapid rise in soil temperature after snowmelt is critical for spring sowing. Delayed soil warming under RT and ZT systems can postpone the accumulation of thermal time, expressed as growing degree days (GDD), which is essential for prompt seedling emergence. For instance, at low soil temperatures (~5°C), barley (*Hordeum vulgare L*) germination may take over 10 days, whereas at optimal soil temperatures between 10–15°C, emergence typically occurs within 4–6 days (Tarnawa et al., 2023). In general, the rate of emergence accelerates between the minimum temperature thresholds approximately 3.1°C for wheat (*Triticum aestivum L*) and 1.9°C for barley and the temperatures where growth begins to slow down, around 31°C for wheat and 27°C for barley (Tenhovuori, 1986).

Moisture conditions also play a crucial role during the emergence period. Optimal 50% emergence rates for cereals were obtained under soil matric pressures between pF 1.3–2.7 (corresponding to -5.0 to -0.20 meters of water column) at a soil temperature of around 10°C, conditions that closely resemble typical Finnish spring soils (Tenhovuori, 1986). Therefore, both soil temperature and moisture, strongly influenced by tillage practices and residue management, determine the timing and uniformity of seedling emergence in boreal clay soils. Managing these factors effectively is critical to optimize stand establishment and achieve high yields in northern climates.

Studies in northern Europe have shown that suboptimal soil temperatures at planting can reduce spring barley yields by 10–20%, especially when combined with excessive soil moisture (Soane et al., 2012). Furthermore, reduced soil temperatures in early spring have been linked to decreased enzymatic activity, slower root growth, and restricted microbial nutrient cycling, all contributing to degraded early-season growth performance (Qu et al., 2023). Additionally, in cold and wet soil, such as clay soil in early spring, water uptake may occur without sufficient warmth, leading to imbibitional chilling injury in seeds (Copeland & McDonald, 2001).

Ultimately, balancing the need for early soil warming with the sustainability benefits of conservation tillage practices represents a central challenge in boreal agriculture. Understanding how tillage impacts soil thermal conditions, particularly in heavy clay soils, is essential for improving crop resilience, optimizing sowing windows, and adapting to the effects of climate change (Honkanen et al., 2021).

2.6 Previous research and knowledge gaps regarding tillage effects on soil temperature in boreal clay soils

Several studies have investigated the impact of tillage practices on soil temperature across a variety of soil types and climatic zones; however, research specifically targeting boreal clay soils remains limited. Table 4 summarizes key findings from studies conducted globally, including those focused on temperate and cold regions. For example, Fabrizzi et al., (2005) reported that CT generally results in higher soil temperatures compared to zero-till systems, with differences of up to 2°C depending on soil type and crop residue management. Similarly, Licht & Al-Kaisi (2005) demonstrated that strip tillage can effectively increase spring soil temperatures, promoting earlier seedling emergence. Känkänen et al. (2011) found that the transition to zero tillage on clay soils in southern Finland led to spring soil temperatures being approximately 1–2°C lower compared to conventionally tilled soils. This temperature reduction contributed to a delay in plant emergence by 3–5 days, particularly during the initial years following the conversion to zero-till management.

Honkanen et al. (2021) further noted that after ten years of zero-till management on boreal clay soils, soil structure improved and erosion decreased; however, the effects on soil thermal properties remained highly variable depending on weather conditions. Despite existing research, there remains a lack of clear understanding of how different levels of tillage intensity, not merely the binary comparison of 'tilled' versus 'zero-till', affects soil temperature dynamics in boreal regions. It is critical to assess how practices such as ploughing, stubble cultivation, and direct drilling influence early spring soil warming, and how these changes impact sowing time, crop growth, and final yields.

In boreal regions, optimizing tillage strategies must carefully balance the trade-offs between promoting long-term soil health and ensuring short-term crop performance. Zero-till and reduced tillage practices support sustainable agriculture through carbon sequestration and improved soil aggregation (Charles et al., 2024). However, without complementary residue management practices or temperature-moderating strategies such as strip-tillage or adjusting sowing dates these approaches may lead to seasonal growth degradation that threatens yield stability.

Table 4. Selected studies on the effect of tillage on soil temperature.

Study	Study Period & Soil Type	Tillage Methods & Crops	Measurement Depth	Key Findings on Soil Temperature
Fabrizzi et al. (2005)	1997–1999; Typic Argiudolls & Petrocalcic Paleudolls	CT (disc harrow) vs. ZT; maize and wheat	Not reported	Maize under CT was ~2 °C warmer than ZT; higher daily variation in CT due to residue
Cook et al. (2006)	1997–1998; Sandy loam & loamy sand	Plowing, ZT, compost mulch; maize	Not reported	Compost and plowed soils warmer; straw mulch reduced temperatures
Wang et al. (2009)	1993–1996; Fine-textured soil	Plowing (15 cm) vs. shallow tillage (9 cm)	5 cm	Plowed soil up to 1.1 °C warmer; greater diurnal fluctuation than shallow tillage
Licht & Al-Kaisi (2005)	2001–2002; Sandy loam & loamy sand	CT, strip-till, and ZT; maize and soybean	5 cm	Strip-till plots warmer than ZT in spring; maintained better temperatures overall
Känkänen et al. (2011)	Multi-year; Clay soil, Southern Finland	CT vs. ZT; spring cereals	5 cm	ZT soils 1–2 °C cooler in spring; 3–5-day delayed emergence initially
Honkanen et al. (2021)	2010s; Boreal clay soils, Finland	ZT vs. CT; various crops	10 cm	ZT retained more moisture; lower early spring temperatures than CT
Alghamdi et al. (2021)	2018–2020; Upper Great Plains	Vertical, strip, chisel tillage; corn and soybean	10 cm	Strip-till warmed fastest; ZT retained moisture and reduced early warming

3. Research objective

The primary objective of this study is to investigate the effect of primary tillage intensity on soil temperature and heat flow in boreal clay soils during the pre-sowing period in spring (from March to May). The specified objectives of the study are:

1. To assess how different tillage practices influence soil warming rates under varying spring conditions.
2. To determine whether ploughed soils warm faster than reduced tillage or zero-till soils by analysing soil temperature fluctuations at a 10 cm depth.
3. To examine the effect of different primary tillage practices on the soil temperature day degree sums of above 0, 2 and 5 °C
4. To provide practical insights for choosing soil management practices to enhance spring field conditions and reduce delays in sowing.

4. Materials and methods

4.1 Field Experiment

The field experiment was established in 2000 (Kauppi et al., 2024) and this study was conducted from 2013 to 2016 in Jokioinen (60°49’N, 23°28’E; Figure 3), a small municipality in southwestern Finland. Located in the Tavastia Proper (Kanta-Häme) region. According to the FAO classification (FAO, 2006), the soil at the experimental site is classified as a clay soil (Vertic Endostagnic Cambisol), with a clay content of 0.61 g clay g^{-1} in the topsoil layer (Kauppi et al., 2024).

The experimental field covers a total area of 10,800 m^2 (108 x 100), with a structured layout to assess soil and crop responses under different tillage treatments. It consists of 24 experimental plots, each measuring 11 meters in width and 40 meters in length. Spring barley (*Hordeum vulgare L.*) was cultivated during the experimental period (2000-2016), except for the year 2003 when spring oats (*Avena sativa* L.) were grown. The experiment utilized a randomized block design with four replicates for each tillage method: ploughed, stubble cultivation, and zero-till. The tillage treatments included:

1. P = Autumn ploughing (20-25 cm depth)
2. S = Autumn stubble cultivation (10-15 cm depth)
3. ZT = Zero-tillage: straw retained on soil surface and direct drilling in spring.

Figure 3. Location of Jokioinen on Finland map (National Land Survey of Finland, n.d.).

4.2 Data collection and measurements

Soil and air temperature were determined before the sowing period over four consecutive years (2013–2016) to analyze how different tillage methods influenced soil thermal conditions. Measurements were taken from March 15 to early May each year, covering the ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till methods. The annual average temperature in the study area between the years (2013–2016) was 5.6°C (Climate JOKIOINEN, n.d.).

For this research experiment, only data for spring barley was used. To ensure accurate measurement of soil temperature and moisture, sensors were installed at a depth of 10 cm within the soil profile to ensure good contact with the soil during the measurement period. The sensors selected for the measurements were the Decagon 5TE and 5TM models (Table 5) due to their high sensitivity and reliability in detecting both temperature and volumetric water content (Decagon Devices, n.d.-a). These sensors operate within a moisture measurement range of 0–50% volumetric water content (VWC) and a temperature range of -40°C to +60°C. The moisture measurement accuracy is ±3% in typical soil conditions, improving to ±1–2% with fine-tuned soil-specific calibration. Additionally, the sensors can detect changes as small as 0.08% VWC. For temperature, they have an accuracy of ±1°C and a resolution of 0.1°C, ensuring precise monitoring of even small thermal fluctuations (Decagon Devices, n.d.-b). The other specifications of the sensors are shown in Table 5.

Table 5. Technical specifications of Decagon 5TE, 5TM, and RH/T sensors adapted from (Decagon Devices, n.d.-a).

Technical Data	**Decagon 5TE Moisture**	**Decagon 5TM Moisture**	**Decagon RH/T**
Measurement Range	Moisture 0–50 vol-% Temperature - 40–+60°C	Moisture 0–50 vol-% Temperature-40-+60°C	0–100% RH 38–60°C
Resolution	Moisture 0.08 vol-% or 0.0008 m³/m³ Temperature 0.1°C	Moisture 0.08 vol-% or 0.0008 m³/m³ Temperature 0.1°C	0.1% RH
Measurement Speed	150 ms	150 ms	-
Power Requirement	3.6–15 VDC, 0.3 mA in idle state, 10 mA during 150 ms measurement	3.6–15 VDC, 0.3 mA in idle state, 10 mA during 150 ms measurement	-
Sensor Dimensions	10 cm × 3.2 cm × 0.7 cm	10 cm × 3.2 cm × 0.7 cm	4.44 cm × 1.68 cm × 0.74 cm
Connection	3.5 mm stereo plug or tinned wires (3 pcs)	3.5 mm stereo plug or tinned wires (3 pcs)	3.5 mm stereo plug

Data collection was carried out using Decagon EM50 data loggers (Decagon Devices, n.d.-b), configured to record measurements at one-hour intervals and the specifications of the data logger are presented in Table 6. This setup ensured high temporal resolution and reliable capture of the dynamic changes in soil temperature and moisture throughout the study period.

Table 6. Technical specifications of the Decagon EM50 data logger, adapted from (Decagon Devices, n.d.-a).

Technical Data	Decagon EM50 Digital/Analog Data Logger
Channels	5 channels, 12-bit analog or 32-bit digital signal
Storage Capacity	1 MB (36,000 measurements per channel)
Operating Range	-40 to +60 °C, 0–100% RH
Power Source	5 × AA batteries (lasting 8–12 months)
Enclosure Dimensions	12.7 cm × 20.3 cm × 5.1 cm
Computer Connection	Serial port or USB
Reading Software	ECH$_2$O Utility, ECH$_2$O Utility Mobile, DataTrac
Protection	Weather-resistant, UV- and impact-resistant (IP55), NEMA 3R

The aim was to install sensors for each tillage treatment plot. However, due to sensor failures or damage from pests like rabbits, the number of replicates varied across tillage methods, as shown in Table 1. The ploughed fields had three replicates for 2013, 2014, and 2016, and two in 2015. Stubble cultivation consistently had three replicates each year, while zero-till fields had three replicates in 2013 and 2016, two in 2014, and one in 2015. The plots were evenly assigned to spring barley or oats to ensure a balanced comparison of crop responses under different tillage treatments.

A weather station was installed in the experimental field to monitor air temperature at 50 cm above the soil surface, providing microclimatic data relevant to soil temperature dynamics across different tillage treatments (Decagon RH/T sensor, Table 5). This sensor height was selected to capture near-surface temperature fluctuations that directly influence soil thermal conditions, especially during winter and early spring.

To assess winter soil conditions in greater detail, key variables such as maximum frost depth, maximum snow cover thickness, period of frozen soil (PFS), and duration of continuous snow cover (SCS) were recorded for each tillage treatment over the winters from 2012–2013 to 2015–2016 (Table 7). This data was obtained from the TALMA research site in Jokioinen and represents the mean values of two replicate measurements.

Table 7. Maximum frost depth (MaxFrost) and thickness of snow cover (MaxSnow), period of frozen soil (PFS), and period of continuous snow cover on soil surface (SCS) in Jokioinen in years 2013–2016. Data of TALMA research. Mean of two measurements. P=ploughed, S= stubble cultivated, and ZT= zero-tilled soil.

winter	**MaxFrost(cm) (date)**	**MaxSnow (cm) (date)**	**PFS**	**SCS**
2012–13			4.12.2012–26.4.2013	4.12.2012–15.4.2013
P	51 (15.4.2013)	36 (22.2.2013)		
S	47 (15.4.2013)	39 (22.2.2013)		
ZT	42 (15.4.2013)	38 (22.2.2013)		
2013–14			3.12.2013–26.4.2014	15.1.–12.2.2014
P	59 (6.2.2014)	8 (6.2.2014)		
S	55 (12.2.2014)	10 (6.2.2014)		
ZT	47 (6.2.2014)	11 (6.2.2014)		
2014–15			7.1.–25.3.2015	7.1.–23.2.2015
P	23 (28.1.2015)	32 (6.2.2015)		
S	16 (28.1.2015)	30 (6.2.2015)		
ZT	11 (28.1.2015)	30 (6.2.2015)		
2015–16			22.1.–4.4.2016	22.1.–21.3.2016
P	70 (5.2.2016)	22 (29.2.2016)		
S	62 (5.2.2016)	15 (29.2.2016)		
ZT	54 (5.2.2016)	17 (29.2.2016)		

Frost depth was determined at two-week intervals using methylene blue tubes (Soveri & Varjo, 1977), a reliable method for visually identifying freezing penetration in the soil. These tubes were filled with a diluted methylene blue solution, which turns colorless when the temperature falls below 0 °C (Richard & Brown, 1972). At the same time, snow cover thickness was manually measured to evaluate its insulating effect on the soil. Snow acts as a buffer, moderating temperature fluctuations and influencing both the rate of soil freezing and thawing. The recorded values showed notable interannual variability in both snow depth and frost penetration, with differences between tillage systems. For instance, during the winter of 2015–2016, zero-tilled plots had a maximum frost depth of 54 cm, while ploughed plots reached 70 cm, highlighting the impact of tillage on soil insulation and thermal buffering.

4.3 Data handling

4.3.1 Data filtering

Daily mean temperature (T_{mean})

$$T_{mean} = \frac{1}{n}\sum_{i=1}^{n} T_i \qquad (1)$$

where T_i is the hourly temperature reading, and n is the number of valid hourly observations for that day.

Daily maximum temperature (T_{max})

$$T_{max} = \max(T_1, T_2, \dots., T_n) \qquad (2)$$

where T_1, $T_2 \dots$, T_n represent the individual temperature values recorded during each day.

Daily minimum temperature (T_{min})

$$T_{min} = \min(T_1, T_2, \dots., T_n) \qquad (3)$$

Daily standard deviation (σT)

$$\sigma\mathrm{T} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(T_i - T_{mean})^2} \qquad (4)$$

Then for the calculations for Daily mean (T $_{\text{mean,period}}$), maximum (T $_{\text{max,,period}}$), minimum (T $_{\text{min,period}}$) and standard deviation (T $_{\text{SD,period}}$)) for the entire period, the equations (1, 2, 3 and 4) are modified into:

Period daily mean temperature

$$T_{mean,period} = \frac{1}{d}\sum_{i=1}^{d} T_m \qquad (5)$$

where:

T_m is the daily mean temperature reading, and d is the number of valid days.

Period daily maximum Temperature (T_{max})

$$T_{max,period} = \max(T_{max,1}, T_{max,2}, \ldots., T_D) \qquad (6)$$

where:

$T_{max,1}, T_{max,2}, \ldots., T_D$ represent the individual daily maximum temperature values recorded during each day.

Period daily minimum Temperature (T_{min})

$$T_{min} = \min(T_{min,1}, T_{min,2}, .., T_D) \qquad (7)$$

Where $T_{min,1}, T_{min,2}, \ldots., T_D$ represent the individual daily minimum temperature values recorded during each day.

Period standard deviation (σT,period)

$$\sigma\mathrm{T,period} = \sqrt{\frac{1}{d-1}\sum_{i=1}^{d}(T_{mean,d} - T_{mean,period})^2} \qquad (8)$$

Where:

d = total number of days in the study period

$T_{mean,d}$ = the mean soil temperature on day,

$T_{mean,period}$ = the overall mean of all daily mean temperatures.

4.3.3 Daily mean values above a certain limit (0, 2 and 5 °C)

For each day, the mean temperature a particular limit was calculated such that values less than or equal to a certain temperature limit (i.e. 0 °C) were set to zero, while temperatures above a certain temperature limit (0 °C) were retained for further analysis.

$$T*(d) = \begin{cases} 0, & if\ T_{mean(d)} \leq To \\ T_{mean(d)}, & if\ T_{mean(d)} > To \end{cases} \qquad (9)$$

Where:

$T_{mean(d)}$ the daily mean temperature on day

T(d):* the adjusted temperature above the threshold on day

To: the temperature threshold (e.g. 0 °C).

4.3.4 Temperature sums (cumulative temperature)

To quantify the accumulation of effective soil warmth, a cumulative temperature sum was calculated using daily mean temperature values. Specifically, for each day, only temperatures above a certain limit e.g. 0, 2 or 5 °C were considered. If the mean temperature on a given day was greater than 0 °C, the amount exceeding 0 °C was added to a running cumulative sum and if the temperature was 0 °C or below, it contributed nothing to the sum. Equation (10) gives a mathematical expression of this calculation:

$$(Cd) \ = \sum_{i=1}^{d} max(0, T_{mean(i)} - T_0) \qquad (10)$$

where:

$T_{mean(i)}$ daily average soil (or air) temperature recorded on the ith day

T_0*:* The threshold temperature

C(d): represents the cumulative total of thermal energy (above the threshold) accumulated from the first day up to the last day in the period.

5. Result

5.1 Daily mean, minimum, maximum temperature and standard deviation

To compare the effects of different tillage methods on soil thermal conditions, the daily mean, maximum, and minimum soil temperatures, as well as their variability, were analyzed over four spring periods from 2013 to 2016. Table 8 presents mean soil temperatures across different tillage methods from 2013 to 2016, which reveals that zero-till and stubble cultivation consistently maintain higher minimum temperatures compared to ploughed soil. It is important to note that the zero-till treatment in 2015 was based on only one replicate. The standard deviation values from Table 8 further indicate that zero-till and stubble cultivation provide greater temperature stability compared to ploughed soil, which exhibits more pronounced fluctuations.

Table 8. The number of replicates (NR), daily mean temperature (DM_T), daily mean maximum (D_{max}) temperature, daily minimum temperature (D_{min}), and daily standard deviation (SD) for three different tillage methods - ploughed (2025 cm), stubble cultivation (10-15 cm), and zero-till at the depth of 10 cm along with air temperature over time.

	15.3.-5.5.2013					15.3.-24.4.2014					15.3.-4.5.2015					15.3.-3.5.2016				
Tillage method	NR	DM_T°C	D_{max} °C	D_{min} °C	SD	NR	DM_T °C	D_{max} °C	D_{min} °C	SD	NR	DM_T °C	D_{max} °C	D_{min} °C	SD	NR	DM_T °C	D_{max} °C	D_{min} °C	SD
Ploughed	3	0.68	1.44	0.01	0.53	3	2.57	4.10	1.41	0.86	2	3.22	4.72	1.91	0.88	3	3.07	4.83	1.55	1.17
Stubble cultivation	3	1.24	1.79	0.74	0.39	3	2.75	4.38	1.54	0.88	3	3.27	4.30	2.37	0.64	3	3.18	4.93	1.76	1.11
Zero-till	3	1.30	1.89	0.85	0.36	2	2.17	2.97	1.55	0.51	1	2.97	3.91	2.14	0.64	3	3.16	4.36	2.08	0.81
Air	1	-1.70	5.20	-8.63	4.90	1	2.70	8.73	-3.84	4.39	1	3.78	8.57	-0.98	3.26	1	3.63	8.72	-1.34	3.30

The analysis of daily mean soil temperature trends across different tillage methods from 2013 to 2016 was illustrated in Figure 4. Based on these results, there was a consistent increase in soil temperature over time, with notable differences emerging between tillage treatments in later years. Daily minimum and maximum soil temperatures during the experimental period are presented in appendix 1.

In 2013, the soil daily mean temperature differences between tillage methods were minimal (Figure 4), with soil daily mean temperatures remaining relatively stable until early April, after which they began to increase. However, in subsequent years, the trend of higher soil temperatures in zero-till and stubble cultivation compared to ploughed plots became more noticeable. By 2014, soil temperatures rise earlier in the season, and stubble cultivation and ploughed tillage method were very close in trend but at the end (sowing date), ploughed tillage had a higher temperature over stubble cultivation while zero-till had the least temperature.

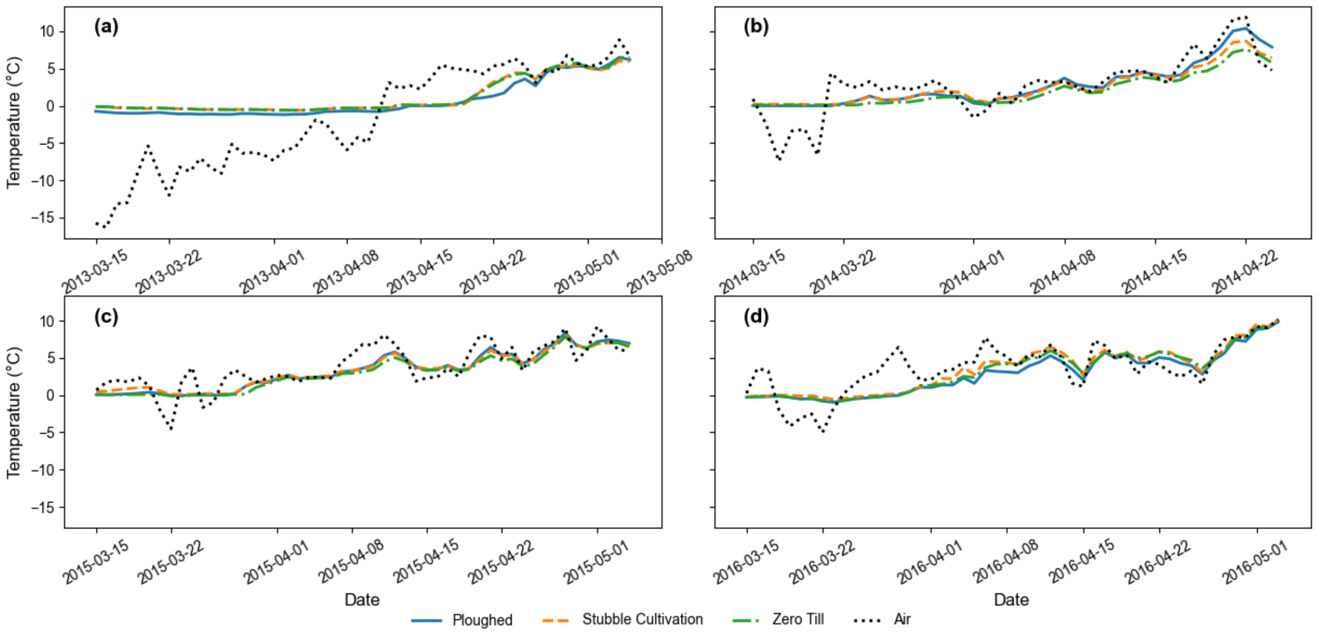

Figure 4. Daily mean soil temperature at 10 cm depth under different tillage methods of ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till along with daily mean air temperature within time interval (a) 15.3.-5.5.2013, (b) 15.3.-24.4.2014, (c) 15.3.-4.5.2015, (d) 15.3.-3.5.2016.

5.2 Temperatures above certain temperatures

For each temperature threshold, (Equation 9) was used to calculate daily mean temperature values exceeding a particular threshold. Figure 5 presents the daily mean soil temperature at 10 cm depth under different tillage methods, along with the corresponding air temperature, during periods when soil and air temperature exceeded 0 °C for the years 2013 to 2016. Across all years, air temperature showed the greatest variability, with frequent and sharp fluctuations, while soil temperatures under all tillage treatments remained more stable and increased gradually. Among the tillage methods, the ploughed treatment generally recorded the highest soil temperatures, particularly toward the end of each spring period.

In 2013, air temperature rose above 0 °C after 29 days on 12 April, followed by the soil temperature under stubble cultivation reaching 0 °C on 13 April (after the same period), zero tillage on 13 April (after 30 days), and ploughing on 18 April (after 35 days). In 2014 and 2015, air and soil temperatures remained above 0 °C throughout the observed periods, indicating earlier seasonal warming across all treatments. Conversely, in 2016, although air temperature rose above 0 °C earlier in spring, it took 14 days for soil under stubble cultivation to exceed this threshold (by 28 March), and 15 days for both ploughed and zero tillage treatments to do so (by 29 March). The specific dates when soil temperature reached 0 °C for each tillage method in all years are summarized in Table 9.

Table 9. Dates when soil temperature reached + 0 °C for three different tillage methods - ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till at the depth of 10 cm.

Date	Ploughing	Stubble cultivation	Zero tillage
2013	18.04.	13.04.	13.04.
2014	1503.	15.03.	15.03.
2015	15.03.	15.03.	15.03.
2016	30.03.	29.03.	29.03.

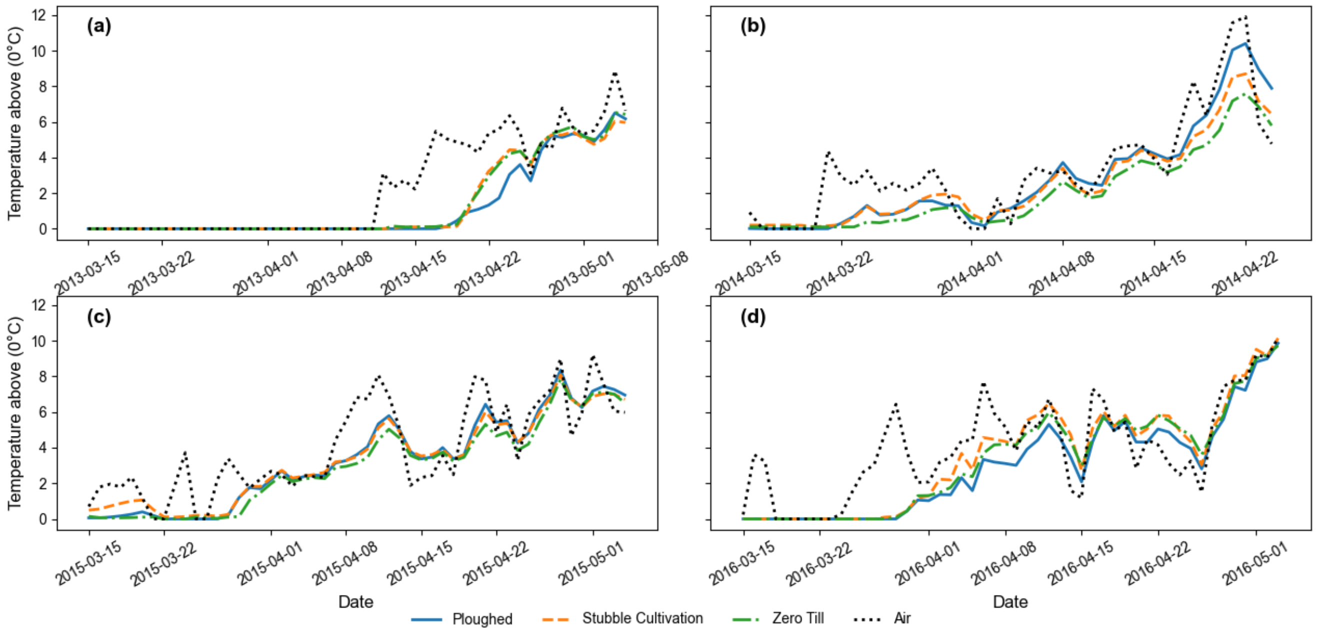

Figure 5. Daily mean soil temperature at 10 cm depth under different tillage methods of ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till compared with daily mean air temperature, when soil and air temperature was > 0°C within time interval (a) 15.3.-5.5.2013, (b) 15.3.-24.4.2014, (c) 15.3.-4.5.2015, (d) 15.3.-3.5.2016.

Figure 6 illustrates the comparison of soil temperatures during periods when the temperature exceeded 2 °C. In 2013, it took 29 days from the start of the observation period for air temperature to reach 2 °C. Soil under both stubble cultivation and zero tillage reached this threshold after 37 days, while the ploughed treatment did so after 40 days. In 2014, air temperature exceeded 2 °C after just 7 days, followed by the ploughed soil reaching the same threshold at 23 days, and both zero tillage and stubble cultivation soils at 24 days.

The 2015 season was marked by greater variability; air temperature first reached 2 °C on 19 March, then fluctuated below the threshold before rising again on 24 March, followed by another drop, and finally exceeding 2 °C consistently from 31 March onward. During this period, ploughed soil reached 2 °C in 18 days, while zero tillage soil reached it in 19 days. In 2016, air temperature surpassed 2 °C just one day into the observation period. Stubble cultivation soil reached this threshold in 23 days, while both ploughed and zero tillage soil followed 25 days. The specific dates when soil temperature at 10 cm depth reached 2 °C for each tillage method are summarized in Table 10.

Table 10. Dates when soil temperature reached + 2 °C for three different tillage methods - ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till at the depth of 10 cm.

Date	Ploughing	Stubble cultivation	Zero tillage
2013	24.04.	21.04.	21.04.
2014	06.04.	07.04.	08.04.
2015	01.04.	01.04.	02.04.
2016	04.04.	02.04.	04.04.

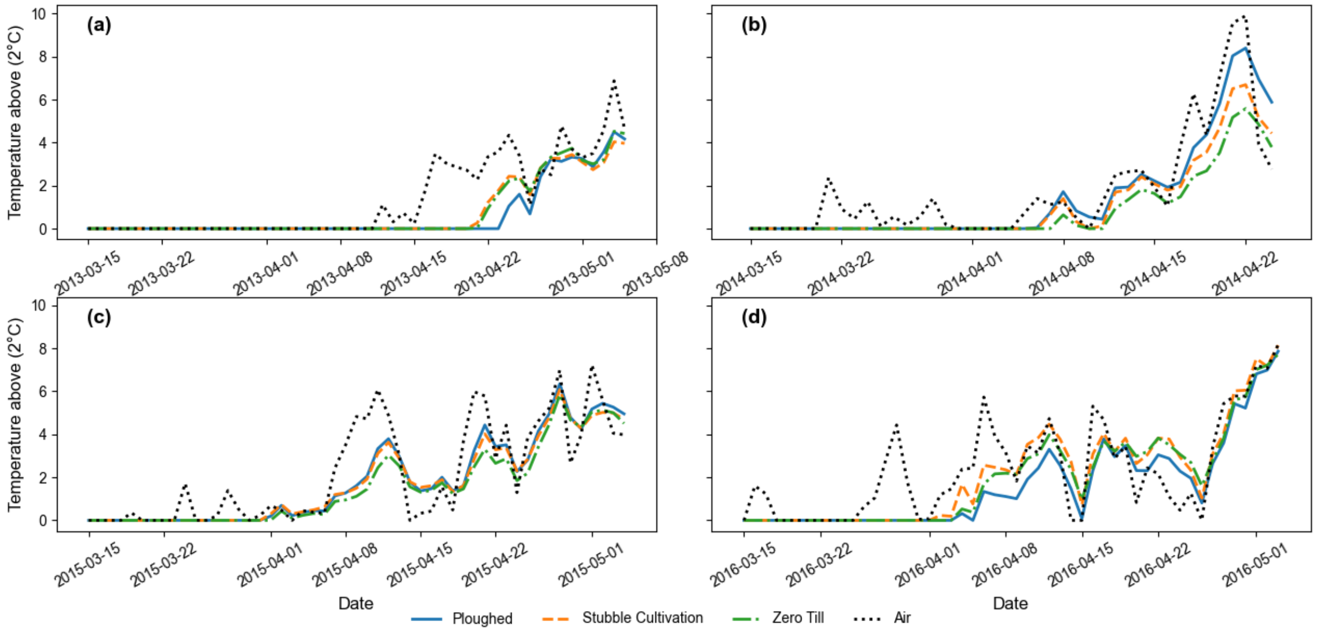

Figure 6. Daily mean soil temperature at 10 cm depth under different tillage methods of ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till compared with daily mean air temperature, when soil and air temperature was > 2°C within time interval (a) 15.3.-5.5.2013, (b) 15.3.-24.4.2014, (c) 15.3.-4.5.2015, (d) 15.3.-3.5.2016.

Figure 7 presents soil temperature trends under the three tillage methods during periods when temperatures exceeded 5 °C for the years 2013 to 2016. In all years, the soil temperature curves for ploughed, stubble cultivation, and zero-till treatments converged after mid-to-late April, showing minimal short-term fluctuations compared to the more variable air temperature, which continued to exhibit distinct peaks. Across all years, the transition to soil temperatures above 5 °C occurred earliest in the ploughed treatment and latest in the zero-till plots. The exact dates when soil temperature at 10 cm depth reaches 5 C for each tillage method are provided in Table 11.

Table 11. Dates when soil temperature reached + 5°C for three different tillage methods - ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till at the depth of 10 cm.

Date	Ploughing	Stubble cultivation	Zero tillage
2013	28.04.	28.04.	28.04.
2014	18.04.	18.04.	20.04.
2015	11.04.	11.04.	12.04.
2016	28.04.	27.04.	28.04.

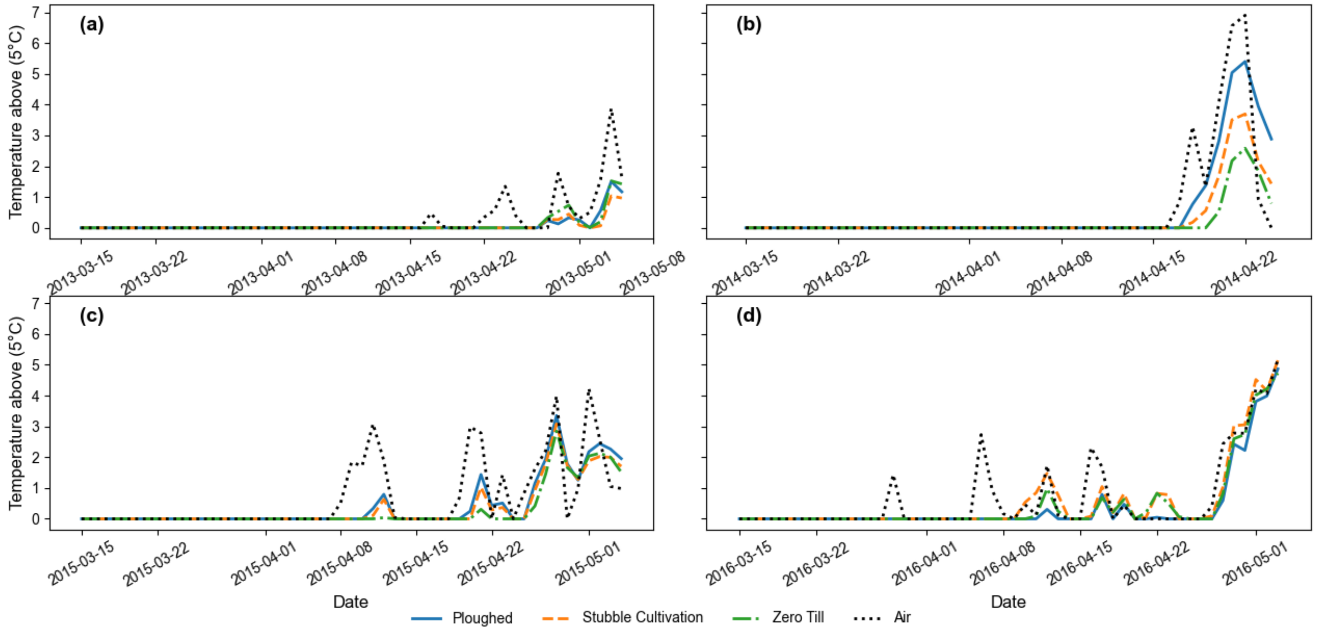

Figure 7. Daily mean soil temperature at 10 cm depth under different tillage methods of ploughed (20-25 cm), stubble cultivation (10-15 cm), and zero-till compared with daily mean air temperature, when soil and air temperature was > 5°C within time interval (a) 15.3.-5.5.2013, (b) 15.3.-24.4.2014, (c) 15.3.-4.5.2015, (d) 15.3.-3.5.2016.

5.3 Cumulative temperature above certain temperature values

For each temperature sum above certain temperature values, (Equation 10) was used to calculate cumulative temperature above such threshold. Figure 8 illustrates the cumulative temperature sums above 0°C in both soil and air across four consecutive spring periods (2013–2016) under three primary tillage intensities: ploughed (20–25 cm), stubble cultivation (10–15 cm), and zero-till. Across all years, air temperatures accumulated more rapidly than soil temperatures, reflecting the delayed thermal response of soil following winter.

In 2013 (Figure 8a), cumulative temperatures for stubble cultivation and zero-till began increasing by April 13, while the ploughed tillage method started increasing by April 18. By May 1, all soil treatments had accumulated approximately 50–60°C, while the air had accumulated about 100°C. There was minimal difference in soil warming among the tillage treatments during this year.

In 2014 (Figure 8b), soil warming started earlier, around March 22–25. The air had accumulated nearly 90°C by April 22, while soil treatments showed moderate differences. Ploughed and stubble cultivation slightly have higher cumulative temperatures than zero-till.

In contrast, 2015 (Figure 8c) experienced a much earlier warming onset, around March 20. By May 1, air cumulative temperature reached approximately 200°C, while soil treatments ranged between 145–155°C. Among them, stubble cultivation demonstrated the highest cumulative soil temperature, followed by ploughed, and zero-till, which lagged notably.

Similarly, in 2016 (Figure 8d), soil warming began around March 27–29. By May 1, the air had accumulated approximately 200°C, while stubble cultivation again showed the highest soil cumulative temperature, followed by zero-till, with ploughed exhibiting the lowest.

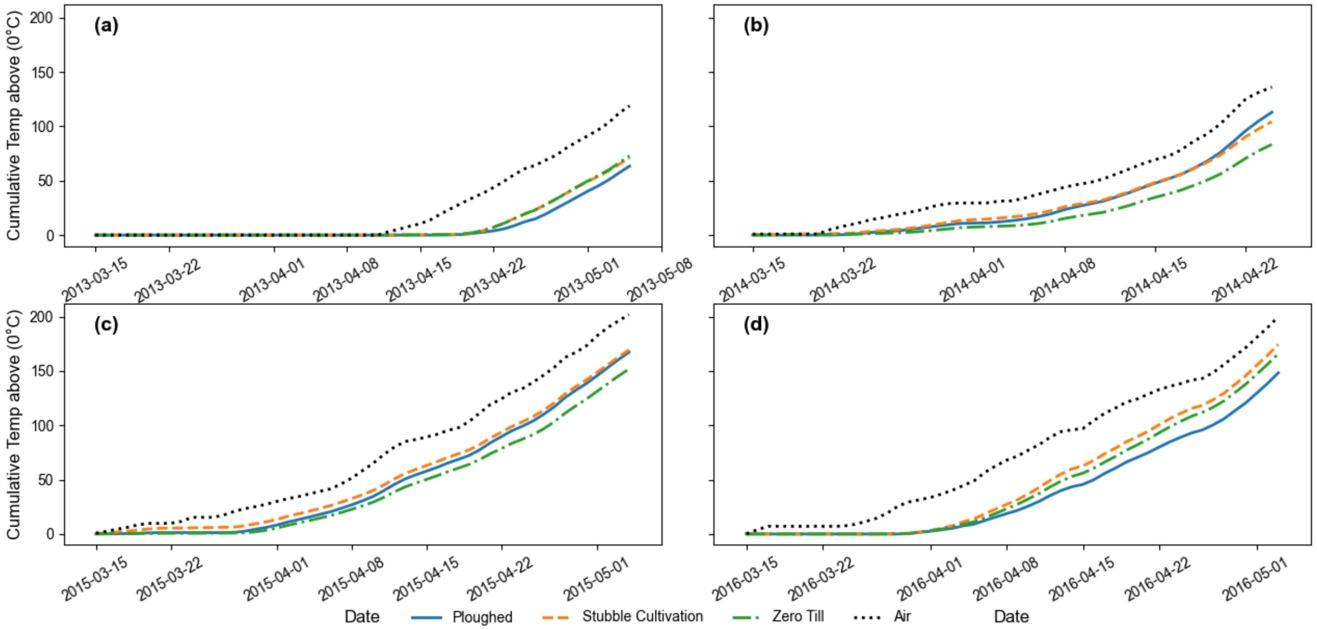

Figure 8. Cumulative soil and air temperature sums > 0°C under different tillage methods of ploughed (20-25 cm), stubble cultivation (10-15 cm), zero-till within time interval (a) 15.3.-5.5.2013, (b) 15.3.-24.4.2014, (c) 15.3.-4.5.2015, (d) 15.3.-3.5.2016.

Figure 9 illustrates the cumulative temperature sums above 2°C in both soil and air during four consecutive spring periods (2013–2016), under three primary tillage intensities: ploughed (20–25 cm), stubble cultivation (10–15 cm), and zero-till. As in the previous (Figure 8), air temperatures accumulated more rapidly than soil temperatures, emphasizing the slower warming response of soils after winter.

In 2013 (Figure 9a), cumulative temperatures for soil treatments began rising notably after April 21, with a steeper increase from mid-April onward. By May 1, all soil treatments had accumulated approximately 30–40°C, while the air had accumulated nearly 100°C. There was little difference between tillage treatments, though stubble cultivation and zero-till showed a slight advantage.

In 2014 (Figure 9b), warming began earlier, around late March to early April. The air temperature reached about 90°C by April 22. Among soil treatments, ploughed led in cumulative temperature, closely followed by stubble cultivation with zero-till consistently lagging.

In 2015 (Figure 9c), soil and air warming started as early as March 22–25. By May 1, the air had accumulated around 90–100°C, while ploughed soil showed the highest cumulative soil temperature (~80°C), followed by stubble cultivation and zero-till.

In 2016 (Figure 9d), cumulative temperatures began increasing around late March. Air temperature reached approximately 100°C by May 1. This year, stubble cultivation led to soil heat accumulation, followed by zero-till, while ploughed soil showed the lowest cumulative temperature among the treatments.

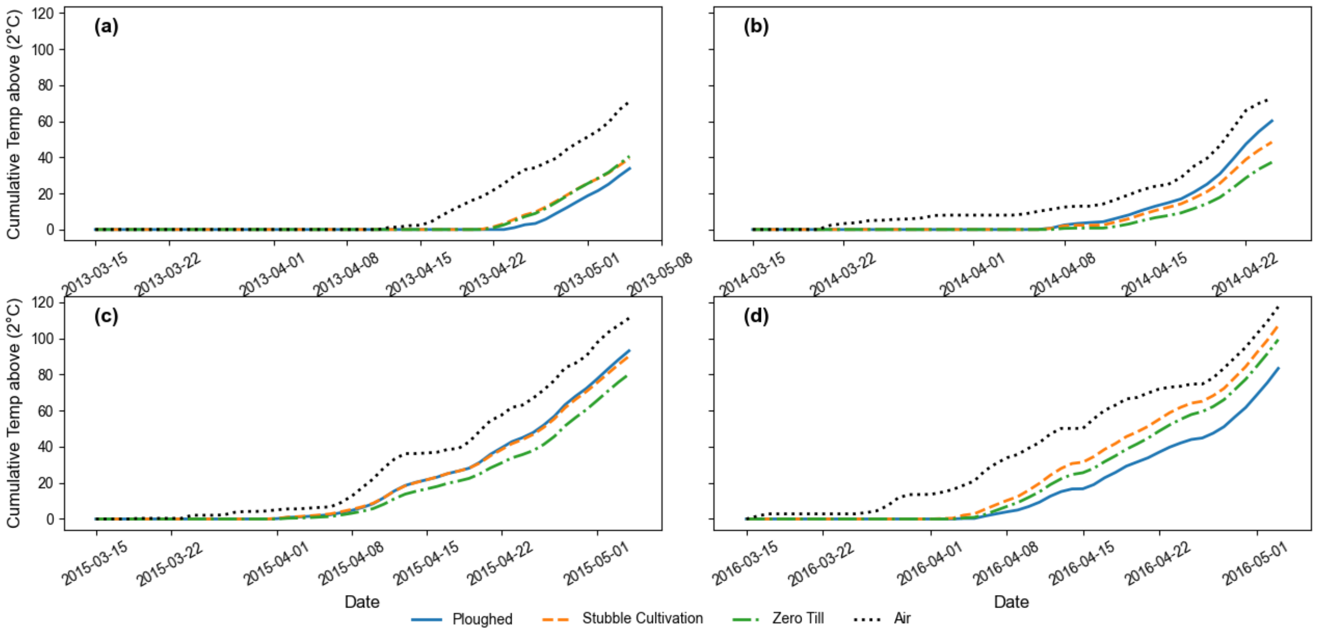

Figure 9. Cumulative soil and air temperature sums > 2°C under different tillage methods of ploughed (20-25 cm), stubble cultivation (10-15 cm), zero-till within time interval (a) 15.3.-5.5.2013, (b) 15.3.-24.4.2014, (c) 15.3.-4.5.2015, (d) 15.3.-3.5.2016.

Figure 10 displays the cumulative temperature sums above 5°C in both soil and air over four consecutive spring periods (2013–2016), under three primary tillage intensities: ploughed (20–25 cm), stubble cultivation (10–15 cm), and zero-till.

In 2013 (Figure 10a), cumulative air temperature above 5°C began to rise slowly after April 15, while cumulative soil temperature above 5°C began to rise slowly after April 28. By May 1, all soil treatments had reached approximately 10–15°C, while air accumulated around 30°C. Differences among tillage treatments were minimal, though stubble cultivation slightly lagged in the final stages.

In 2014 (Figure 10b), warming was delayed, with little accumulation before April 15. A sharp rise occurred after that date, with air temperature reaching around 30°C by April 22. Among soil treatments, ploughed plots warmed fastest, followed by stubble cultivation, with zero-till showing the lowest cumulative temperature.

In 2015 (Figure 10c), cumulative temperatures above 5°C began increasing after April 10, with a sharp rise between April 15 and May 1. By the end of the observation period, ploughed soil had the highest cumulative temperature (~25°C), followed by stubble cultivation, and then zero-till.

In 2016 (Figure 10d), cumulative temperatures above 5°C remained near zero until after April 11, with marked increases starting around April 15. By May 1, stubble cultivation had the highest soil temperature accumulation, followed closely by zero-till, with ploughed soil slightly behind.

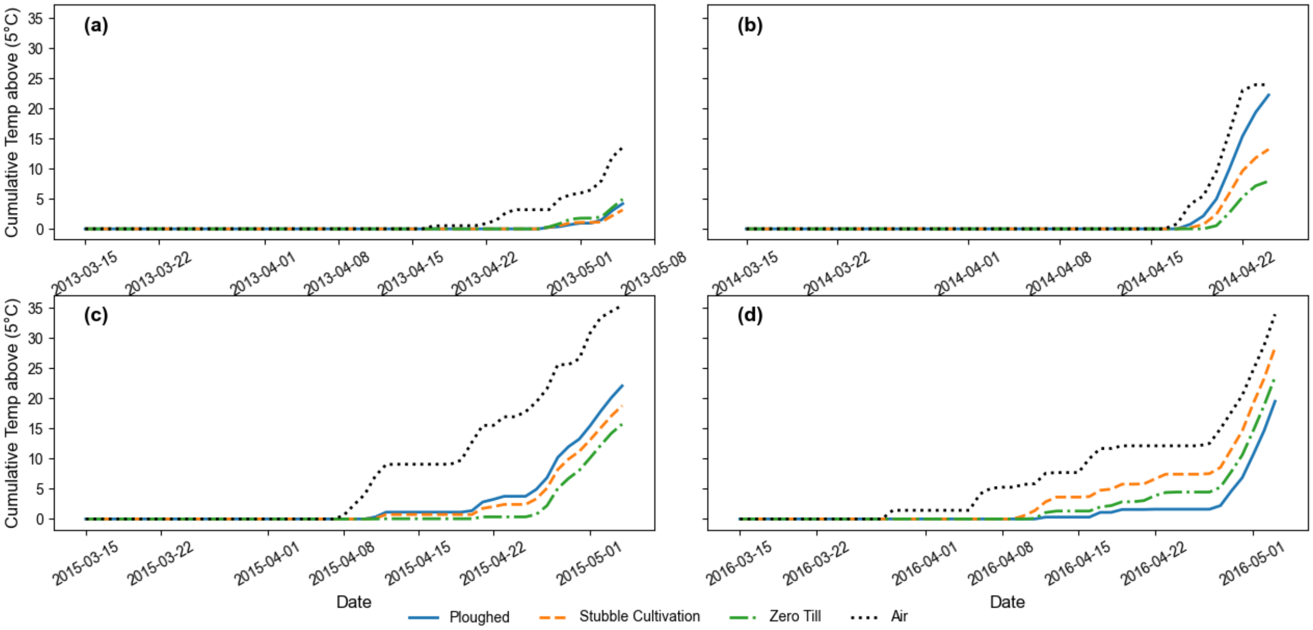

Figure 10. Cumulative soil and air temperature sums > 5°C under different tillage methods of ploughed (20-25 cm), stubble cultivation (10-15 cm), zero-till within time interval (a) 15.3.-5.5.2013, (b) 15.3.-24.4.2014, (c) 15.3.-4.5.2015, (d) 15.3.-3.5.2016.

6. Discussion

This study examined how primary tillage intensity affects soil temperature dynamics in boreal clay soils before spring sowing. By analyzing data collected from 2013 to 2016 across ploughed, stubble-cultivated, and zero-till treatments, this research provides insights into the thermal buffering capacities of different tillage systems. The placement of soil sensors at 10 cm depth was intentional, recognizing this layer as a critical zone for root-soil interactions, microbial activity, and water retention (Anbarasan & Ramesh, 2021). The results confirm that tillage influences early-season soil thermal regimes, which may have important implications for sowing time, crop emergence, and management decisions in cold-climate farming systems.

6.1 Soil thermal buffering and stability

The results demonstrate a consistent trend: soils under zero-till and stubble cultivation generally maintained higher minimum temperatures and exhibited smaller daily standard deviations compared to ploughed soils (Table 8). This indicates that reduced soil disturbance helps conserve thermal energy in the upper soil layers during early spring. The insulation effect of surface residues in zero-till and stubble cultivation likely plays a central role, reducing nocturnal heat loss and mitigating thermal extremes. This is especially important in boreal environments, where maintaining minimum soil temperatures above critical thresholds is vital for initiating microbial activity and root growth early in the season (Anbarasan & Ramesh, 2021; Blanco-Canqui & Lal, 2008). Daily air temperatures in spring exhibited large swings (often exceeding ±8 °C around the daily mean i.e. high diurnal variation in both maxima and minima), whereas soil temperatures remained much more stable due to the soil's thermal buffering capacity and the insulating effect of crop residues. For example, in 2016, while air minimum temperatures dropped to -1.3°C, zero-till soils maintained minimum temperatures over 2°C (Table 8). Such stability is essential for seed germination and microbial processes, which are inhibited under freezing or near-freezing conditions (Copeland & McDonald, 2001; Qu et al., 2023). This supports the notion that conservation tillage systems, particularly those retaining surface residues, can effectively moderate soil temperature extremes. To mitigate the cooler soil temperatures observed in zero-till systems, management of crop residues and soil moisture should be optimized. Light incorporation of residues or the use of strip tillage can enhance warming in key seed zones while retaining the benefits of surface cover elsewhere (Licht & Al-Kaisi, 2005). Additionally, effective drainage and avoidance of soil compaction common in boreal clays can reduce excess spring moisture and promote faster warming (Subin et al., 2013).

6.2 Influence of tillage on frost penetration and snow insulation

Table 7 provides further insight on understanding the thermal differences observed across treatments. Across all winters analysed, ploughed soils exhibited deeper frost penetration than stubble cultivation and zero-till. For example, in 2015–2016, frost depth reached 70 cm in ploughed soils, compared to 54 cm in zero-till plots. This deeper frost may be a direct consequence of disturbed soil structure and lower surface residue, which increase soil exposure to atmospheric cooling (Lal, 2004). In contrast, residue-covered soils insulate the surface, reducing frost penetration and preserving higher temperatures in the soil.

Snow covers also contributed to the observed differences in soil temperature. Although snow accumulation varied annually, the zero-till and stubble cultivation plots consistently had thicker snow cover than ploughed fields in some years (e.g., 2013 and 2014). Snow acts as a thermal buffer, reducing the rate of heat loss from the soil and moderating temperature fluctuations (Durán et al., 2014; Iwata et al., 2010). In addition to snow, crop residue covers, which is more prevalent in zero-till, and stubble cultivation also affects soil thermal dynamics. Residue acts as an insulating layer that shields the soil from direct solar radiation, thereby slowing early spring warming (Licht & Al-Kaisi, 2005). While this leads to delayed warming in zero-till systems, the combined insulating effects of snow and residue may help these soils retain more heat during colder periods, ultimately contributing to the higher minimum soil temperatures observed in these treatments. The interaction between snow cover, crop residue, and tillage-induced surface conditions is therefore likely important in explaining why zero-till soils warmed more slowly at first but maintained higher base temperatures over time than ploughed soil.

6.3 Progressive thermal benefits of reduced tillage over time

One important observation from the dataset is that the thermal benefits of reduced tillage became more pronounced as the experiment progressed. In 2013, differences in mean daily soil temperature among the tillage methods were minimal. However, from 2014 through 2016, zero-till and stubble cultivation consistently outperformed ploughed plots in both minimum and average soil temperatures. These patterns reflect the delayed yet stable warming characteristic of reduced tillage systems and indicate that cumulative soil temperature responses are influenced not only by the rate of initial warming but also by factors such as moisture retention and the insulating effect of surface residues (Blanco-Canqui & Lal, 2007; Gadermaier et al., 2012). Over time, this trend may be further enhanced by the cumulative benefits of reduced tillage practices, including the accumulation of surface residues, improved soil structure, and increased organic matter content (Gadermaier et al., 2012). It is worth noting, however, that the actual amount of straw or crop residue on the soil surface was not measured during the study years, which limits a more direct assessment of residue impact.

By 2016, for example, the daily mean soil temperatures were 3.16 °C in zero-till and 3.18 °C in stubble cultivation, compared to 3.07 °C in ploughed fields. Although this ~0.1 °C difference in mean temperature may seem small, it can be agronomically relevant under cold spring conditions typical of boreal regions. More importantly, the minimum soil temperature in zero-till reached 2.08 °C, compared to only 1.55 °C in ploughed soil an increase of over 0.5 °C. This difference is particularly significant, as minimum temperatures near freezing represent critical biological thresholds that influence seed germination, early root growth, and microbial activity (Copeland & McDonald, 2001; Qu et al., 2023). Even modest increases in minimum soil temperature can reduce the risk of chilling injury and support more reliable crop establishment. These findings suggest that reduced tillage systems offer improved thermal conservation, which may enhance crop emergence and soil biological functioning during the early growing season in northern climates.

6.4 Temperature thresholds and sowing implications

Thermal thresholds of 0, 2, and 5°C are commonly used to assess the viability of sowing in cold soils. The study results showed that stubble cultivation tillage treatments often reached these critical thresholds earlier or simultaneously with ploughed soils. For instance, in 2016, zero-till and stubble cultivation plots crossed the 0°C mark by March 29, while ploughed plots lagged slightly. While the difference may seem small, even a delay of a few days can have significant agronomic consequences in regions with a short growing season (Licht & Al-Kaisi, 2005). The study reinforces the value of using thermal thresholds such as soil temperature ≥ 5°C as a benchmark for spring sowing readiness. Precision agriculture tools like soil sensors and real-time data logging systems used in this study should be widely adopted by farmers to guide sowing dates and reduce risks of poor germination due to premature planting. Real-time monitoring can also support better fertilizer timing and frost avoidance strategies (Alvarado & Bradford, 2002).

Furthermore, cumulative temperature sums (Figures 10b and 10c) showed that ploughed soils initially accumulated warmth more rapidly above 5°C, but stubble cultivation often caught up or even exceeded (Figure 10d) ploughed plots as the season progressed. This finding suggests that although CT may appear advantageous for early warming, it does not sustain that advantage consistently throughout the pre-sowing period. This result echoes findings from Alghamdi et al. (2021), where strip- and reduced-tillage systems eventually matched or outperformed ploughed soils in cumulative temperature accumulation.

An important determinant of early crop establishment is the thermal status of the soil during the days preceding sowing. In this study, soil temperatures at 10 cm depth measured on the final day of each observation period served as a practical indicator of field readiness. As shown in Table 8, by the end of each spring season, daily mean soil temperatures under all tillage treatments generally exceeded the base germination threshold for spring barley (approximately 1–3 °C). However, in 2013 a notably cold spring the ploughed treatment recorded a mean temperature below 1 °C, suggesting less favorable conditions for germination. Although optimal germination typically occurs at around 10 °C (Longo et al., 2017), the temperatures observed in this study, while suboptimal, indicate that germination could still proceed under most treatments. Notably, reduced tillage systems such as stubble cultivation and zero-till maintained slightly higher soil temperatures compared to ploughing, which may confer an advantage under cool spring conditions. Supporting this, Table 10 shows that in 2013, stubble cultivation and zero-till reached soil temperatures above 2 °C three days earlier than the ploughed treatment. This finding suggests that reduced tillage can help mitigate the risk of delayed sowing by promoting earlier soil warming, particularly in cold conditions, a potentially valuable trait in boreal regions with short growing seasons and high interannual variability in spring temperatures.

6.5 Year-to-year variation and climatic influences

One of the key findings from this research is the significant year-to-year variability in soil warming patterns, reflecting the broader climatic instability characteristic of the boreal zone. In 2013, all tillage methods exhibited relatively low temperature gains due to prolonged cold conditions and persistent snow cover. In contrast, the springs of 2014 and 2015 were marked by an earlier onset of warming and higher cumulative temperature sums, which favored faster germination and earlier sowing particularly in ploughed plots Although ploughed plots initially warmed faster in early spring, especially in dry or sunny conditions, this advantage was not sustained. For instance, in 2016, zero-till and stubble cultivation soils surpassed ploughed soils in cumulative daily mean temperature by late April (Table 8; Figures 4 and 7). These results affirm that while ploughing accelerates surface warming due to residue removal and darker soil exposure (Licht & Al-Kaisi, 2005), it also increases thermal variability and deeper frost penetration (Durán et al., 2014; Table 7) and long-term risks, including soil structure degradation, increased erosion, and carbon loss (Grandy & Robertson, 2006; Lal, 2004). Reduced tillage practices, by comparison, enhance soil aggregation and carbon sequestration (Lal, 2004), yet may delay early crop establishment due to cooler seedbed temperatures.

Given the high inter-annual variability in spring conditions, a flexible and climate-responsive tillage strategy is advisable for farmers in boreal regions. For instance, ploughing may be better suited to springs forecasted to be dry and warm, as it improves soil aeration and can facilitate earlier sowing when soil moisture is not limiting (Sharma & Kumar, 2023). Conversely, in dry springs, reduced tillage methods such as stubble cultivation and zero-till offer advantages in conserving soil moisture often a more critical factor than temperature under such conditions (Lu & He, 2023). Although conservation tillage systems tend to retain more heat in autumn, they generally exhibit slower soil warming in spring. Nevertheless, their more stable temperature profile can still support timely sowing, particularly in years with delayed warming.

Moreover, during cold or wet springs, reduced tillage and zero-till systems may provide greater thermal stability and reduce the risk of frost-induced sowing delays (Bulgakov et al., 2022; Iwata et al., 2010). It is important to note that in this study, primary tillage was performed in the autumn, meaning that the observed spring soil conditions reflect the residual effects of those autumn operations. Since spring ploughing is generally impractical on Finnish clay soils due to poor workability and the risk of compaction, alternative approaches such as shallow stubble cultivation in spring may be more appropriate (Pitkanen, 1994). Previous research in Finland has demonstrated the viability of shallow spring cultivation as a management practice for clay soils (Pitkanen, 1994), offering a practical option when spring intervention is needed.

6.6 Bridging the knowledge gap

This research addresses a critical gap in understanding how varying intensities of primary tillage beyond the conventional dichotomy of ploughed versus zero-till systems affect spring soil temperature in boreal clay soils. Previous studies have largely focused on the extremes of tillage intensity (Honkanen et al., 2021; Känkänen et al., 2011), often overlooking the effects of intermediate practices such as RT or stubble cultivation.

The multi-year dataset from this study shows that intermediate tillage systems can moderately enhance spring soil warming while preserving soil structure. These systems may offer a practical compromise in boreal conditions, where soil temperature is a key factor for timely sowing and early crop development. Supporting this interpretation, Kauppi et al. (2024) found that both ploughing and RT yielded 12–13% more grain and 18–21% higher nitrogen yields compared to zero-tillage. Phosphorus yields were also 12% higher under ploughing and RT. While zero-till had slightly better nutrient balances especially for nitrogen, it resulted in lower productivity. The comparable performance of ploughing and RT in both yield and nutrient use efficiency highlights the agronomic viability of intermediate tillage systems, reinforcing their potential role in sustainable intensification strategies on boreal clay soils.

7. Conclusion

This study investigated how primary tillage intensity influences soil temperature dynamics in boreal clay soils before spring sowing, using field data from 2013 to 2016 in southwestern Finland. Through comparative analysis of conventional ploughing, stubble cultivation, and zero-till systems, the study achieved its aim of evaluating tillage effects on soil warming, cumulative heat accumulation, and implications for early-season field operations.

Through the four study years, each characterized by distinct spring conditions, the data indicated that the tillage method influenced soil warming rates. Over the experimental period, the number of replicates for each treatment was as follows: ploughed tillage (n = 11), stubble cultivation (n = 12), and zero tillage (n = 9), each influencing soil warming rates. However, the 2015 zero tillage data were based on only a single replicate, so results from that year was interpreted with caution. In cold years, soil warming was slow across all treatments, but stubble cultivation and zero-till began warming earlier than ploughed soils once thawing initiated. In milder years, warming occurred earlier and more rapidly overall, but differences between tillage systems became more pronounced. Stubble cultivation often achieved moderately high cumulative warming rates in all the years, indicating that intermediate tillage intensity may provide an adaptive advantage under variable spring climates.

Soil temperature measurements at 10 cm depth revealed that ploughed soils generally reached higher maximum daily temperatures, mostly in warmer conditions, while reduced tillage (stubble cultivation and zero-till) maintained higher minimum temperatures and lower daily variability. Although ploughed plots initially warmed faster in early spring, especially in dry or sunny conditions, this advantage was not sustained. Cumulative temperature sums above biologically relevant thresholds (0°C, 2°C, and 5°C) were used to quantify the effective soil heat accumulation across tillage systems. In nearly all years, stubble cultivation either matched or exceeded ploughed plots in cumulative day-degree sums by the end of the pre-sowing period. Zero-till typically lagged in early accumulation but closed the gap as the season progressed.

From a practical standpoint, the findings suggest that while conventional ploughing may provide a short-term thermal advantage early in the spring, it is also associated with deeper frost penetration, greater soil temperature variability, and potential delays in reaching critical temperature thresholds during colder years. In contrast, stubble cultivation presents a functional compromise by balancing moderate early-season warming with improved thermal stability and better moisture retention, making it particularly suitable for boreal clay soils under variable climatic conditions.

However, further research is required to explain the complex interactions among winter conditions such as snow cover duration, frost depth, freeze–thaw cycles, and the quantity of crop residue retained under reduced tillage and their influence on subsequent spring soil warming across different tillage systems. Such investigations would enhance the understanding of how antecedent winter weather shapes early-season soil thermal regimes and could improve the accuracy of tillage planning in the context of increasing climate variability. Moreover, long-term studies are necessary to evaluate how cumulative changes in soil structure and organic matter content under varying tillage intensities affect both thermal and hydrological soil functions critical for early crop establishment.

8. Use of artificial intelligence and language models

ChatGPT was used to translate some source materials that were not originally written in English, and Grammarly was employed to improve the clarity and readability of parts of the text in this study.

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Appendix

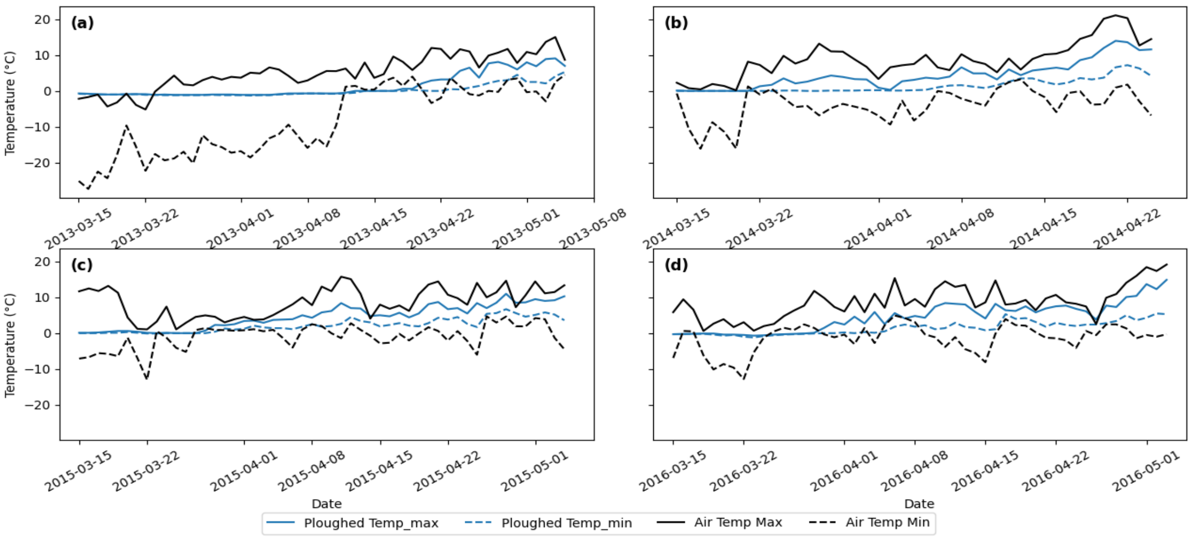

Figure 11. Daily maximum and minimum soil temperatures at 10 cm depth under ploughed (20–25 cm) tillage, along with corresponding daily air maximum and minimum temperatures, during the periods: (a) 15.3.–5.5.2013, (b) 15.3.–24.4.2014, (c) 15.3.–4.5.2015, and (d) 15.3.–3.5.2016.

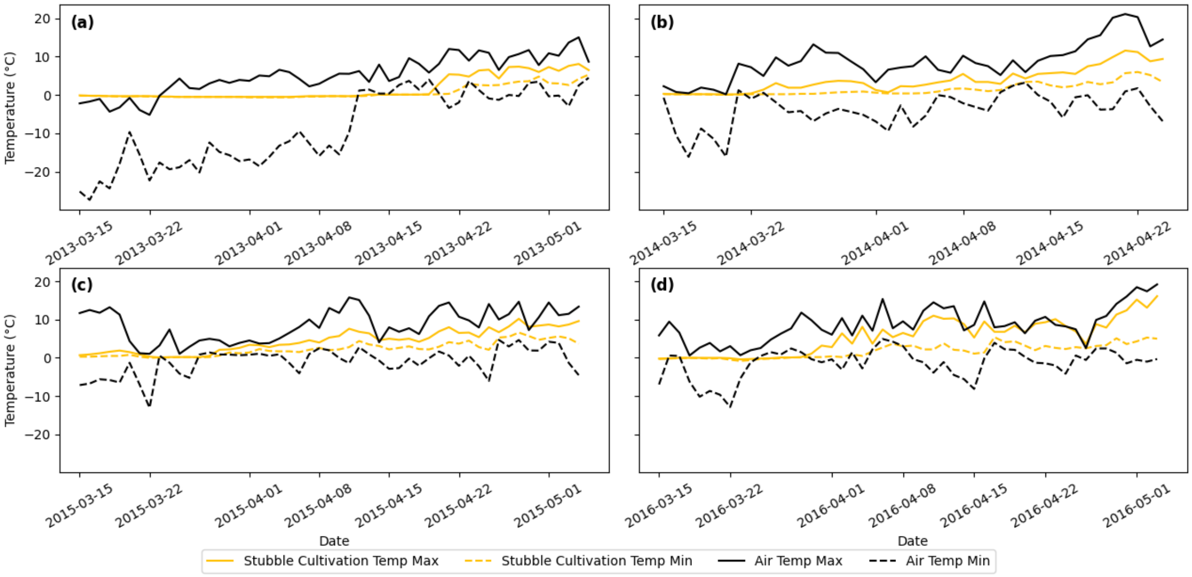

Figure 12. Daily maximum and minimum soil temperatures at 10 cm depth under stubble cultivation (10-15 cm) tillage, along with corresponding daily air maximum and minimum temperatures, during the periods: (a) 15.3.–5.5.2013, (b) 15.3.–24.4.2014, (c) 15.3.–4.5.2015, and (d) 15.3.–3.5.2016.

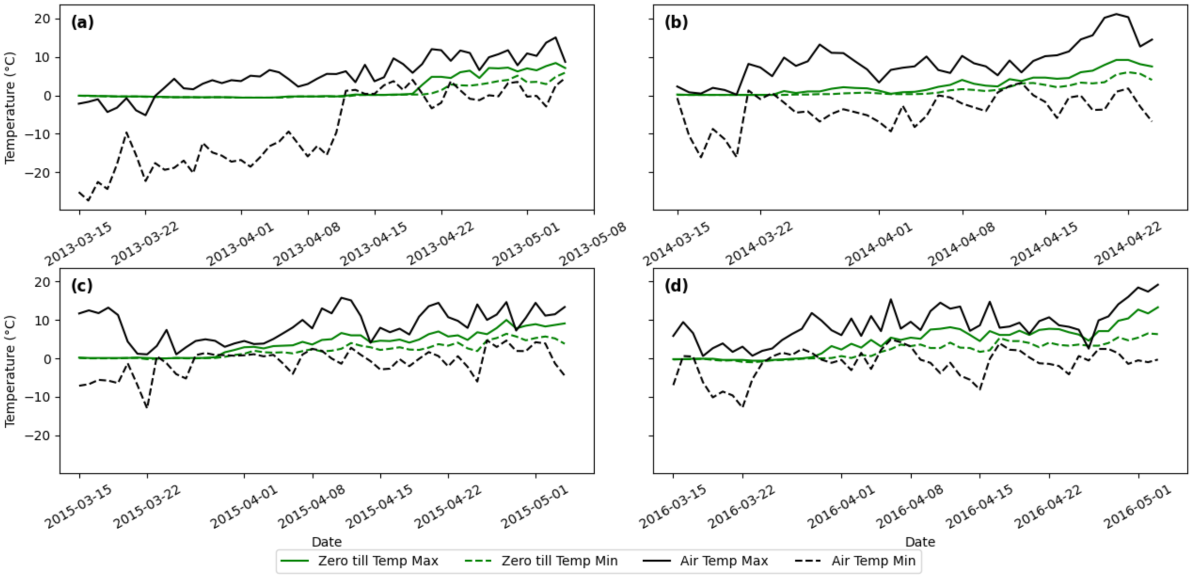

Figure 13. Daily maximum and minimum soil temperatures at 10 cm depth under zero-till tillage, along with corresponding daily air maximum and minimum temperatures, during the periods: (a) 15.3.–5.5.2013, (b) 15.3.–24.4.2014, (c) 15.3.–4.5.2015, and (d) 15.3.–3.5.2016