How to handle crop residues in no-till systems: Effects of stubble height on soil conditions and crop emergence

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How to handle crop residues in no-till systems: Effects of stubble height on soil conditions and crop emergence

Hur växtrester kan hanteras i direktsådda system: Stubbhöjdens påverkan på markförhållanden och grödans uppkomst.

Moa Magnusson Osmund

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Abstract

How crop residues are managed is crucial in no-till systems, yet the optimal way to handle them under Nordic conditions remains unclear. This field study examined how different stubble heights and associated straw residue levels influence soil temperature, soil water content, decomposition parameters and crop emergence across four Swedish farms with contrasting soil textures and climates. Each farm had one field experiment with three treatments: Control without straw residues (C), low stubble with chopped straw residues (LS) and high stubble with chopped straw residues (HS). Soil microclimate was monitored using TMS sensors and decomposition was measured using the Tea Bag Index method.

High stubble slightly reduced soil temperature, probably through decreased solar radiation due to shading, while low stubble with more straw residues often increased soil water content by reducing evaporation and increasing infiltration. However, the treatment effect was highly variable and site-specific. Soil moisture and accumulated temperature explained more of the variation in decomposition rate and stabilization factor than stubble height alone. Effects on early crop biomass were limited and inconsistent among crop species and sites.

Overall, the results suggest that local conditions had a larger effect on soil conditions than stubble height alone. However, a high stubble tends to have no negative effects and could be used as a cheaper, less labour-intensive alternative. To further improve no-till systems in Sweden, more research on alternating straw residue management is needed, along with improved drilling technology, crop rotations and long-term adjustments to the system.

Keywords: No-tillage, stubble height, crop residues, soil temperature, soil water content, decomposition, crop emergence.

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Abbreviations

AST	Accumulated soil temperature
C	Control without straw residues
HS	High stubble with straw residues
LS	Low stubble with straw residues
SOC	Soil organic carbon
SOM	Soil organic matter
SWC	Soil water content
TBI	Tea Bag Index

1. Introduction

Soil degradation and climate change pose a threat to agricultural production and food security (IPCC 2022). Traditional tillage methods, characterized by an intensive mechanical disturbance of the soil, usually with a plough, have been questioned for their role in depleting soil organic matter (SOM), increasing soil erosion and contributing to the decline of soil biodiversity. These practices may be effective in the short term for crop production but weaken the sustainability of agricultural systems (Jug et al. 2025). Implementing minimal soil disturbance with techniques like no-tillage has therefore been suggested as a more sustainable and environmentally friendly management system (Hobbs et al. 2008).

1.1 No-till cropping systems

No-tillage, also known as direct drilling or zero tillage, is defined as a system in which crops are sown directly into the soil without any prior loosening. The only disturbance is very shallow (< 5cm), done by the passage of the drill coulters when seeding. Usually, 30-100% of the surface remains covered with plant residues (Soane et al. 2012). General benefits of no-till include better soil erosion control, improved water retention, lower energy costs, increased soil organic carbon (SOC) and microbial diversity (Sadiq et al. 2025). However, the benefits of no-till are highly context-specific. No-till can be less effective in cold, wet areas with poorly drained soils or in places where the system has not been well-adapted to local conditions, considering agronomic, social and environmental challenges (Page et al. 2020).

The climate in northern Europe is generally characterised by low-intensity rain, long winters, late and wet springs, cool moist summers and an early return of autumn rains, sometimes before crop harvests have been completed (Soane et al. 2012). In Sweden, soil conditions are wet after winter but in some places, like eastern Sweden, springs are rather dry (Rasmussen 1999). The adoption of no-till in northern Europe has therefore, primarily been to reduce costs, increase area capability and reduce pollution of water courses, rather than reducing soil erosion and runoff (Soane et al. 2012). The adoption of no-tillage has so far been limited in Scandinavia (Hydbom et al. 2020). In long-term field experiments in Sweden, Arvidsson et al. (2014) showed that it is hard to obtain the same yields as with ploughing and shallow tillage. Farmers are unlikely to adapt to no-tillage if there is a risk of lower yields, even if production costs are lower (Unger & McCalla 1980). Therefore, the system needs to be improved to secure a good plant establishment and crop yields (Arvidsson et al. 2014).

1.1.1 Crop emergence and plant residues

Successful germination requires viable, undamaged seeds, adequate temperature, water and oxygen supply, and the absence of toxic substances (Håkansson et al. 2011). For the crop to emerge after seeding, the distance to the soil surface cannot be too large, mechanical resistance to seedling growth cannot be too excessive and the seedlings must not be damaged in any way. If emergence is delayed, it will result in a smaller leaf area during the early growth period, causing lower yields (Håkansson et al. 2011).

Crop residues from the preceding crop and difficulties in crop establishment were the main causes of decreased yields in no-tillage systems in Sweden (Soane et al. 2012; Arvidsson et al. 2014). The issues relate to the transfer of plant pathogens and to plant residues affecting the physical environment during germination and emergence (Arvidsson et al. 2014; Achankeng & Cornelis 2023). Other factors affecting the crop emergence include what crop is grown, the preceding crop and soil type (Rasmussen 1999). A European meta-analysis showed that yields are approximately 5% lower for no-till compared to conventional tillage (Achankeng & Cornelis 2023). In addition, results from long-term field trials in Sweden show yield decreases from 5-20% (Arvidsson et al. 2014).

When cereal crops are drilled in the presence of plant residues, factors like the amount and form of the residues, the height of the stubble, whether the residues are still attached to the crop roots and if they are still standing are important (Soane et al. 2012; Seehusen et al. 2017). These factors will reduce access to solar radiation and water evaporation from the surface, affecting the drilling operation. It may delay drilling in spring because the soil surface will be both wetter and colder than soils that are ploughed in the autumn, especially in Scandinavia (Soane et al. 2012). Therefore, spring-sown crops yield less than winter-sown crops in no-tillage systems (Arvidsson et al. 2014).

In addition, crop residues can harm early growth and crop establishment due to water-soluble toxins produced by the residues or by micro-organisms during decomposition (Morris et al. 2010). The number of fine aggregates around the seed is usually less in no-till compared to systems with shallow tillage or ploughing. This might increase evaporation and thus, leading to poor germination if the seed is placed in a shallow depth (Arvidsson et al. 2014).

It is generally believed that residues of no-till cereal crops are best handled by chopping them and spreading them evenly. When the straw is used as a source of biomass, or for animal bedding and feeding, the stubble is usually cut short and removed prior to direct drilling (Soane et al. 2012).

Due to issues associated with plant residues and seeding in no-till systems, there has been greater interest in alternative ways to handle straw. One solution is to adjust the stubble height to see whether yields change. Several studies have shown that increased stubble height can improve crop yield through enhanced soil water conservation and reduced losses from evapotranspiration, particularly in direct-seeded systems (Aase & Siddoway 1980; Cutforth & McConkey 1997). But studies in Swedish climate are missing.

1.2 Crop residues impact on soil physical and biological processes in no-till systems

By modifying stubble height, farmers directly influence the amount, distribution and physical form of crop residues remaining on the soil surface. This alters the soil microclimate by regulating temperature, evaporation and substrate availability for microorganisms (Aase & Siddoway 1980; Rasmussen 1999; Singh et al. 2018). Soils beneath high amounts of crop residues are generally cooler, wetter and less aerated compared to bare soils (Unger & McCalla 1980).

1.2.1 Soil temperature

Soil temperature determines many physical, chemical, hydrological and biological processes in the soil (Blanco-Canqui & Lal 2009), including seed germination, emergence and growth of the seedling, plant development, evaporation rates, soil water storage, soil air composition and gaseous fluxes, microbial activity, nutrient availability and cycling (Onwuka 2018). The amount of crop residues on the soil surface will determine the soil thermal regime. Any removal or addition of crop residues can therefore rapidly change the soil temperature dynamics (Blanco-Canqui & Lal 2009).

Previous research by Aase & Siddoway (1980) showed that tall stubble (30-35 cm) had lower soil temperature than short stubble (15-19 cm) in a loamy soil in Montana, USA. The difference between treatments was largest during the cold season. They concluded that standing stubble influenced minimal and maximum temperatures and prevented temperatures from dropping below freezing in the winter (Aase & Siddoway 1980).

A Canadian study also showed that tall stubble (>30 cm) captured or reflected more of the incoming solar radiation relative to short stubble (15 cm) and cultivated treatments. This resulted in less solar radiation reaching the soil surface. The experiment also showed that the average daily soil temperature decreased with increasing stubble height (Cutforth & McConkey 1997). Light coloured straw also has a higher albedo, reflecting more of the incoming solar radiation (Blanco-Canqui & Lal 2009; Turmel et al. 2015). Aase & Siddoway (1980) concluded that stubble had a 1.5 times greater albedo than bare soil in the fall.

Residues insulate the soil surface from abrupt changes in air temperature, but the amount of residues will determine the degree of insulation (Onwuka 2018; Sharma & Kumar 2023). Soils with higher amounts of crop residues will have lower diurnal temperature variation, remaining cooler during the day and warmer at night. Additionally, soils will be cooler in summer and warmer in winter than bare soil (Rasmussen 1999; Sharma & Kumar 2023). In cool and temperate climates that have late and short growing seasons, more residues may delay crop emergence, plant development and ripening (Rasmussen 1999). Partly removing residues may be an option to avoid excessive cooling of no-till soils during spring (Blanco-Canqui & Lal 2009; Turmel et al. 2015).

However, more residues on the soil surface during winter increase soil roughness, leading to more snow accumulation/trapping compared to bare soil. This reduces soil freezing and may accelerate early-spring thawing due to warmer conditions compared to removing the straw (Blanco-Canqui & Lal 2009).

1.2.2 Soil moisture

Leaving crop residues on the soil surface instead of removing them improves the soils' capacity to store water by increasing infiltration rate and decreasing runoff, reducing evaporation and abrupt fluctuations in soil surface temperature (Singh et al. 2018; Fu et al. 2021). Residues will also increase soil organic matter (SOM) content because the input of organic carbon is higher. This improves the water retention capacity of the soil since it increases the specific surface area, which is essential for adsorbing and retaining water molecules (Unger & McCalla 1980; Blanco-Canqui & Lal 2009). The soil water content (SWC) will therefore increase with increasing amount of plant residues, especially in spring and summer (Blanco-Canqui & Lal 2009; Singh et al. 2018).

In addition, studies show that changes in stubble height affect the evaporation rate from the soil surface. Cutforth & McConkey (1997) concluded that tall stubble (>30 cm) reduced evaporation rate by approximately 25% and short stubble (15 cm) by about 5% compared to the cultivated treatment. Aase & Siddoway (1980) also observed reduced evaporation from the tall stubble plots. They also concluded that tall stubble accumulated more water during winter than bare soil did, due to its ability to capture more snow.

Lower evaporation and higher water content in the upper soil layers can be valuable in areas with low precipitation after sowing in spring, such as in the eastern parts of Sweden (Rasmussen 1999). However, in areas where rainfall is excessive, more crop residues in the fields can lead to saturated soils and waterlogging (Turmel et al. 2015). Water saturation lowers the oxygen concentration in the soil, leading to reduced root and microbial respiration. This can result in decreased plant growth and productivity (Ben-Noah & Friedman 2018).

1.2.3 Soil biological activity and decomposition

Soil biological processes, such as microbial activity, are interconnected with soil physical and chemical properties, including aeration, SOM and pH, and directly influence carbon and nutrient cycling in soil systems. Consequently, biological properties are highly sensitive to changes in soil conditions due to management (Delgado & Gómez 2024).

Leaving crop residues on the soil surface instead of removing them can enhance microbial biomass, primarily due to an increased supply of organic substrates, improved soil moisture conditions and more favourable soil temperatures (Blanco-Canqui & Lal 2009; Turmel et al. 2015; Fu et al. 2021). SOM serves as a major carbon source for many soil organisms, particularly microorganisms. The quantity and chemical composition of organic inputs determine the biological activity (Delgado & Gómez 2024).

Microbial decomposition of organic matter plays a crucial role in controlling nutrient availability, soil water dynamics and development of soil structure, thereby linking biological activity to broader soil functioning (Turmel et al. 2015). Decomposition rate and microbial activity are dependent on the relationship between soil temperature and soil moisture (Sierra et al. 2015). Decomposition rate increases with temperature. However, this is only applicable when soil moisture is not limiting. If soil moisture is low, microbial activity will be reduced due to water stress and limited substrate solubility. If the soil moisture is too high, decomposition will be reduced due to limited oxygen. Therefore, decomposition rates are at their highest when soil moisture is intermediate (Sierra et al. 2015). Decomposition is most sensitive to temperature changes when the temperature is high and when soil moisture is near critical thresholds (drying or waterlogging) (Sierra et al. 2015).

The presence of crop residues will result in a slower decomposition rate compared to when they are incorporated into the soil (Lupwayi et al. 2004). The residues will have less surface area available to microorganisms when left on the soil surface. They will also be more susceptible to fluctuating environmental conditions, which can, on the other hand, favour physical breakdown of the residues. A fast decomposition rate is not always desirable because mineralized nutrients can be lost from the soil (Lupwayi et al. 2004).

Adding crop residues can affect nutrient availability for the crop. Cereal residues generally have a high C/N composition, which can temporarily immobilize nitrogen during decomposition. A loss of mineral nitrogen fertilizer through denitrification can be greater if residues are left on the surface due to a higher SWC or if fertilizers are not well incorporated (Turmel et al. 2015).

1.3 Knowledge gaps

To adapt to more sustainable agricultural systems, conservation agriculture or no-tillage is suggested as a possible solution. However, the implementation must be adapted to countries' specific contexts and capacities (IPCC 2022). To encourage farmers to choose conservation tillage as a practice, more knowledge is needed (Hydbom et al. 2020). For example, Jug et al. (2025) concluded that farmers are unsure how to manage large amounts of crop residue in no-till systems and that there is a knowledge gap regarding the optimal stubble height and the amount of crop residue left on the surface. There is an identified need for further research on how to best handle crop residues in no-till systems, especially in temperate climates.

1.4 Objectives

The aim of this study was to examine how different stubble heights and straw residues affect physical and biological conditions such as soil temperature, soil water content and microbial activity in no-till cropping systems. The specific objectives were to:

1. Quantify the effects of different stubble heights and straw residue levels on soil temperature, soil water content, and decomposition in no-till systems.
2. Assess how stubble height and crop residues influence crop establishment and plant development.
3. Evaluate how climate and soil texture modify the effects of stubble height and straw residue management on soil conditions and crop response.

2. Materials and methods

2.1 Study sites

This study was conducted on four different farms located in Tärna, Munsö, Fyllingarum and Helsingborg. Tärna and Munsö are situated in the east of the southern half of Sweden, while Fyllingarum is even further south. Helsingborg is in the south-west of Sweden. The locations of the farms are shown in Figure 1. The farms were chosen based on the criteria that they should be in slightly different climates and that they would all practice no-till in the selected fields. On each farm, one field was selected. In that field, a field trial was conducted with three different stubble-height treatments.

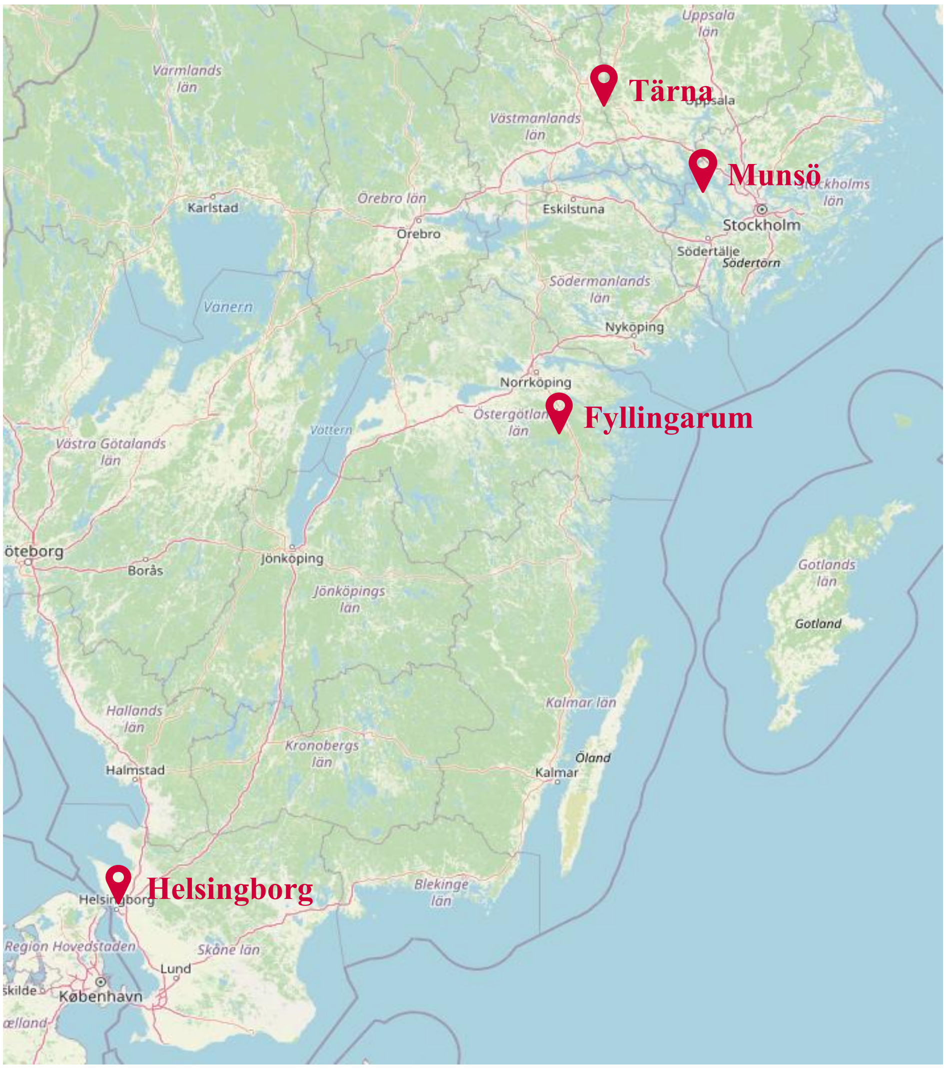

Figure 1: Map of the approximate locations of the studied fields from north to south; Tärna, Munsö, Fyllingarum and Helsingborg. Basemap: © OpenStreetMap contributors. Points and text: Placed by the author.

2.1.1 Weather conditions

The study period extended from the end of August until the beginning of November. During this period, the weather was slightly different between the sites (Figure 2). The fields located further north in Sweden, Tärna and Munsö, had a slightly colder weather and a total precipitation of 155.7 mm and 169.5 mm during the study period. The mean daily temperature was 10.3 °C and 11.8 °C respectively. The fields further south, Fyllingarum and Helsingborg had a total precipitation of 149.3 mm and 174.6 mm. The mean daily temperature for the period was 11.6 °C and 12.7 °C.

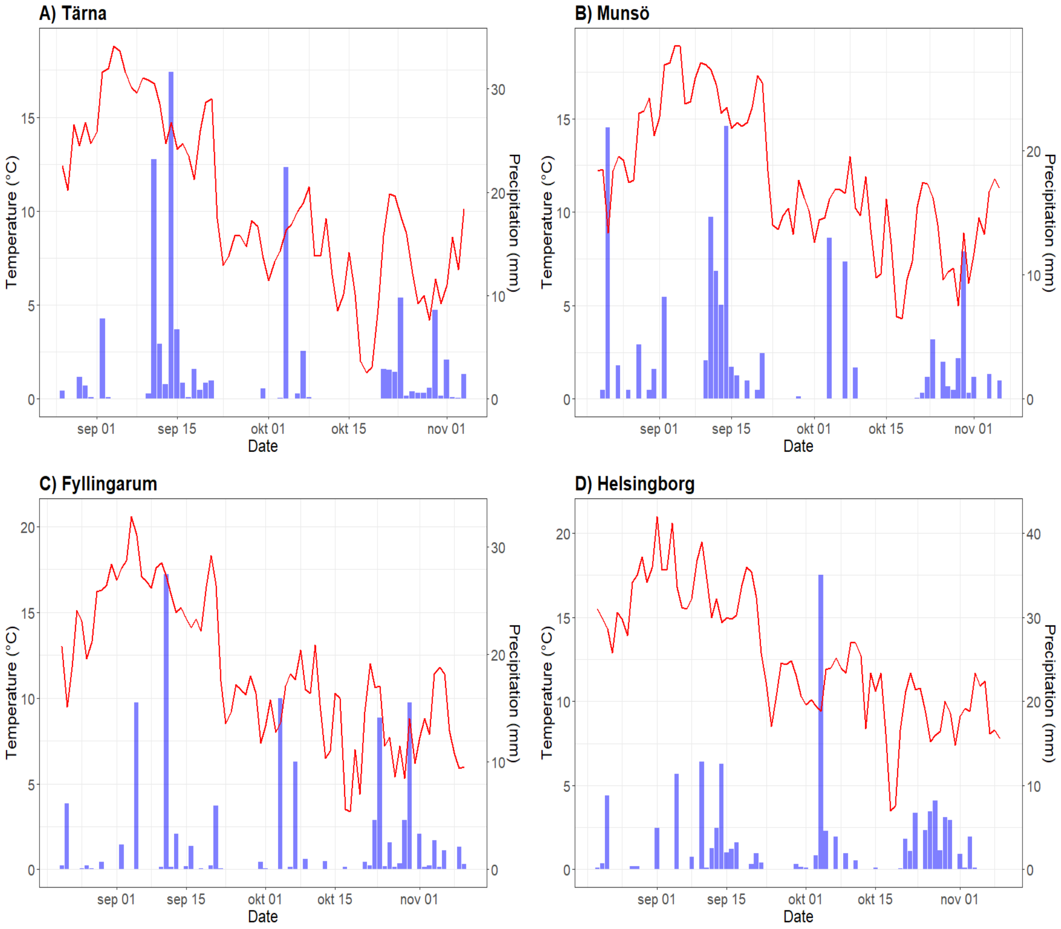

Figure 2: Mean daily temperature (red) and precipitation (blue) for the study sites: A) Tärna, B) Munsö, C) Fyllingarum, D) Helsingborg. Weather data derived from SMHI.

2.1.2 Soil and crop management

All the fields were managed under no-tillage with annual cropping. The field in Tärna had been under no-till for 5 years, the Munsö field for 18 years and the Helsingborg field for 10 years. The Fyllingarum field had previously been tilled with reduced tillage, but for this particular experiment, a part of the field was left untilled to fit the purpose of the trial.

All the fields were, the year of the experiment, cultivated with wheat (*Triticum aestivum L.*) that was harvested in July or August 2025 (Table 1). Rapeseed (*Brassica napus*) was later sown in Helsingborg and winter wheat in Fyllingarum. In Tärna rye (*Secale cereale*) was sown as a cover crop and in Munsö the seeding was postponed until spring due to unfavourable weather conditions. All the soil and crop management was done with the farmer's own machinery. The harvesting and sowing dates, as well as the type of sowing machine that was used, are presented in Table 1.

Suitable fields were selected together with the farmers. Originally, the same winter crop was planned for each field. The purpose of sowing the same crop was to ensure controlled and comparable results. But finally, the selection of winter crops differed between fields, depending on farmers' crop rotations and their decisions about which field to use. The field history and crop rotations for each farm are listed in Table 2.

Table 1: Harvest date for wheat, seeding rate and date for the winter crops, and type of sowing machine, divided into disc or tine coulter.

Farm	Harvesting date	Winter crop	Seeding rate	Sowing date of winter crops	Type of sowing machine
Tärna	2025-08-13	Rye	100 (kg/ha)	2025-08-21	Tine coulter
Munsö	2025-08-09	No crop	-	No crop	Disc coulter
Fyllingarum	2025-08-08	Wheat	220 (kg/ha)	2025-09-21	Double disc coulter
Helsingborg	2025-07-29	Rapeseed	40 (pl/m^2)	2025-08-20	Tine coulter

Table 2: Fertiliser and pesticide applications during autumn 2025 and crop rotations for Tärna, Munsö, Fyllingarum and Helsingborg.

Farm	Crop rotation	Fertiliser application in sown winter crops	Chemical application in sown winter crops
Tärna	Wheat, peas/rapeseed/ oats/flax, wheat, peas/rapeseed/ oats/flax	Non	Non
Munsö	Wheat, rapeseed, rye/pasture, wheat, (Sometimes peas, oats, flax or barley)	No crop	No crop
Fyllingarum	Wheat, wheat, rapeseed, wheat, wheat, faba bean.	160 kg/ha Yaramila 10-14-12	Herbicides: Credit Xtreme, Mateno duo, Boxer
Helsingborg	Rapeseed, wheat, oats, cover crop, wheat,	300 kg/ha NPK 13-8-14 Kombi Ya	Herbicides: Jablo, Centium 36 CS, Gajus, Agil 100 EC. Pesticides: Artemis, Sluxx HP, DK Exavance. Other: Bio pH Control, Bio Ammoniumsulfat, Caryx (growth regulator), vixeran (biostimulant).

2.2 Field experiment layout

On each farm, a field experiment was designed in order to examine how different stubble heights affect the soil environment for the next coming crop in no-till cropping systems. A randomized block design was chosen for this with three different treatments: control (C) with standard stubble height and no straw left on the soil surface, low stubble (LS) with a stubble height that was lower than the control and chopped straw left on the soil surface, and high stubble (HS) with a stubble height higher than the control and chopped straw left on the soil surface. The different stubble heights across the four farms are shown in Table 3. The original idea was to have similar stubble heights for each treatment on all farms, but this was later adjusted based on farmers' preferences. This resulted in a slightly different experimental design on all the farm fields. The treatments were repeated four times in a random order in blocks 1-4 (Figure 3). Each block was as wide as the farmer's combine harvester (see Table 3). The length was chosen by the farmer and was not relevant for the execution of the experiment.

In total, four fields were examined with 16 plots per treatment, resulting in 48 plots for the whole study. In each field, soil temperature, soil water content (SWC), decomposition, and plant biomass were measured. At Helsingborg, rapeseed plant development was also measured. Soil samples from each field were also taken to determine soil texture, microbial respiration and total amount of C and N. The samples were collected by taking a bucket of soil from the first 10 cm of the soil surface. This was only conducted in the control treatment at each field, resulting in four soil samples in total, one from each farm. Analyses were done in the SLU soil lab according to standard procedures. The data were collected from August until the beginning of November.

Table 3: Approximate stubble height and width of the plots on the four different farms.

Farm	C (cm)	LS (cm)	HS (cm)	Width (m)
Tärna	15	10	20	7.5
Munsö	25	15	50	9
Fyllingarum	25	20	40	7
Helsingborg	15	10	30	10.5

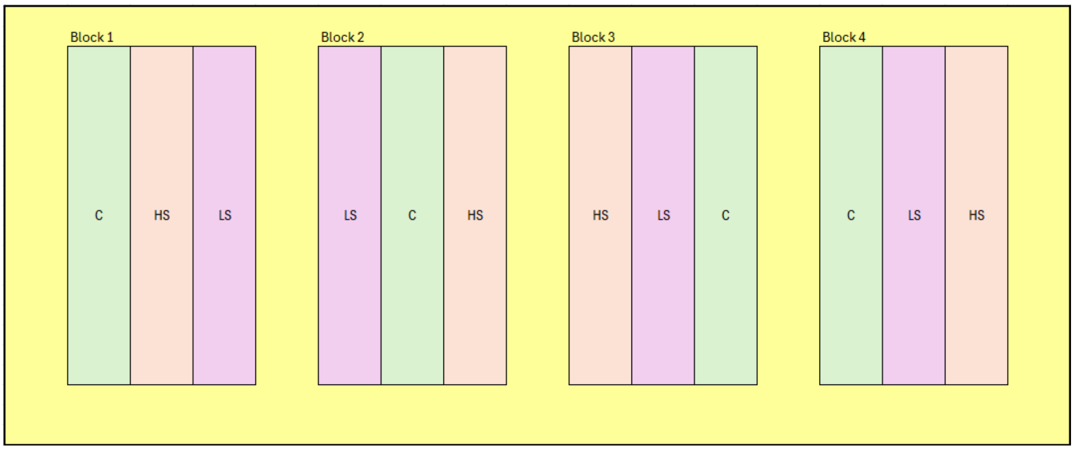

Figure 3: Illustration of the layout of the randomized block design.

2.2.1 Soil moisture and temperature sensors

Temperature and SWC were measured with “TMS4 Cable data loggers” (Tomst s.r.o., Prague, Czech Republic). In this field experiment, six sensors, two in each treatment, were used in Tärna, Munsö and Fyllingarum. Only four sensors could be used in Helsingborg due to accessibility issues before installation. The sensors were randomly placed in the treatments. They were installed by making a hole in the soil with a wooden stick and then pushing them into the soil (see Figure 4). The dates for the installation and uptake of the sensors are presented in Table 4.

Table 4: Dates of installation and uptake of TMS sensors and tea bags, together with the number of incubation days and of disturbed sensors. Treatments that are missing data in each field are also included in the number of disturbed sensors.

Farm	Date of installation	Date of uptake	Number of days	Number of disturbed sensors
Tärna	2025-08-26	2025-11-04	70	2 (LS, HS)
Munsö	2025-09-26	2025-11-06	41	4 (C, HS, both in LS)
Fyllingarum	2025-08-21	2025-11-10	81	4 (LS, HS, both in C)
Helsingborg	2025-08-20	2025-11-09	81	Non

The data was collected using Tomst Lolly software. Some of the sensors were removed from the soil by wild animals prior to the uptake date (as marked in Table 4). For these sensors, only the data that was still correctly measured was used. Therefore, some treatments lack data for parts of the measurement period, especially from the Munsö field. This was taken into consideration when analysing the results.

Figure 4: Data logger inserted in the soil

The data logger has three temperature sensors and one soil moisture sensor. The temperature sensors are positioned at different heights and are designed to capture the microclimate experienced by a small herbaceous plant (Wild et al. 2019). The data is collected every 15 minutes. The temperature sensors are located 8 cm down into the ground, by the soil surface and at the top of the cable (See Figure 5). The sensors have an accuracy of ± 0.5 °C in the range from 0 °C to 70 °C (Wild et al. 2019). The values from temperature sensor 1 (at 8 cm depth) were chosen as the most relevant for data processing in this field experiment (Figure 5).

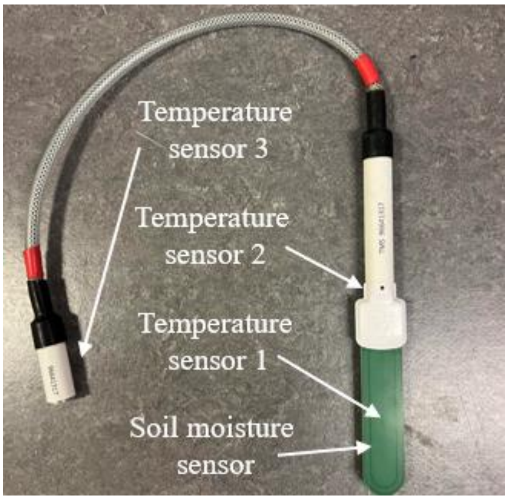

Figure 5: The locations of the soil temperature and moisture sensors on the data logger.

To visualize temperature differences more easily, mean soil temperature (°C) and accumulated soil temperature (°C·day) were used. Accumulated soil temperature reflects the soil's thermal response over time and integrates the temperature history more effectively than using daily means (Park et al. 2018). This was calculated as the cumulative sum of daily temperature from the T1 sensors (see Equation 1). $AST(t)$ is the accumulated soil temperature at time t (°C·day). T_i is the daily mean soil temperature on day i (°C) and t is the number of days since the start of the experimental period. The data were first summarized for each day, since measurements were recorded every 15 minutes (a total of 96 measurements per day).

The differences in accumulated temperature between treatments were calculated by subtracting the temperature value of the control treatment from that of the high stubble and low stubble treatments, respectively, for each field (Equation 2). The accumulated temperature was normalized to zero at the start of the measurement period of each site to facilitate comparison among treatments (Equation 3). This approach was used to visualize the long-term differences in soil temperature between treatments. Similar approaches have been used in previous studies (Zhang et al. 2022; Li et al. 2024).

$$\textit{Equation 1: } AST\ (t) = \sum_{i=1}^{t} T_i$$

$$\textit{Equation 2: } \Delta AST(t) = \sum_{i=1}^{t} \left(T_{treatment,i} - T_{control,i}\right)$$

$$\textit{Equation 3: } AST_{norm}\ (t) = \sum_{i=1}^{t} T_i - \sum_{i=1}^{1} T_i$$

The sensor that is measuring soil moisture is located at a depth of approximately 14 cm. The sensor measures the moisture by counting electromagnetic pulses. The number of pulses is directly related to the soil moisture. A higher soil moisture will reduce the number of pulses received. The counts are inverted and scaled into a numerical range of 1-4095. This relative value can later be transformed into volumetric soil water content through calibration (Wild et al. 2019).

The standard calibration for silt loam, developed by Wild et al. (2019), was used to convert the readings to volumetric soil water content. The calibration was chosen based on the values that gave the most realistic results for each soil. The calculation of the calibration was done in Excel using Equation 4, where *Hu* is the number of electromagnetic pulses. It should be noted that the calculated soil water content is based on a standard calibration and not on soil samples from each site. This may have caused an error in the estimated soil water content.

$$\textit{Equation 4: } Vol(\%) = (0.000000017 \times Hu^2 + 0.000118119\ \times Hu - 0.101168511) \times 100$$

Daily changes in soil water storage were calculated as the difference between consecutive days for each treatment and farm in mm (Equation 5). The absolute differences in mm and percentage points between the stubble height treatments and the control at time *t* were later calculated to quantify the potential effects of stubble height (Equation 6).

$$\textit{Equation 5: } \Delta W_{treatment}(t) = W_{treatment}(t) - \ W_{treatment}(t-1)$$

$$\textit{Equation 6: } \Delta W_{treatment-C} =\ W_{treatment}(t) - W_C(t)$$

To examine potential days with temperatures too low or SWC too high for plant development and decomposition, threshold values from the literature were applied. The temperature threshold was based on growing degree days for rapeseed and wheat, and was set to 5 °C (Kjellström 1993).

The threshold for water saturation was set at volumetric water content exceeding 40%, corresponding to an air-filled porosity below 5% when assuming a soil porosity of 45% (Villalobos & Fereres 2024). To plot these together with decomposition parameters, the proportion of days over 40% was calculated as the number of days with a SWC over 40%, divided by the total number of measured days.

2.2.2 Litter decomposition: Tea bag index (TBI) method

To measure litter decomposition across different stubble heights, the TBI (tea bag index) method was used. Two different types of tetrahedron-shaped tea bags by Lipton Unilever were used according to the protocol established by Keuskamp et al. (2013). Green tea has a high cellulose content, a lower C/N ratio and a higher soluble fraction, while rooibos tea has a high lignin content, a higher C/N ratio and a lower soluble fraction. The rooibos tea is therefore expected to have a slower decomposition rate (Keuskamp et al. 2013). The tea bag material is synthetic and has a mesh size of 0.25 mm, which allows microorganisms, very fine roots and root hairs to access the tea (Gmach et al. 2024).

A total of 96 green tea bags and 96 rooibos tea bags were used. All the tea bags were initially weighed, and the weight of an empty bag was subtracted from the total dry weight. For green tea, the tea bag content mean dry mass was 1.792 ±0.063 g and that for rooibos tea was 1.975 ± 0.040 g. All the tea bags were marked with a number to be able to compare the weight of the same tea bag after incubation.

Two green tea bags and two rooibos tea bags were placed in each plot on every field, approximately 10 cm deep (see Figure 6). A total of 48 tea bags were incubated in each field, and the spot was marked with a flag.

Figure 6: The placement of green and rooibos tea in each treatment and block.

According to the protocol by Keuskamp et al. 2013, the optimal incubation time for the tea bags is approximately 90 days. However, the tea bags in this experiment were collected after 41, 70 and 81 days (see Table 4). The incubation time for the tea bags was chosen depending on what was most practical. In the Fyllingarum field, the tea bags were incubated after harvest and were left in the soil when winter wheat was sown. For the other fields, a decision to install after sowing was made. But due to the weather, the decision not to drill the Munsö field was made later, resulting in a later installation date than the others. When the tea bags were collected, a few were lost, resulting in a total of 62 green tea bags and 67 rooibos tea bags available for calculations.

Using the collected data, the decomposition rate, *k*, and stabilisation factor, S (Keuskamp et al. 2013), were calculated for each treatment and field. The decomposition rate reflects the short-term microbial activity driven by soil temperature and moisture, whereas the stabilization factor represents the long-term carbon stabilization processes. The stabilization factor is less sensitive to short-term management effects (Keuskamp et al. 2013).

The decomposition rate of rooibos tea is lower than that of green tea. As a result, decomposition of labile material in rooibos tea will continue after all labile material in green tea has already been consumed (Gmach et al. 2024). Keuskamp et al. (2013) showed that the initial decomposition of green tea was fast and levelled off after 40-60 days. The decomposition of rooibos tea was much slower and was still decomposing after 90 days. The limit value of green tea is reached within the study period, allowing estimation of *S*. The labile fraction of rooibos was still actively decomposing during this period, allowing estimation of *k*.

To calculate *k,* Equation 7 is used, where *W(t)* is the weight of the substrate after incubation time *t*, *a* is the labile fraction and *1-a* is the recalcitrant fraction of the litter.

$$\text{Equation 7: } W(t) = ae^{-kt} + (1 - a)$$

W(t) is calculated as the fraction that is left after incubation from both the tea types through Equations 8 and 9. The mass of the dry green tea after incubation (m_{gd}) is divided by the initial mass of the tea (m_{g0}). The same applies to rooibos tea.

$$\text{Equation 8: } W_g(t) = m_{gd}/m_{g0}$$

$$\text{Equation 9: } W_r(t) = {}^{m_{rd}}/_{m_{r0}}$$

Parts of the labile compounds will stabilise and become recalcitrant during decomposition. The stabilisation depends on environmental factors such as temperature, moisture and litter quality (Berg & Meentemeyer 2002). The actual amount that becomes decomposed, the labile fraction *a,* is usually less than the amount that is chemically easy to break down, the hydrolysable fraction, *H*. The difference between the potential decomposition, *H* and the actual decomposition, *a* is the stabilisation factor, *S* (Equation 10).

$$\text{Equation 10: } S = 1 - a_g/H_g$$

The decomposable fraction (a_g) is calculated with $W_g(t)$ for green tea. It is estimated that only the recalcitrant fraction remains after the end of the incubation period, see Equation 11. The H_g is estimated to be 0.842 for green tea (Keuskamp et al. 2013).

$$\text{Equation 11: } a_g = 1 - Wg(t)$$

The S value and the hydrolysable fraction of rooibos tea can be used to calculate the decomposable fraction of rooibos tea, a_r. (Equation 12). This assumes that both the tea types have the same S. The hydrolysable fraction for rooibos tea is 0.552 (Keuskamp et al. 2013).

$$\text{Equation 12: } a_r = H_r(1 - S)$$

The $W_r(t)$ and a_r are known, therefore, k can be calculated using the exponential decay function given in Equation 7.

When tea bag data were missing from the data set, values from other tea bags were used instead to make the calculations. For example, in one replicate, only one green tea bag was found but two rooibos tea bags. Then the value of the green tea bag was used together with each value from the rooibos tea.

2.2.3 Microbial respiration: MicroResp

Soil microbial activity was assessed using the MicroResp method, developed by Campbell et al., (2003). This method was used to get a better insight into the functional characteristics of the soils at the different farms. It measures carbon dioxide (CO_2) production from the whole soil after addition of different carbon substrates. The method is a colorimetric technique with two microplates, one deep-well plate containing soil samples and carbon substrates and one detection plate containing an indicator gel. The released CO_2 causes a pH change in the indicator gel, creating a change of color that can be quantified using a microplate reader. The intensity of the color change reflects the microbial respiration rate and the ability of the soil microbial community to utilize different carbon sources (Campbell et al. 2003; Chapman et al. 2007; Onica et al. 2018). The MicroResp measurements were performed by SLU soil lab.

2.2.4 Crop biomass

For the fields that had been direct-drilled, the early biomass of the sown winter crop was measured. This was done by placing three 0,5 m x 0,5 m squares at random within each treatment and block. The crops that were in the square were then cut with a grasscutter and placed in marked paper bags. The bags were then transported to the laboratory for drying. Biomass collection was conducted on the same day as the placement of sensors and tea bags (Table 4). Any leftover straw or weeds were sorted out from the crops. The rye and rapeseed were later dried in an oven at 70 °C for 48h, while the wheat was placed in a drying room at 40 °C for 72 h. This was done due to a lack of time and oven space. Each crop was then weighed after being completely dried.

2.2.5 Plant development of rapeseed

To get a better understanding of how different stubble heights and residues on the soil surface affected the plant development. Rapeseed was chosen as a suitable crop to analyse. When the biomass was collected, two rapeseed crops from each square were also collected by dragging them up (including the roots). Six plants were collected from each block and treatment, giving a total of 24 collected plants per treatment. The plants were collected in marked paper bags and brought to the laboratory to be examined. Stem diameter, the height of the growth point and the plant length were measured, and the number of leaves was counted before they were placed in paper bags together with the rest of the collected biomass. The measurements were done with a ruler. How the height of the growth point was measured can be seen in Figure 7. The length of the plant was measured from the root collar up to the longest tip of the leaf. The stem diameter was measured at the thickest point.

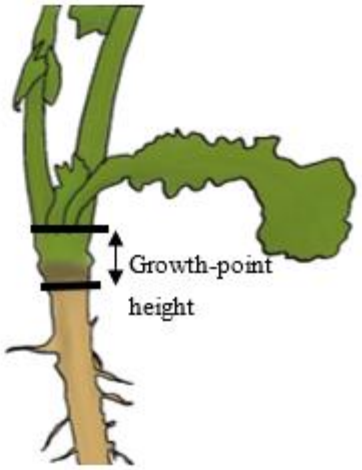

Figure 7: The position of the growth-point. Illustration by Kollberg 2026.

2.3 Statistical analysis

All statistical analyses were performed using RStudio (version 2026.01.0; R version 4.5.2). Data were analysed primarily using linear mixed models. This was done to account for the experimental design and repeated measurements over time and space.

For the analyses of soil temperature, soil water content, decomposition parameters and plant development, treatment was used as fixed effect. Random effects were selected for each dataset based on its structure to account for repeated measurements. Date was included as a random effect for time-series data (soil temperature and soil water content) to account for temporal variability. Farm was included as a random effect when the aspect of the multiple sites was considered. For plant development, replicate and sampling plot (nested within replicate) were included as random effects to account for the hierarchical sampling structure.

Soil water content and soil temperature were analysed separately for each farm, whereas decomposition parameters were additionally analysed across farms using models that included farm as random effect.

When significant treatment effects were found, pairwise comparisons between treatments were conducted using Tukey´s post hoc test. Estimated marginal means and associated standard errors were calculated for all treatments.

In cases where mixed-effects modelling was not required by the data structure, one-way analysis of variance (ANOVA) or simple linear regression was applied. One-way ANOVA was used to analyse biomass data and decomposition parameters at individual farms. Linear regression was used to examine the relationship between decomposition parameters and soil conditions. It was also used to assess whether there was a relationship between stubble height in general and soil temperature, soil water content, and decomposition parameters. All statistical tests were conducted at a 95% confidence interval.

Principal component analysis (PCA) was used to explore differences in microbial activity between farms based on the MicroResp substrate respiration data. The values were standardised using a Hellinger transformation to reduce the influence of large values. The PCA was performed using the “prcomp” function in R.

3. Results

3.1 Basic Soil Properties

The studied agricultural soils are dominantly Cambisols (FAO 1980). Tärna and Fyllingarum were identified as having a silt loam texture. Munsö and Helsingborg had a higher sand content and were classified as sandy loam. Particle sizes, pH, total N, total C and organic C for the different farm fields can be found in Table 5.

Table 5: Particle size distribution, pH, amount of total N, total C and organic C in %.

Farm	Sand (%)	Silt (%)	Clay (%)	pH-H2O	Tot-N(%)	Tot-C(%)	Org-C(%)
Tärna	22	57	21	6.1	0.16	1.7	1.7
Munsö	56	25	19	6.6	0.15	1.6	1.6
Fyllingarum	24	50	26	6.4	0.21	2.4	2.4
Helsingborg	69	25	6	6.7	0.20	2.2	2.2

3.2 Soil temperature

Soil temperature differed between treatments across farm fields during the measurement period. The treatment effect developed over time and varied among the four fields, resulting in site-specific cumulative temperature deviations related to the control. The results of the Tukey-adjusted pairwise comparisons and estimated marginal means for each treatment in each field are presented in Table 6.

Table 6: Estimated marginal means (°C ± SE) of soil temperature for each treatment and field over the measurement period, derived from linear mixed models to account for day-to-day variation. Means that share the same letter within a farm are not significantly different (Tukey-adjusted pairwise comparisons, α = 0.05).

Farm	Treatment	Stubble height (cm)	Soil temperature (°C) ± SE	Group (Tukey)
Tärna	C	15	10.1 ± 0.51	a
	HS	20	10.0 ± 0.51	a
	LS	10	10.1 ± 0.51	a
			n.s	
Munsö	C	25	9.0 ± 0.24	b
	HS	50	8.5 ± 0.24	a
	LS	15	8.6 ± 0.26	a
			p= < 0.001	
Fyllingarum	C	25	10.6 ± 0.42	ab
	HS	40	10.5 ± 0.42	b
	LS	20	10.6 ± 0.42	a
			p= 0.019	
Helsingborg	C	15	12.6 ± 0.38	c
	HS	30	12.3 ± 0.38	a
	LS	10	12.5 ± 0.38	b
			p= < 0.001	

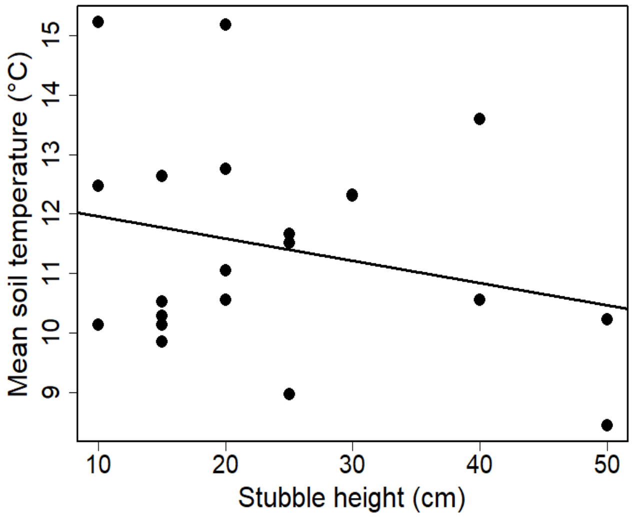

Figure 8: Relationship between plot-level mean soil temperature and stubble height (cm) across all fields. Each point represents the plot mean temperature for each height and replicate over the measurement period. The line shows the fitted linear regression.

The relationship between stubble height and soil temperature, across all fields, is illustrated in Figure 8. The linear regression shows a weak non-significant (p =

0.269) decreasing trend with increasing stubble height. The fitted regression indicated a small negative slope (-0.037 °C per cm), meaning that for every 10 cm increase in stubble height, the mean temperature would be 0.37 °C lower. However, stubble height did not significantly explain the variation in mean soil temperature ($p = 0.269$), and the explained variance was low ($R^2 = 0.064$). Figure 9 shows the accumulated soil temperature (ΔAST) of low stubble and high stubble treatments relative to the control for each farm's field. The accumulated soil temperature, without the comparison, can be found in Figure S1.

For Tärna, no significant treatment effect was observed. Both LS and HS initially showed negative values during early September, indicating cooler soil temperatures relative to the control. Later, LS gradually increased and reached positive ΔAST by the end of October, while HS remained below zero.

At Munsö, soil temperature differed significantly between treatments ($p = <0.001$). ΔAST showed declining values over time, reaching strongly negative values by early November. This indicates that HS experienced consistently cooler conditions throughout the measurement period. LS and HS showed the same trend until the LS data were lost.

The Fyllingarum field showed a less significant effect on soil temperature ($p = 0.019$). During September, ΔAST for HS decreased profoundly, reaching a minimum in early October. In contrast, LS showed a positive ΔAST for most of the measuring period, indicating warmer temperatures than the control. The divergence between LS and HS increased over time. Tukey-adjusted pairwise comparisons showed a significant treatment effect. HS was significantly cooler than LS ($p = 0.0169$), whereas the control did not differ from any of them.

Soil temperature also differed significantly between treatments in Helsingborg ($p<0.001$). Both treatments in Helsingborg showed a rapid decrease in ΔAST during early autumn. However, LS started to come closer to the control later in the season, while HS continued to decline. This resulted in a clear separation between treatments by the end of the measurement period.

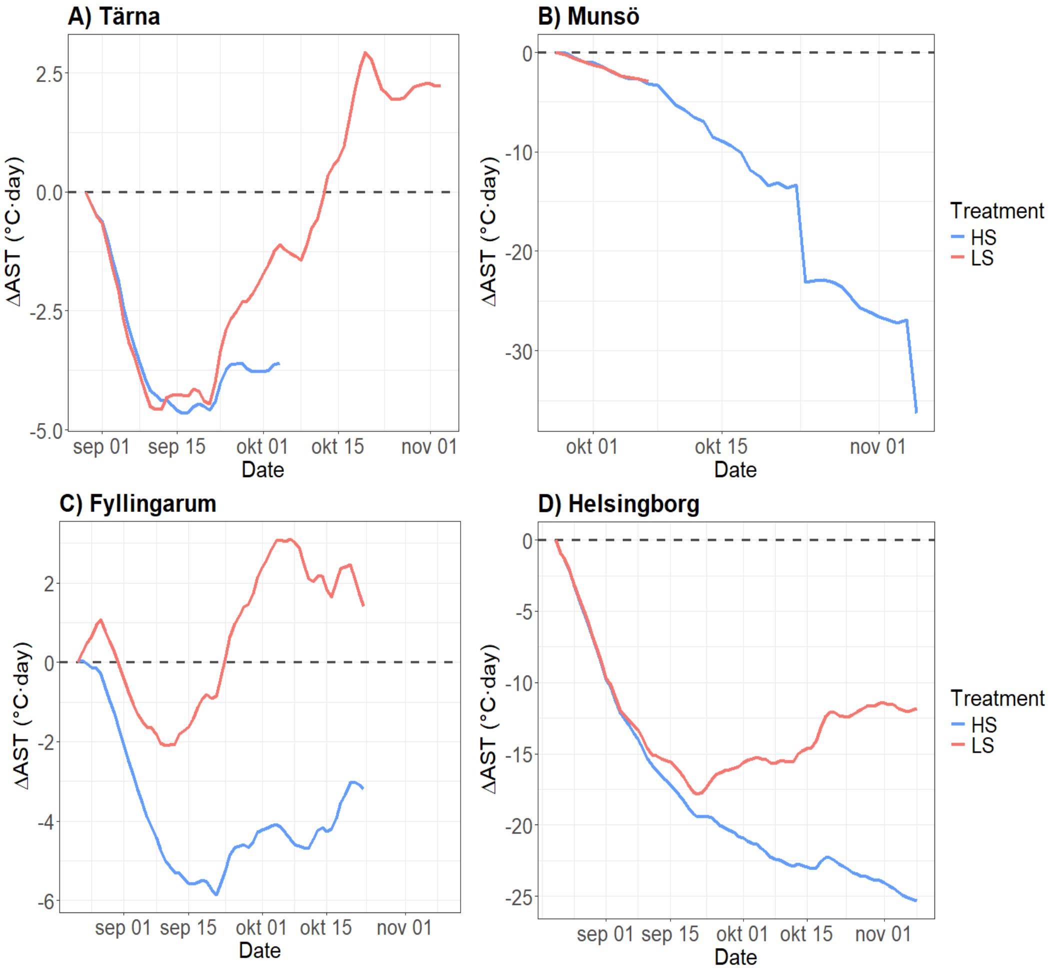

Figure 9: Accumulated soil temperature difference (Δ °C·day) between treatments with high stubble with straw (HS), low stubble with straw (LS), relative to control (C) at four field sites (A)Tärna, (B) Munsö, (C) Fyllingarum, (D) Helsingborg. Accumulated temperature was calculated as the cumulative sum of daily mean soil temperature and was normalised to zero at the start of the measurement period for each site. Positive values indicate higher accumulated soil temperature compared to the control, while negative values indicate lower accumulated soil temperature. The dashed horizontal line represents no difference relative to the control. Some of the lines end early due to a lack of data.

3.3 Soil water content

Soil water content (SWC) significantly differed between treatments at each farm's field ($p<0.05$). However, the magnitude of these differences varied between sites, but remained consistent over time. The differences in mean SWC and net water gain are presented in Table 7. Low stubble resulted in higher soil water content at Fyllingarum and Helsingborg, while the control had the highest values at Tärna. Differences between stubble heights were smaller and less consistent at Munsö. The linear regression between stubble height and soil water content showed no significant trend, see Figure S2.

Table 7: Mean soil water content (% ± SE) and net water gain (mm) for different stubble height treatments at four fields. The treatment effect was analysed using linear mixed models, with date as random effect, per farm. Net water gain is the sum of the changes in water storage during the study period in mm. Different letters indicate significant differences between treatments according to Tukey´s test (α = 0.05).

Farm	Treatment	Stubble height (cm)	Soil water content (%) ± SE	Net water gain (mm)	Group (Tukey)
Tärna	C	15	40.0 ± 0.51	17.9	a
	HS	20	39.5 ± 0.73	0.86	ab
	LS	10	38.9 ± 0.63	19.2	b
			p = 0.0026		
Munsö	C	25	39.5 ± 0.73	10.9	ab
	HS	50	40.5 ± 0.72	8.4	a
	LS	15	38.4 ± 0.95	11.7	b
			p = 0.0108		
Fyllingarum	C	25	35.1 ± 0.47	3.5	a
	HS	40	35.3 ± 0.31	11.9	a
	LS	20	39.3 ± 0.43	5.3	b
			p < 0.001		
Helsingborg	C	15	27.6 ± 0.83	15.7	a
	HS	30	28.3 ± 0.82	22.8	ab
	LS	10	33.8 ± 0.83	24.3	c
			p < 0.001		

Figure 10 illustrates the differences in SWC between low stubble (LS) and high stubble (HS) compared to the control. The difference relative to the control in millimetres can be found in Figure S3. The patterns over time largely correspond with the treatment effects identified in the linear mixed models (Table 7). The daily mean soil water content in percent and millimetres for all the treatments, without comparison, is illustrated in Figures S4 and S5.

At Tärna, both stubble treatments frequently showed negative values, indicating a lower SWC relative to the control. This is consistent with the statistical analysis, in which the control treatment had a significantly higher mean SWC than LS, while HS showed intermediate values.

Munsö showed smaller and more variable differences over time. LS stayed close to the control, whereas HS showed positive and negative deviations throughout the study period. Accordingly, the statistical difference between treatments was weak. There was only a significant difference between LS and HS.

At Fyllingarum, LS were consistently positive relative to the control, during most of the measuring period, while HS gradually increased from negative to positive values later in the fall. LS showed a significantly higher SWC compared to both C and HS.

The LS treatment in Helsingborg also showed strong and persistent positive values compared to the control, unlike HS, which remained closer to the control throughout the period. This is consistent with the statistical results, in which LS had a significantly higher mean SWC than both C and HS.

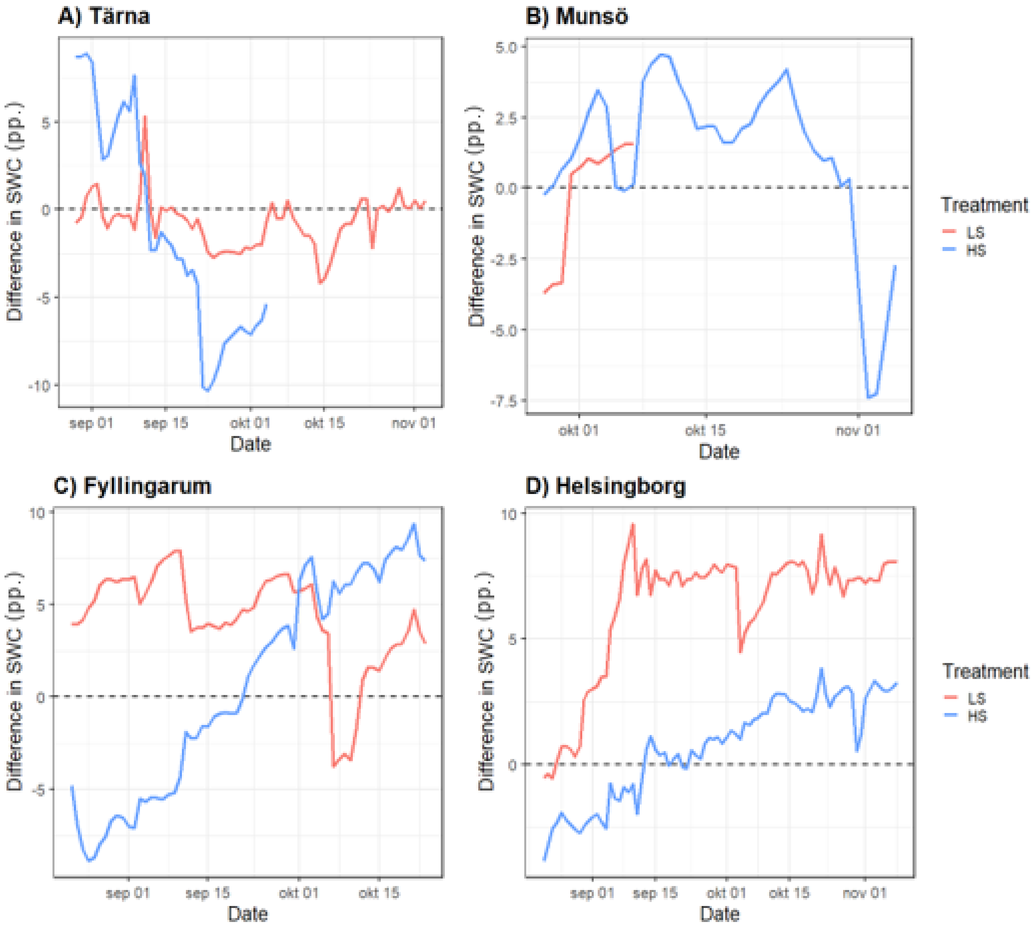

Figure 10: Difference in soil water content (Percentage points) between the low stubble (LS) and high stubble (HS) treatments relative to the control (C) at four different fields. The dashed line represents the control, set to zero. Positive values indicate a higher SWC compared to the control, while negative values indicate lower SWC relative to the control. Some lines end early due to a lack of data.

3.4 Decomposition

For decomposition parameters such as decomposition rate (k) and stabilization factor (S), no significant differences between treatments ($p > 0.05$) were observed within individual farm fields. However, a small trend towards treatment effect on k was observed at Tärna ($p = 0.06$) as well as a weak treatment effect on S at Fyllingarum ($p = 0.07$).

Decomposition rate and stabilisation factor varied substantially across fields, and the differences between stubble height treatments were small and inconsistent. This is illustrated by the separation of farm-specific symbols in Figure 11. In addition, the mixed-effects model confirmed that there were no significant treatment effects on either k or S ($p > 0.05$), which was consistent with the within-farm analyses. Instead, farm-level differences dominated the variation in both k and S. In addition, the linear regressions for stubble height and k/S showed no significant trend (Figure S6).

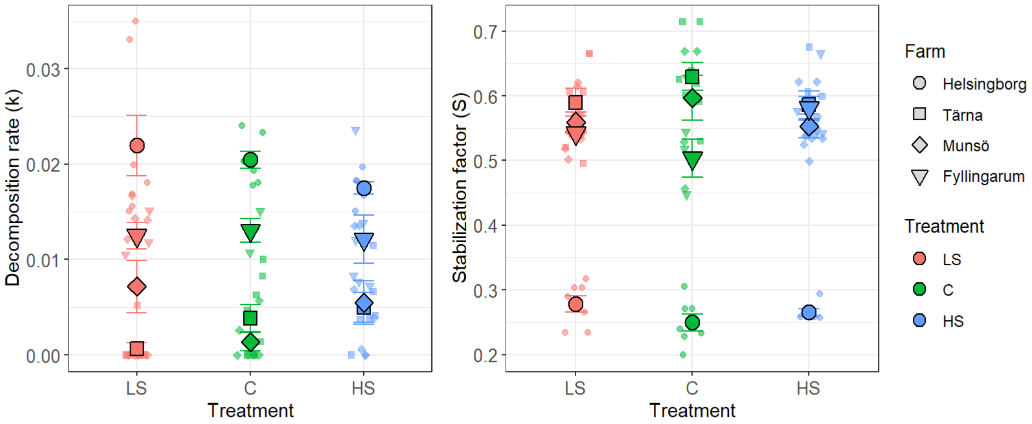

Figure 11: Decomposition rate, k (left) and stabilisation factor, S (right) across stubble height treatments (LS= low stubble with straw, C=Control, HS=high stubble with straw) at four farm fields (Helsingborg, Tärna, Munsö and Fyllingarum). The small, transparent symbols represent individual observations. Large symbols with black outlines show mean values per farm and treatment, with error bars indicating ± standard error (SE). The symbol shape represents the different farm fields, while symbol colour represents treatment.

3.4.1 Decomposition and soil conditions

Soil temperature and moisture were analysed, along with decomposition parameters, to assess whether changes in soil conditions influenced litter decomposition. Decomposition rate and stabilization factor, derived from TBI, were related to accumulated soil temperature during the measurement period, as well as to soil moisture conditions, expressed as the proportion of days with high SWC. Together, these analyses provided insight into how thermal conditions and the occurrence of potentially water-saturated periods affected the decomposition and stabilization of organic matter across fields and different stubble heights.

Soil temperature

Accumulated soil temperature is related to k and S in Figure 12. The figure shows a non-linear increase in k and a non-linear decrease in S as accumulated soil temperature increases. Linear mixed-models showed that the relationship between temperature and decomposition was not statistically significant when farm-level variation was accounted for (p >0.05 for both k and S). To account for differences in incubation time between fields, accumulated soil temperature per day was illustrated (Figure S7). However, this showed a similar trend as in Figure 12.

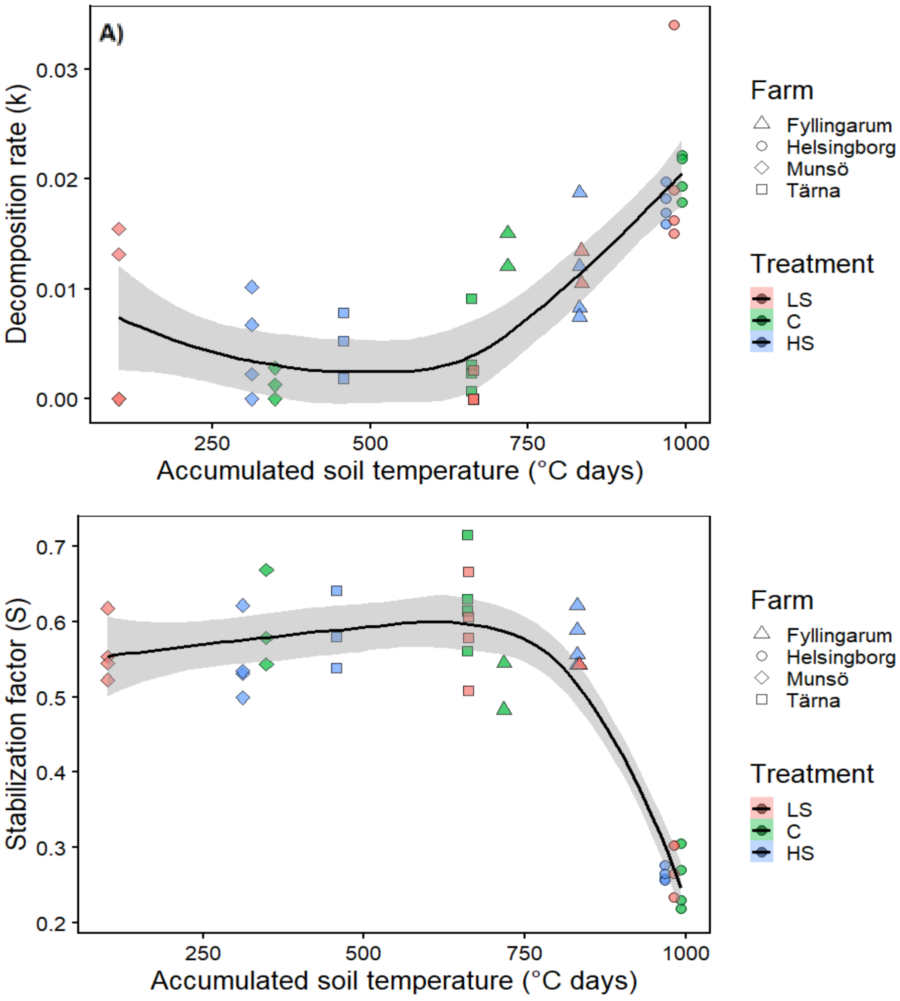

Figure 12: Relationship between accumulated soil temperature (°C·day) and decomposition parameters derived from TBI from four fields. The panel A) shows the relationship between accumulated soil temperature and decomposition rate (k), while B) shows the relationship between accumulated soil temperature and stabilization factor (S). Points represent individual replicates, symbols indicate fields, and colours indicate treatments (LS=low stubble, C= control, HS= high stubble). The solid line shows the trend, and the shaded area indicates the 95% confidence intervals.

Soil moisture

The effect on decomposition parameters when SWC was higher than 40% are illustrated in Figure 13. Decomposition rate, k, decreased significantly with an increasing proportion of days with SWC over 40% ($p = 0.0038$, $R^2 = 0.58$). In contrast, stabilization factor, S, increased significantly with increasing exposure ($p = 0.0018$, $R^2 = 0.64$). This indicates a shift from rapid decomposition towards enhanced stabilisation of organic matter under wetter soil conditions. Although there is an overall trend between wetness and decomposition parameters, variation in k and S was observed between farm fields, reflecting differences in site-specific conditions.

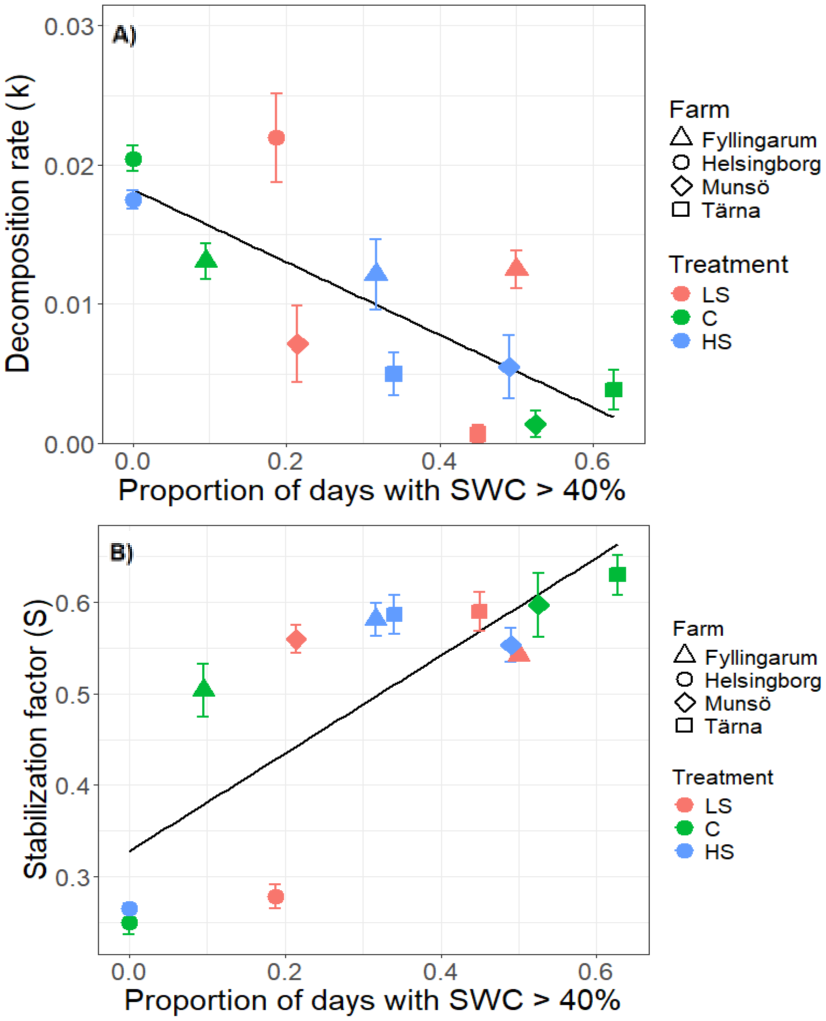

Figure 13: The relationship between the proportion of days with SWC over 40% and decomposition parameters derived from TBI from four fields. Decomposition rate (k) is shown in panel A) and stabilization rate (S) are shown in panel B). Colours represent treatments LS (low stubble), C (control), HS (high stubble), while symbols represent farms. Points are mean values per farm and treatment, with error bars indicating standard error (SE). Solid black line shows linear regression fits across all farms and treatments.

3.4.2 Soil microbial community

The PCA revealed differences in how the microorganisms used the different substrates among the farm fields (Figure 14). The first principal component (PC1) explained 71.1 % and the second principal component (PC2) explained 21.4%, in total 92.5% of the variation. Helsingborg was separated from the other fields, primarily along the PC1 and was associated with cysteine (CYST) as substrate. Tärna was instead located in the negative side of PC1 together with ascorbate (ASCORB) and keto acids (KETO). Munsö and Fyllingarum were clustered closer together. Fyllingarum was slightly more associated with fructose (FRUCT) and galactose (GALACT) on the positive side of PC2.

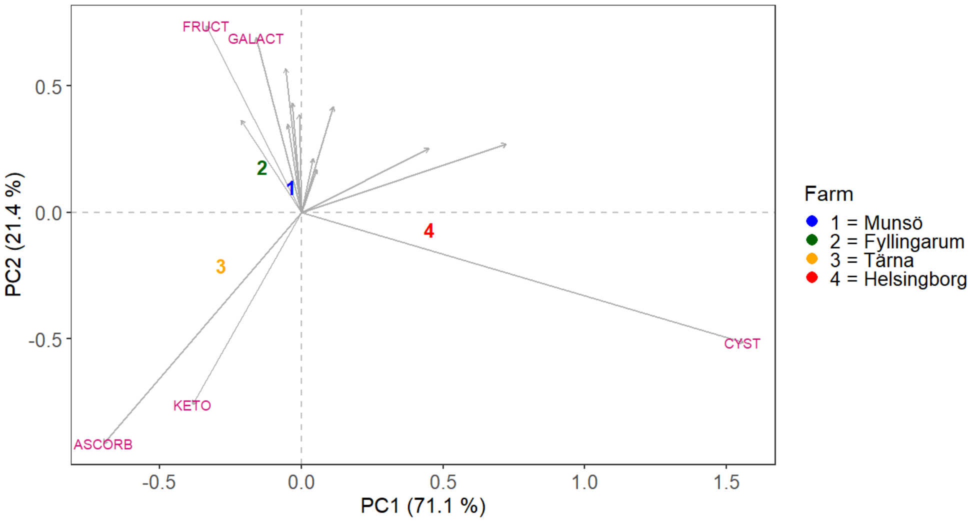

Figure 14: Principal component analysis (PCA) of microbial substrate utilisation patterns based on MicroResp data from four farm fields. Numbers represent fields: 1= Munsö, 2= Fyllingarum, 3= Tärna, 4= Helsingborg. Arrows represents subrates. Longer arrows indicate a stronger contribution to the differences between farms. The two principal components explained 71.1% (PC1) and 21.4% (PC2) of the total variation.

3.5 Crop biomass and plant development

Aboveground biomass differed between stubble heights to some extent. A significant treatment effect was observed for wheat, but not for rye or rapeseed. This can be seen in Figure 15, where wheat biomass was lower with low stubble than with high stubble and the control. Biomass values for rye and rapeseed instead show an overlap among treatments. However, low stubble never has the highest biomass for any of the crops.

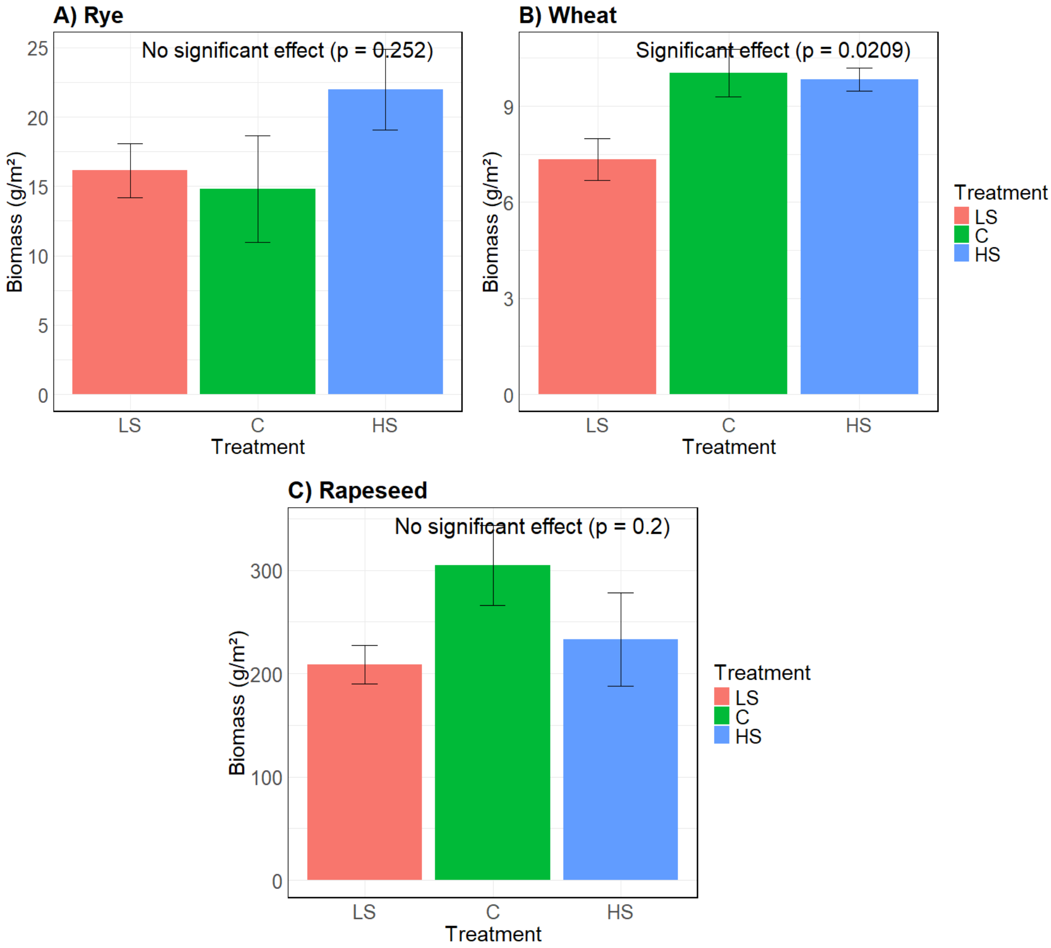

Figure 15: Mean aboveground biomass (± SE) for different stubble height treatments (LS=low stubble, C= control, HS= high stubble) in A) Rye, B) Wheat and C) Rapeseed. One-way ANOVA showed a significant treatment effect for wheat (p = 0.0209) but not for rye or rapeseed (p > 0.05).

The statistical analysis confirmed these observations (see Table 8). One-way ANOVA analyses showed a significant treatment effect for wheat (p=0.0209), but no significant differences for rye or rapeseed (p > 0.05). The Tukey´s HSD test for wheat showed that LS had significantly less biomass than both C and HS.

Table 8: Mean aboveground biomass (± SE) for each stubble height treatment and crop. Treatment effects were tested using one-way ANOVA, followed by Tukey´s HSD test when significant. Treatments sharing the same letter do not differ significantly (α = 0.05).

Crop	Farm	Treatment	Stubble height (cm)	Biomass (g/m^2) ± SE	Group (Tukey)
Rye	Tärna	C	15	14.8 ± 3.84	a
		HS	20	22.0 ± 2.91	a
		LS	10	16.1 ± 1.94	a

				n.s	
Winter wheat	Fyllingarum	C	25	10.0 ± 0.74	a
		HS	40	9.8 ± 0.37	a
		LS	20	7.3 ± 0.65	b
				p = 0.0209	
Winter oilseed rape	Helsingborg	C	15	304.7 ± 38.63	a
		HS	30	233.2 ± 45.16	a
		LS	10	208.5 ± 18.64	a
				n.s	

3.5.1 Crop biomass and soil conditions

To assess whether a change in microclimate influenced crop biomass, soil temperature and SWC were analysed for the two cash crops (winter wheat and rapeseed). Daily mean soil temperature and SWC were examined over the measurement period to identify growth-limiting periods using biologically motivated thresholds. Potential differences between stubble height treatments were also considered.

Temperature

Daily soil temperature progressively decreased over the autumn months at both fields (Figure 16). For Fyllingarum, where winter wheat was sown, soil temperatures were highest around the seeding date (21 September), then decreased towards October. A pronounced drop in temperature occurred in mid-October, falling below the 5 °C threshold for a few days. After, temperatures remained over the threshold and stayed relatively low into November.

For Helsingborg, where rapeseed was sown, a similar pattern was observed. But soil temperatures remained above the threshold throughout the measurement period. The temperatures were overall higher and more stable during late autumn than in winter wheat.

Differences between treatments were negligible and therefore not illustrated.

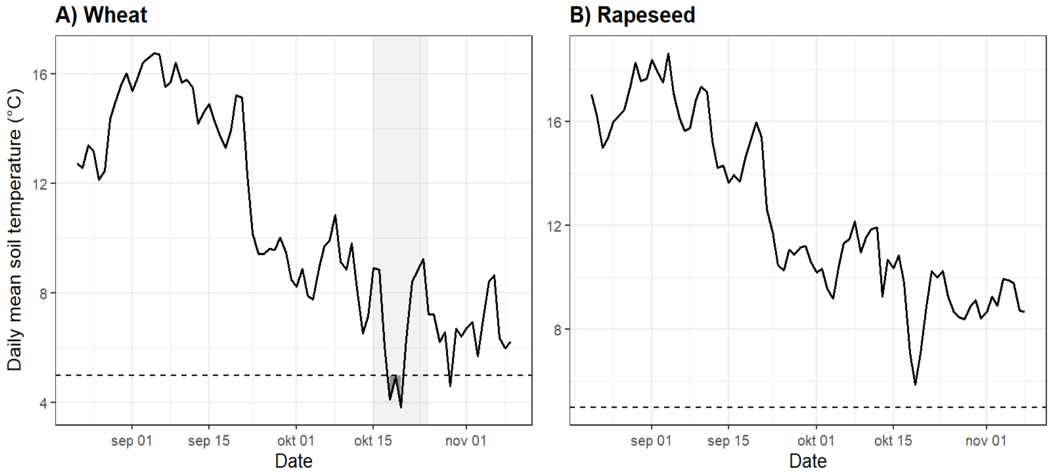

Figure 16: Daily mean soil temperature (℃) during the autumn study period for A) Fyllingarum (Wheat) and B) Helsingborg (Rapeseed). The values represent daily averages per treatment and replicate. The dashed line indicates a temperature threshold of 5 ℃. The grey area in panel A highlights a period under the threshold.

Soil moisture

Daily mean SWC varied over time and between stubble heights in both crops (Figure 17). For winter wheat, SWC generally ranges between 30-45%. The control showed relatively stable SWC throughout the measurement period, with one short period in mid-September exceeding the threshold. HS showed a higher SWC than the control. Several periods exceeded 40% in October, with the longest lasting from the beginning to the middle of the month. In contrast, LS was also higher than the control, but at different periods than HS. SWC was over 40% in September and again in late October to early November, separated by a period of lower SWC in late September.

In rapeseed, SWC levels were lower than in wheat but showed similar tendencies. The control and HS stayed below 40% throughout the period. However, HS showed consistently higher SWC values than the control, approaching the threshold in the latter part of the period. LS reached even higher SWC values, staying close to or above the threshold in late October and early November.

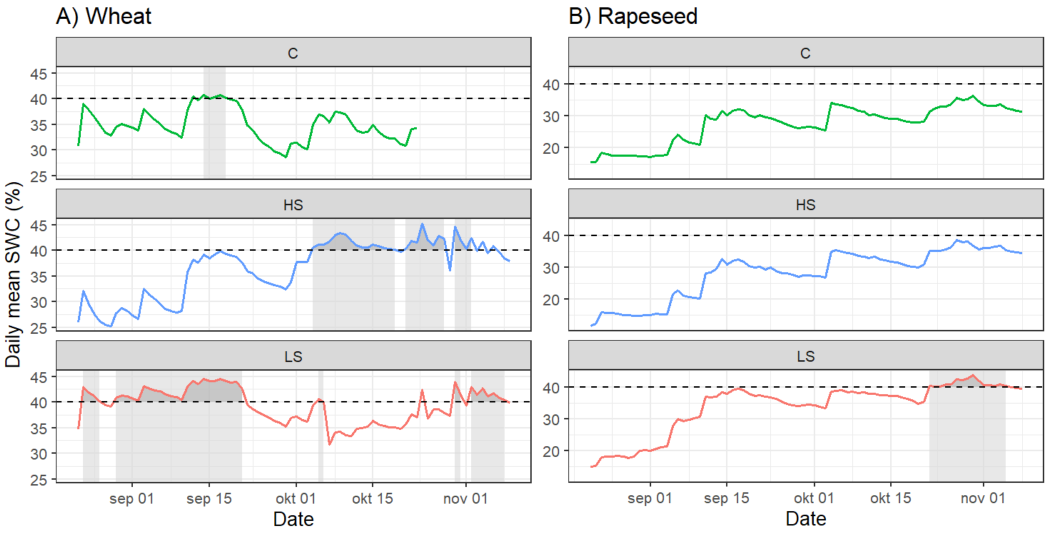

Figure 17: Daily mean soil water content (SWC) during the autumn study period for A) wheat and B) rapeseed under three stubble heights (C = control, HS = high stubble, LS = low stubble). Values represent daily averages. The dashed line indicates a soil water content of 40%. The grey shaded areas mark periods when SWC exceeded the threshold.

3.5.2 Plant development of rapeseed

The effect of stubble height on the plant development of rapeseed was weak (Table 9). Stem thickness and growth-point height showed a tendency to be affected by treatment (p = 0.072, p = 0.083). Plants in HS were thinner than those in the control, but no significant difference was observed for LS and the control. In addition, the growth point in LS tended to be lower than in the control, but no significant difference was found between HS and the control. In contrast, the number of leaves and plant length were not significantly affected by a difference in stubble height.

Table 9: Mean values (± SE) of rapeseed plant traits under different stubble height treatments (C = control 15 cm, HS = high stubble 30 cm, LS = Low stubble 10 cm) in Helsingborg.

Trait	Treatment	Mean ± SE	Group (Tukey)*
Stem thickness (cm)	C	2.49 ± 0.16	a
	HS	1.97 ± 0.16	a
	LS	2.23 ± 0.16	a
Growth-point height (cm)	C	1.69 ± 0.09	a
	HS	1.66 ± 0.09	a
	LS	1.43 ± 0.09	a
Plant length (cm)	C	45.40 ± 1.76	a
	HS	43.92 ± 1.76	a
	LS	42.50 ± 1.76	a
Amount of leaves	C	7.54 ± 0.31	a
	HS	7.42 ± 0.31	a
	LS	7.83 ± 0.31	a

* No significant pairwise differences were detected (Tukey-adjusted post hoc test).

4. Discussion

This field study examined how variation in stubble height and straw residues influences soil microclimate and decomposition dynamics during early crop establishment in Swedish no-till systems. Overall, the effects of stubble height are modest and site-specific. In contrast, differences between farm fields in climate and soil texture partly explained the variation in soil temperature, soil water content and decomposition parameters. The following sections discuss the potential mechanisms behind these patterns and their agronomic implications under Nordic conditions.

4.1 Stubble height effects on soil microclimate in no-till systems

4.1.1 Soil temperature

Across sites, soil temperature generally decreased with increasing stubble height, although the magnitude of this effect was modest (Figure 8). The linear regression indicated a small negative slope (-0.37 °C per 10 cm increase in stubble height) and treatment effects were only statistically significant in some fields (Table 6). This suggests that standing stubble modified the soil surface energy balance, although to a limited extent.

The lower temperatures under high stubble (HS) are consistent with previous findings (Aase & Siddoway 1980; Cutforth & McConkey 1997) and can likely be explained by increased albedo. A tall stubble reflects and intercepts incoming solar radiation, thereby reducing the amount of energy reaching the soil surface. In addition, shading reduces daytime heating and these processes can dampen soil temperature fluctuations.

In contrast, the low stubble (LS) showed a more dynamic response. LS was initially cooler than the control at some sites but later became warmer than either the control or HS later in the season (Figure 9). This pattern likely reflects the greater amount of chopped straw left on the soil surface in LS. A greater amount of residues functions as an insulating layer, reducing heat loss from the soil and buffering short-term temperature fluctuations (Onwuka 2018; Sharma & Kumar 2023). Insulation may become more influential as temperatures decline later in the season, which could explain the warmer late-autumn temperatures.

The magnitude of the treatment effects was strongly site-specific. Helsingborg showed the clearest and most consistent temperature differences between treatments, whereas Tärna showed no significant effect. This variation likely reflects differences in soil texture, climatic conditions and differently defined stubble heights. A high stubble in Helsingborg was not the same as in Tärna, for example (Table 3). This limits the ability to compare effects across farm fields.

A sandy loam (Helsingborg and Munsö) may have responded more rapidly to changes in surface cover due to higher thermal conductivity and lower water-holding capacity. In contrast, the silty loam in Tärna and Fyllingarum likely buffered temperature changes due to higher moisture retention (Hillel 2004; Villalobos & Fereres 2024).

Furthermore, accumulated soil temperature differed between the sites, largely following a latitude gradient. This indicates that variation in macroclimate had a stronger influence on soil thermal conditions than stubble height alone.

Overall, the results show that stubble height can influence soil temperature in no-till systems, likely through shading or insulation mechanisms. However, under Swedish autumn conditions (cold and moist), these effects are modest.

4.1.2 Soil moisture

Significant treatment effects on soil water content were detected across all fields, yet the magnitude of these effects varied among sites. This indicates that stubble height and residue management influenced soil moisture, but that the response was highly dependent on local soil and climatic conditions.

At Fyllingarum and Helsingborg, LS resulted in consistently higher SWC compared with both the control and HS. In contrast, at Tärna the control often showed the highest SWC, whereas at Munsö the differences were less consistent and harder to interpret due to missing data (sensor removal by wild animals). These contrasting patterns imply that residue amount may have played a more prominent role than stubble height alone. The LS treatment retained more chopped straw on the soil surface, likely reducing evaporation and enhancing infiltration, thereby increasing soil water storage (Blanco-Canqui & Lal 2009).

High stubble (HS) can also reduce evaporation by increasing aerodynamic resistance and shading the soil surface (Aase & Siddoway 1980; Cutforth & McConkey 1997). However, the present results indicate that the insulating effect of chopped residues in LS may have been more influential than only standing stubble in modifying soil moisture.

The inconsistent responses across sites further highlight the importance of soil texture and drainage conditions. Sandy loam soils, such as those in Helsingborg and Munsö, drain more rapidly and have lower water-holding capacity than silty loam soils (Villalobos & Fereres 2024). In such soils, surface residues may significantly reduce evaporation losses and thus increase SWC. This may explain why increased SWC under LS was most pronounced at Helsingborg. In contrast, finer-textured soils with higher capacity to retain water may be more prone to waterlogging during wet periods if more residues are added. Fyllingarum had, for example, more and longer periods of a high SWC (Figure 17).

Importantly, the proportion of days exceeding the 40% SWC threshold varied substantially among sites and treatments. Higher soil moisture levels may cause oxygen limitation and create less optimal conditions for both microbial activity and root growth. Thus, while residue retention can increase water conservation under drier conditions, it may also increase the risk of temporary water saturation in wetter environments.

Methodological weaknesses must also be considered when interpreting the SWC results. The use of a standard calibration across soils with differing textures and bulk densities may have introduced consistent errors. In addition, the limited number of sensors per treatment increases sensitivity to local soil moisture variability (i.e., within a specific plot). Nevertheless, the consistent treatment patterns observed at certain sites suggest that the overall trends are robust. Study limitations are further discussed in section 4.5.

In summary, stubble height and residue management influenced soil water content, but the effects were strongly site dependent. Residue amount appeared to have a greater impact than standing stubble height alone, and soil texture and drainage conditions largely determined whether increased residue cover increased the risk of saturation. These findings show that residue management strategies in no-till systems must be adapted to local soil hydrological characteristics.

4.2 Soil biological activity and decomposition

No consistent treatment effect of stubble height was detected within or across fields on decomposition rate (k), nor stabilization factor (S). Instead, variation between sites dominated over variation between treatments, indicating that soil temperature, water conditions and litter availability were the primary drivers of decomposition during the autumn measurement period. Furthermore, the role of microbial community differences could also have been important. This suggests that short-term adjustments in surface residues may have a limited influence compared to other environmental and biological factors.

Although treatment effects were statistically non-significant, distinct differences in decomposition parameters were observed among fields. Helsingborg exhibited the highest k values and lowest S values, whereas Munsö and Tärna showed the lowest decomposition rates (Figure 12). These site-specific patterns corresponded closely with accumulated soil temperature and soil moisture conditions. Helsingborg had the highest accumulated soil temperature and the lowest proportion of days exceeding the 40% SWC threshold, indicating more aerated soil conditions. This is consistent with previous research indicating that decomposition is maximized under warm, moderately moist conditions (Sierra et al. 2015).

Across all sites and treatments, the proportion of days with SWC above 40% was strongly associated with reduced decomposition rates and increased stabilization (Figure 13). The negative relationship between high soil moisture and k ($R^2 = 0.58$), together with the positive relationship with S ($R^2 = 0.64$), suggests that oxygen limitation during wetter periods constrained microbial activity. These data are supported by the findings of Sierra et al. (2015), which show that decomposition is highest under intermediate moisture conditions but declines sharply if soils approach saturation or drying. Thus, stubble height may indirectly influence decomposition dynamics by altering the soil's microclimate.

The apparent latitude gradient in k values, decreasing from Helsingborg to Fyllingarum, Tärna and Munsö, further stresses the importance of local climate conditions. Lower temperatures and potentially higher soil moisture variability at northern sites likely constrained microbial activity. The similarity between Tärna and Munsö, which are geographically closer, reinforces the significance of regional climate effects.

The MicroResp results showed differences in functional diversity between fields, which may provide an additional explanation for the observed variation in decomposition parameters among farms. The results for Tärna and Helsingborg were more distinct, while Munsö and Fyllingarum are more similar to each other. In Tärna, the high utilisation of oxidized organic acids indicates a microbial community specialised in degrading chemically modified and more recalcitrant carbon sources. In contrast, the high utilisation of cysteine in Helsingborg indicates an active metabolism of sulphur-containing amino acids, which could reflect differences in nutrient cycling or microbial community composition. In Fyllingarum, the relatively high use of simple sugars may indicate the presence of fast-growing, sugar-specialised microbial communities. However, the observed differences could not be explained by soil pH, texture or the total amounts of soil carbon and nitrogen. More research is needed to further understand the microbial communities in the different soils and their role in decomposition dynamics.

Overall, the observed relationship between k and S followed the expected theoretical pattern described by Keuskamp et al. (2013), in which higher decomposition rates correspond to lower carbon stabilization. However, it is important to note that the Tea Bag Index reflects the decomposer environment rather than the decomposition of wheat straw specifically. Tea material differs from crop residues in lignin content, structural integrity and C:N ratio. Therefore, the absence of treatment effects does not necessarily imply that stubble height does not influence actual residue decomposition under field conditions.

Furthermore, the relatively short experimental duration and differences in incubation time among sites may have limited the possibility of detecting subtle management effects. Munsö, for example, had a shorter incubation time than the others, which resulted in lower k and S values. Decomposition processes respond slowly to management changes, and longer-term implementation of an altered stubble height may be required before measurable changes emerge.

In summary, decomposition in this study was mainly governed by soil temperature and moisture conditions rather than by differences in stubble height. These results suggest that, under Swedish autumn conditions, microclimatic variation is driven by local climate and soil conditions rather than stubble height.

4.3 Crop establishment and development

The effects of stubble height and residue management on early crop establishment were generally limited and inconsistent among sites. Although some statistically significant differences were observed, particularly for winter wheat in Fyllingarum, overall responses were modest and crop specific. However, since the crop and site changed simultaneously, this needs to be considered when interpreting the results.

Generally, LS never gave the highest biomass for any of the crops (Figure 15). One possible explanation is that a LS led to higher soil water content during several periods, including periods exceeding the 40% SWC threshold. Higher soil moisture can reduce soil aeration, impair root respiration and restrict early plant development (Håkansson et al. 2011). In addition, reduced decomposition rates under wetter conditions may have temporarily limited nitrogen mineralization, thereby constraining nutrient availability during early growth stages (Turmel et al. 2015). The combination of higher moisture and slower nutrient turnover may therefore have contributed to the lower wheat biomass observed in LS.

Residue quantity may also have influenced crop emergence. The greater amount of chopped straw in LS could have interfered with seed-soil contact during drilling, thereby obstructing proper establishment. Poor seed placement and reduced contact with fine aggregates are known constraints in no-till systems, particularly under high residue loads (Arvidsson et al. 2014). Surface residues may also act as physical barriers to emerging seedlings, increasing mechanical resistance and possibly delaying development.

The relationship between soil moisture and biomass was not consistent across all fields. In Tärna, the control treatment exhibited both the highest SWC and the lowest rye biomass, indicating that other site-specific factors likely influenced crop response. Differences in crop species, sowing date and soil texture complicate direct comparison among sites.

In contrast to soil moisture, the observed differences in soil temperature between treatments appeared to have limited influence on crop establishment during the autumn period (Figure 16). Soil temperatures generally remained above the 5 °C threshold relevant for early growth, and only a short cold period was observed in Fyllingarum. This suggests that the modest cooling effect of high stubble was insufficient to significantly constrain autumn development under the studied conditions.

The analysis of rapeseed plant development in Helsingborg showed only weak trends. Plants in HS tended to have thinner stems, possibly reflecting reduced radiation reaching the crop due to shading by taller residues. However, no statistically significant differences were detected in plant length, leaf number, or growth-point height. This indicates that the structural effects of stubble height on early development were minor during the study period.

Overall, the results suggest that under Swedish autumn conditions, soil moisture dynamics and residue quantity may have a stronger influence on early crop growth than the modest differences in soil temperature associated with stubble height. However, the absence of yield measurements limits the ability to determine whether early biomass differences would translate into agronomically meaningful outcomes.

4.4 Agronomic implications

The findings of this study indicate that there is no universally optimal stubble height in Swedish no-till systems. Instead, residue management must be adapted to site-specific soil properties, climatic conditions and cropping systems, which are aspects that are important in general when choosing no-till as a suitable method (Page et al. 2020).

A tall stubble with chopped up straw (higher than 20 cm) results in slightly cooler soils, reflecting increased shading and altered surface energy balance (Aase & Siddoway 1980; Cutforth & McConkey 1997). In autumn or during early spring, such cooling could potentially delay crop development or postpone drilling operations (Soane et al. 2012). However, the magnitude of temperature reduction observed in this study was small and did not appear to substantially affect autumn biomass (Table 8). In warmer or drought-prone conditions, the cooling effect of taller stubble may be beneficial by reducing evaporation and mitigating heat stress.

Choosing a shorter stubble with chopped-up straw (below 20 cm) frequently increased soil water content, particularly in sandy loam soils. In areas where water availability limits crop establishment, this may be an advantage, for example, in parts of eastern Sweden. However, in wetter climates or in poorly drained soils, increased residue cover may increase the risk of temporary waterlogging, reduce soil aeration and constrain both microbial activity and crop growth. Thus, the hydrological context is critical when evaluating a suitable stubble height.

Conversely, a short stubble with chopped residues could improve the isolation of the soil in winter, which may help with the crop's wintering, especially in cold winters. Blanco-Canqui & Lal (2009) showed that more residues in the field can help reduce soil freezing and accelerate spring thawing.

Stubble height and residue retention also influence operational aspects of no-till systems. Maintaining large quantities of chopped straw in low stubble may complicate seeding operations, reduce seed-soil contact, and increase variability in emergence. In contrast, having a taller standing stubble (over 35 cm) may reduce the need for straw removal and lower labour requirements, but can introduce practical challenges if residues interfere with drilling equipment. For example, by lodging or getting stuck in the machine. However, the seeding results likely depend on the type of sowing machine that is used. For example, the use of tine or disc coulters can have an effect. This aspect has not been examined in this study but should be considered in future studies.

From a wider sustainability perspective, leaving crop residues on the soil surface compared to removing them offers environmental benefits, including reduced erosion risk, improved soil water retention and potential increase of soil carbon (Blanco-Canqui & Lal 2009; Sadiq et al. 2025). However, these benefits must be balanced against possible drawbacks such as increased waterlogging risk, nitrous- and methane gas emissions and enhanced pathogen transfer (Arvidsson et al. 2014; Wiréhn 2018; Achankeng & Cornelis 2023).

In the context of climate change, residue management may become increasingly important. Regions expected to experience more frequent droughts may benefit from methods that improve soil water conservation, whereas areas with increasing precipitation intensity may require other ways to handle residues that avoid excessive soil moisture. Adaptive, farm-specific management strategies are therefore essential.

4.5 Study limitations

Several methodological limitations must be considered when interpreting the results of this study.

First, the experimental implementation differed among fields with respect to stubble height levels, crop species and incubation duration. Even if conducting on-farm experiments increases practical relevance, it reduces experimental control and, in this case, limits direct comparability between sites. Furthermore, the presence and amount of straw residues appeared to be as important as stubble height in influencing the soil microclimate. Therefore, measuring the amount of chopped straw within the treatments would have provided a better estimate of its relative importance.

Second, the limited number of soil moisture and temperature sensors per treatment increases sensitivity to small-scale spatial variability, particularly for soil water content, which is known to vary within sites more than temperature. Loss of sensors due to disturbance from wild animals further reduced data completeness, especially at Munsö. A risk of poor soil contact during sensor placement is a common issue in soils with higher clay content, further increasing the risk of weak data collection (Wild et al. 2019). Increasing sensor density in future studies would improve the robustness of microclimate measurements.

Third, the use of a standard calibration curve for soil water content across soils with different textures and bulk densities may have introduced systematic error. A field-specific calibration would likely provide more accurate volumetric water content estimates and improve the interpretation of the moisture conditions, but it was not possible in this study due to time scarcity.

The TBI method also entails limitations. The insertion of the tea bags disturbs the surrounding soil, likely affecting microenvironmental conditions. Furthermore, incubation periods differed among sites and were shorter than the recommended 90 days. This may have limited comparability and reduced sensitivity to treatment effects. Since microbial activity decreases during the autumn season, an earlier incubation would have been better to capture more of the microbial active period.

Importantly, tea material differs from wheat residues in chemical composition and physical structure. Therefore, TBI parameters reflect general decomposer activity rather than direct decomposition of straw residues. Earthworm activity, physical fragmentation processes, and bacterial and fungal dynamics were not included in the method; however, they are also potentially affected by changes in residue management and could be included in future studies.

Finally, biomass was measured only once during autumn, and no yield data were collected. Early-season biomass differences do not necessarily predict final yield, particularly in winter crops, where most growth occurs in spring. Long-term experiments, including yield measurements and additional monitoring, would therefore provide more comprehensive insight into the agronomic relevance.

Regardless of these limitations, the study presents valuable field-based evidence on how stubble height interacts with soil microclimate and decomposition processes under Swedish no-till conditions.

4.6 Conclusion

This study evaluated how variation in stubble height and straw residues influences soil temperature, soil water content, decomposition dynamics, and early crop establishment in Swedish no-till systems.

Stubble height had measurable but modest effects on soil microclimate. High stubble slightly reduced soil temperature, while low stubble with a greater straw residue cover often increased soil water content. However, these effects were site-specific and governed by soil texture and climatic conditions. Furthermore, a high stubble tends to have no or little negative effects, meaning it could be used as a cheaper and less labour-intensive alternative.

Decomposition was primarily controlled by soil moisture and temperature rather than by stubble height alone. Periods of high soil water content significantly reduced decomposition rates, underscoring the importance of aeration in temperate no-till systems.

The effects of early crop biomass were limited and inconsistent. Overall, the results indicate that stubble height and straw residue management should be adapted to local soil, climate and crop requirements.

Further studies are needed to fully understand how stubble height can alter the system's performance. For example, long-term studies that include yield and greenhouse gas measurements to fully assess the agronomic and environmental consequences of crop residue management under future climate conditions. In addition, the development of no-till systems also requires improved drilling technology, adapted crop rotations and long-term adoption of the system, not only a change in stubble height. This is important for getting more farmers to adopt and implement no-till in future Swedish cropping systems.

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Popular science summary

Today, more farmers are interested in reducing soil disturbance to improve soil health and lower production costs. One way to do this is to use no-tillage, where crops are sown directly into the soil without any previous tillage. Using no-till can reduce erosion, save fuel and improve the structure of the soil. However, no-till systems introduce challenges, especially in colder and wetter climates like Sweden. One of these challenges is how to manage crop residues that are left in the field after harvest.

When cereal crops are harvested, the remaining straw and stubble are left. These will affect soil temperature, soil moisture and biological activity in the soil. Large amounts of residues can make drilling more difficult and delay crop establishment. More knowledge on how to best handle the residues are therefore needed.

This study examined how different stubble heights influence soil conditions and early crop growth in no-till systems in Sweden. Field experiments were carried out on four farm fields in Tärna (Sala), Munsö (Stockholm), Fyllingarum (Norrköping) and Helsingborg. Three treatments were compared: a control with no straw residues, low stubble with chopped straw and a high stubble also with chopped straw. Soil temperature and soil moisture were measured with sensors, while biological activity was studied with the Tea Bag Index method and Microresp. Crop biomass was measured in the fields where a crop was grown.

The results showed that stubble height and crop residues influence soil conditions, but the effects were generally small and varied between farms. High stubble slightly lowered soil temperature due to shading, while low stubble with more chopped straw often increased soil moisture by reducing evaporation. However, local conditions such as soil type and climate had a larger influence than stubble height itself.

The results also showed that local soil temperature and moisture as well as differences in microorganism communities were more important for decomposition than stubble height alone. Very wet soils can slow down decomposition which highlights the importance of good soil aeration.

In conclusion, this study suggests that there is no optimal stubble height for all farms. Residue management needs to be adapted to local conditions. However, a high stubble might be a practical option since it requires less work. But the results may depend on the drilling equipment.

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Supplementary material

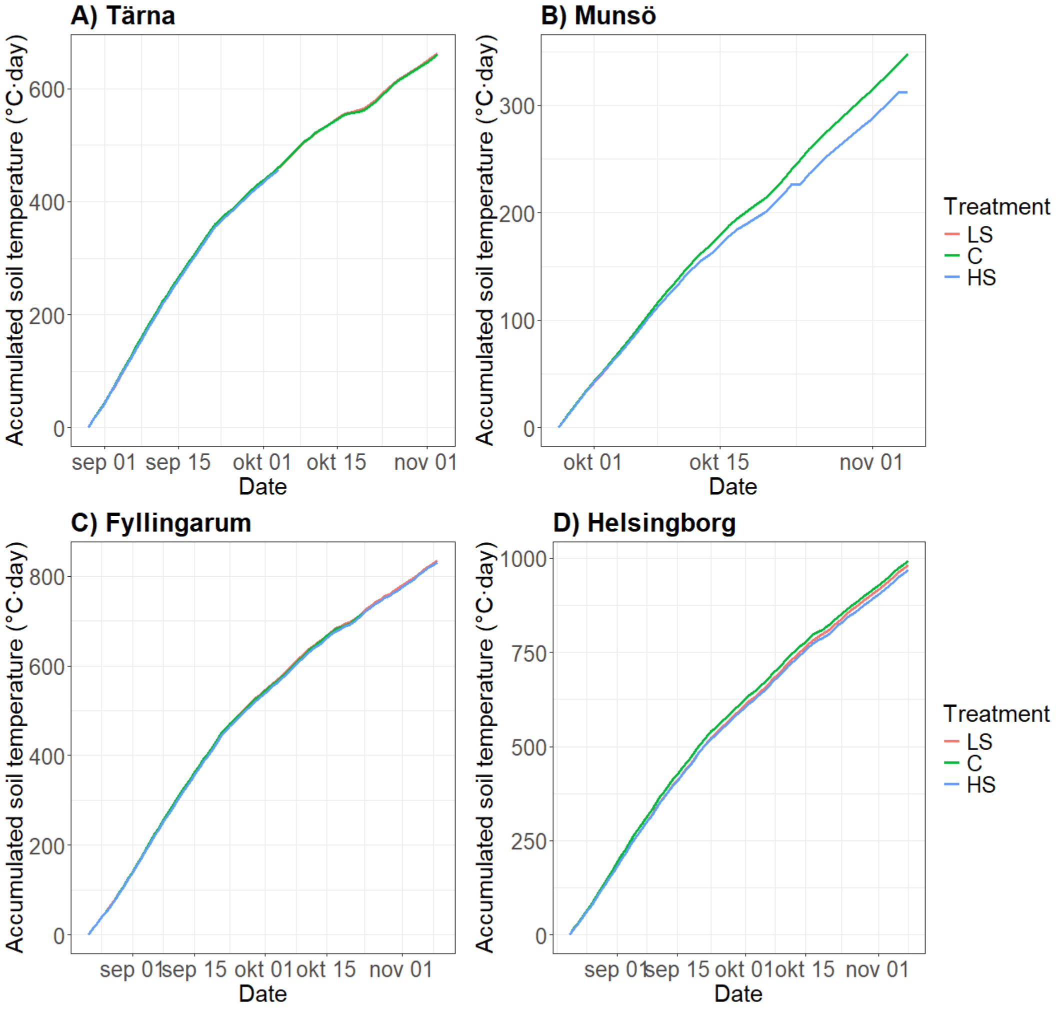

Figure S1: Accumulated soil temperature (°C·day) over time for low stubble (LS), control (C) and high stubble (HS) for four different fields A) Tärna, B) Munsö, C) Fyllingarum,

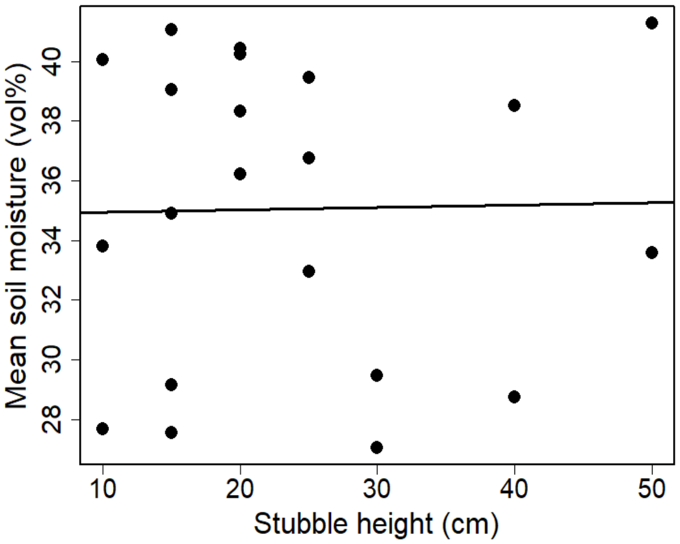

Figure S2: Relationship between plot-level mean soil moisture and stubble height (cm) across all fields. Each point represents the plot mean temperature for each height and replicate over the measurement period. The line shows the fitted linear regression.

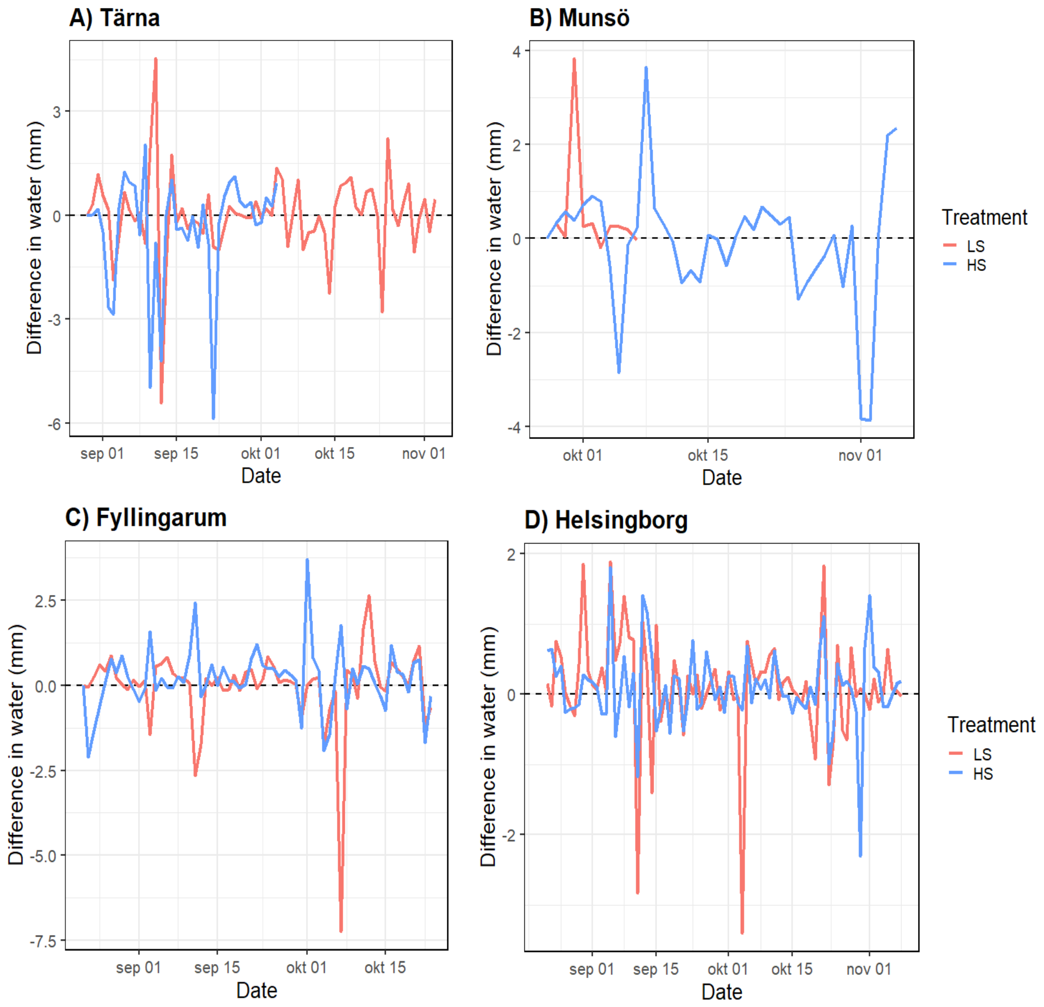

Figure S3: Difference in soil water content expressed in mm between the low stubble (LS) and high stubble (HS) treatments relative to the control (C) at four different fields. The dashed line represents the control, set to zero. Positive values indicate a higher amount of stored water compared to the control, while negative values indicate a lower amount of stored water relative to the control.

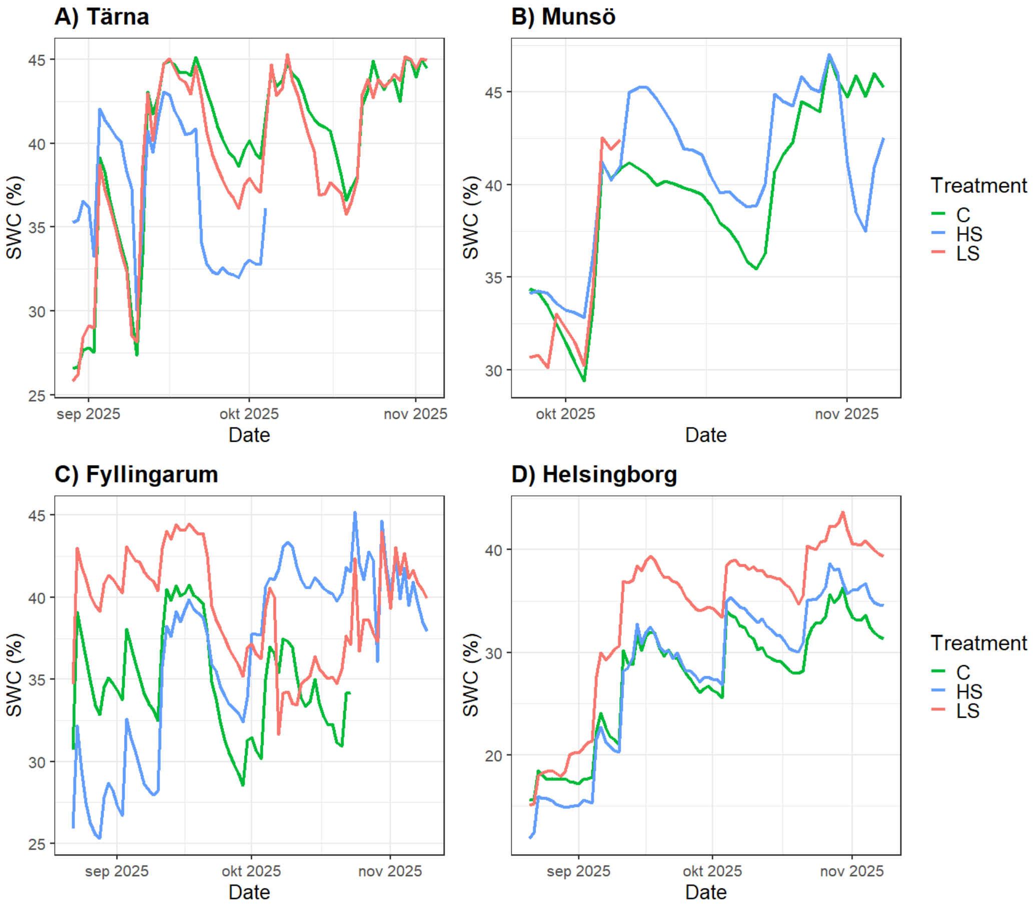

Figure S4: Estimated daily mean soil water content (SWC, %) over time for three stubble height treatments (LS = low stubble, C = control, HS = high stubble) at four experimental sites: A) Tärna, B) Munsö, C) Fyllingarum, and D) Helsingborg. Soil water content was measured continuously using soil moisture sensors and aggregated to daily means per treatment.

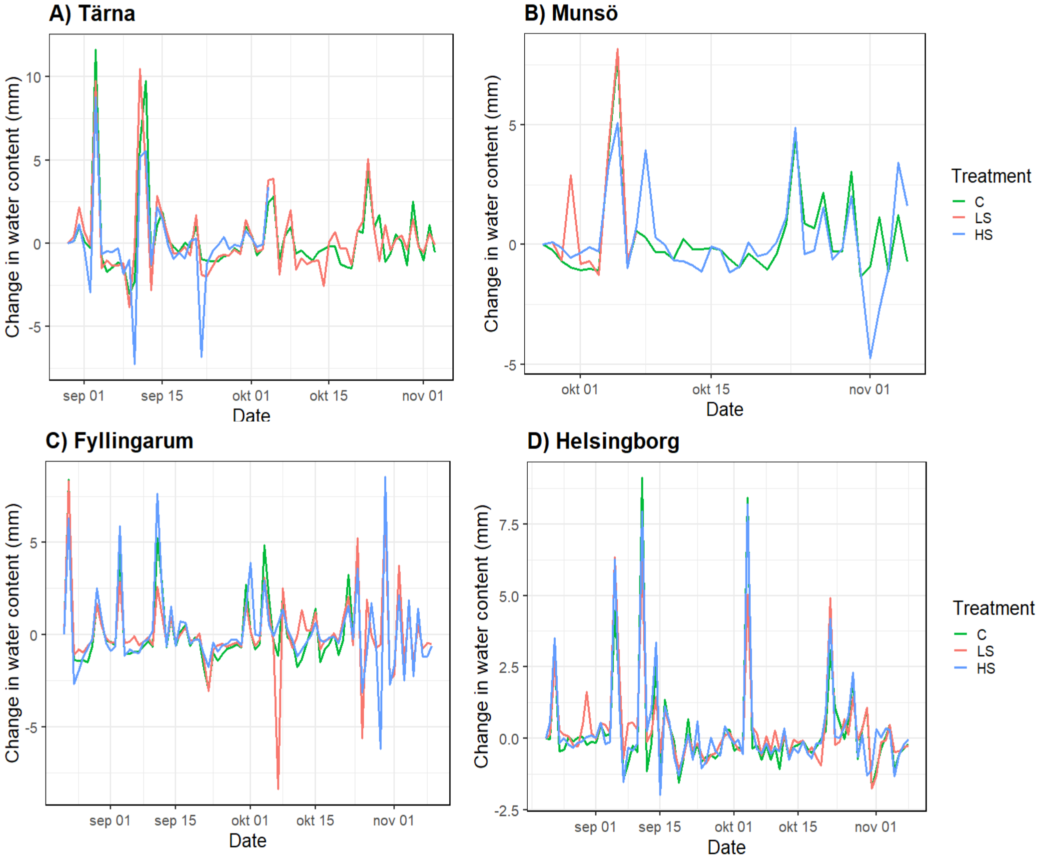

Figure S5: Temporal changes in soil water content expressed as daily differences (mm) for three treatments: C (Control), LS (low stubble), HS (high stubble), at four different fields. Positive values indicate an increase in soil water content compared to the previous day, while negative values indicate a decrease. This illustrates the short-term dynamics in soil moisture during the autumn period.

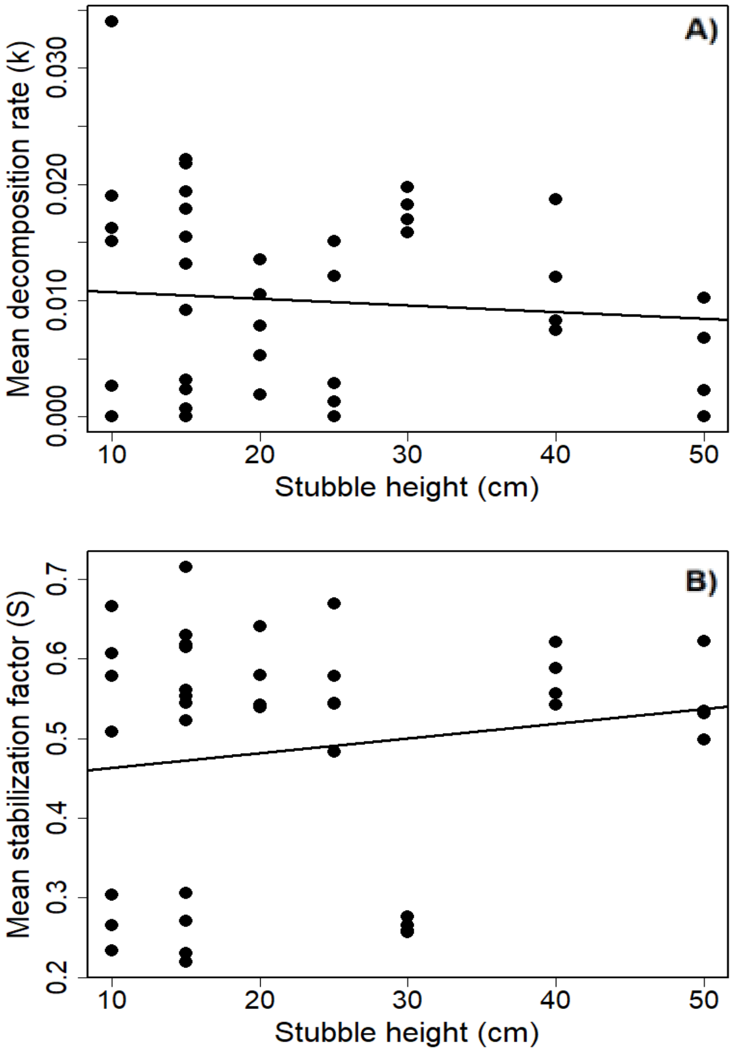

Figure S6: Relationship between stubble height (cm) and mean decomposition parameters derived from Tea Bag Index (TBI) across all fields. A) shows the relationship between stubble height and mean decomposition rate (k), while B) shows the relationship between stubble height and stabilization factor (S). The solid line shows the fitted linear regression models across all observations.

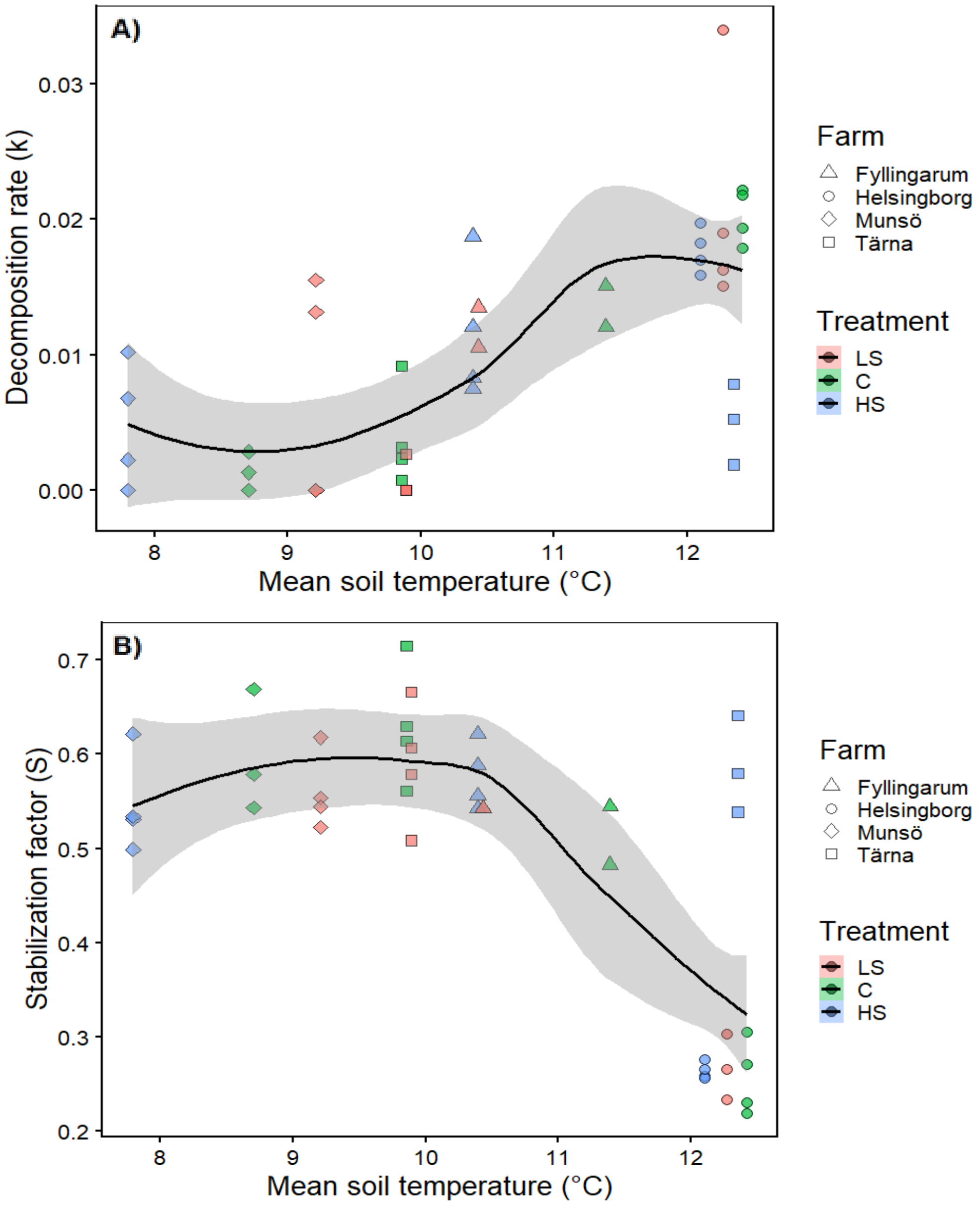

Figure S7: Relationship between mean soil temperature and decomposition parameters derived from Tea Bag Index (TBI). The mean soil temperature is calculated as accumulated soil temperature per day (AST/day). Panel A) shows the relationship between AST/day and decomposition rate, k, while panel B) shows the relationship between AST/day and stabilization factor, S. Shape indicates farm and colour indicates treatment (LS= low stubble, C=control, HS= high stubble). The solid line shows the trend, and the shaded area indicates the 95% confidence interval.

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