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Non-inversion tillage benefits soil N retention during bare soil period coinciding with wet spell

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Abstract. Recent meta-analyses suggest risks of increased nitrate leaching with the implementation of reduced tillage practices. This study aimed to quantify effects of a subsidized and commonly implemented form of non-inversion tillage in Switzerland (NIT, i.e. chisel ploughing) in comparison to conventional tillage (CT, i.e. mouldboard ploughing) on nitrate leaching and its driving processes (i.e. water fluxes, soil temperature, plant uptake). A lysimeter experiment was conducted at the lysimeter facility Reckenholz/Zurich in Switzerland, mimicking tillage differences. Results after three years of treatment implementation show that during the following three years, cumulative nitrate leaching was 26% higher under CT than under NIT (i.e. 63±10 kg/ha N with CT vs. 46±9 kg/ha N with NIT). The observed effect was driven by differences in nitrate concentrations in seepage water rather than seepage water amounts. The beneficial effect of NIT on nitrate leaching was most pronounced during and shortly after a bare soil period following sugar beet cultivation, which coincided with above-average spring precipitation. These findings suggest that reduced soil management may hold the potential to reduce nitrate leaching during winter and spring wet spells with poor plant cover, which are expected to become more frequent with progressing climate change.

Keywords: nitrate leaching; lysimeter; chisel plough; mouldboard plough; arable; Switzerland

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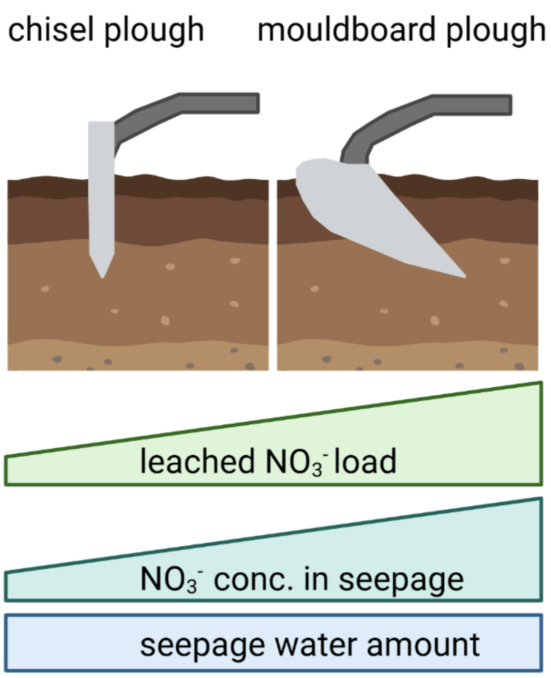

1. Introduction

Common soil management practices in arable farming are mouldboard ploughing, chisel ploughing, strip-till, ridge-till or no-till. These practices cover a spectrum of intensities of soil disturbance and soil inversion in association with the machinery used. Mouldboard ploughing inverts the topsoil, while breaking soil aggregates and continuous biopores. It is therefore also termed inversion tillage. Non-inversion tillage practices such as strip-tillage/zone-tillage or mulch-tillage create less soil disturbance than inversion-tillage practices as they operate on a shallower basis (i.e. mulch-tillage), are confined to parts of the soil surface (i.e. chisel ploughing) or both (i.e. strip-tillage). No-tillage avoids soil disturbances in general and crops are sown or planted directly into the mulch-layer.

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Reduced tillage practices are widely promoted as effective means to reduce soil erosion (Montgomery, 2007; Prasuhn, 2012; Seitz et al., 2018; Skaalsveen et al., 2019). Moreover, reduced tillage and no-till were also found to reduce soil carbon losses or even to increase carbon sequestration in some pedo-climatic conditions and/or depending on initial state (Follett, 2001). Co-benefits for climate mitigation are highlighted in some studies but are in general controversial as potential carbon sequestration benefits may be offset through increases in N2O emissions (Vandenbygaart, 2016). More recently, no-till implementation was found to benefit the reduction of fine-particle air pollution (Behrer and Lobell, 2022).

Regarding tillage impacts on the leaching of nitrate below the root zone and subsequent groundwater contamination, the findings from existing studies are not conclusive. Evidence from experimental studies suggests that no-till or non-inversion tillage can lead to decreases in nitrate leaching (e.g. Koskiaho et al., 2002; Spiess et al., 2020; Norberg and Aronsson, 2025), no effect (e.g. Hooker et al., 2008; Pisani et al., 2017; Jabro et al., 2019) or increases (e.g. Huang et al., 2015; Bhattacharyya et al., 2022). Recent field data syntheses and meta-analyses by Daryanto et al. (2017), Li et al. (2023) and Huang et al. (2024) addressed the inconsistence of documented tillage impacts on nitrate leaching. Based on their studies they conclude that overall, nitrate leaching tends to be higher under no-tillage than under conventional tillage, the difference attributable to altered water fluxes. Huang et al. (2024) even highlight precautions regarding the implementation of no-tillage or reduced tillage to promote sustainable agriculture under changing climatic conditions.

These conclusions fundamentally question the recommendation of reduced tillage as a measure to reduce nitrate leaching as for example suggested by Kirchmann et al. (2002) or Frick et al. (2023).

It was therefore the aim of this study to quantify the effects of reduced tillage on nitrate leaching and its driving processes (i.e. water fluxes, soil temperature, plant uptake). An experiment was conducted in an advanced lysimeter facility equipped with high precision weighable lysimeters and soil moisture and temperature probes in different depths to shed light on the role of soil water dynamics in driving treatment differences.

2. Methods

2.1 Lysimeter station

The experiment was conducted on 18 lysimeters of a facility at Agroscope in Zürich-Reckenholz (47°25‘41“N, 8°31‘05“E; 444 m above sea level; Prasuhn et al. (2009); Appendix A). The lysimeter casings were of stainless steel, having a diameter of 1.13 m, a surface area of 1 m2 and a depth of 1.50 m. The top 1.35 m are soil monoliths while the lowest 0.15 m are composed of three layers of quartz sand and gravel that contain small quartz grains on the top (0.10 to 0.50 mm diameter) and the largest ones at the bottom (3.15 to 5.60 mm). The quartz sand layers are used to minimize the disruption of the water flux from the soil monolith to the exposure of atmospheric pressure at the bottom of the monolith (Abdou and Flury, 2004; Meissner et al., 2014).

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At the bottom of the lysimeters, the volume of seepage water is measured with 100 ml tipping buckets, with the exact time of each tipping recorded by a data logger. With every second tipping, about 2-4 ml of water also flows into a sample bottle, which allows a flow-proportional collection of small samples.

Six of the lysimeters were weighable and instrumented with different types of probes. Frequency domain reflectometry sensors (FDR; ThetaProbe ML2x, Delta-T Devices, Burwell, UK), equilibrium tensiometers (EQ15, Ecomatic, Munich, Germany), pressure transducer tensiometers (Tensio 150, UGT, Müncheberg, Germany) and temperature sensors were installed in two replications at soil depths of 10, 30, 60 and 90 cm. The measurement accuracy of the weighing load cells (UGT WM 100, UGT, Müncheberg, Germany) is indicated to be 10 g (or 0.01 mm of water). The temporal resolution of all sensors has been set to 5 min. The recorded data on lysimeter weights was used to derive estimates of actual evapotranspiration on an hourly basis as describes in equation 1. Times series of ETa were filtered to remove outliers and noise.

$$ET_{a,i} = w_{i-1} - w_i + p - s \qquad (1)$$

where

$ET_{a,i}$ = actual evapotranspiration at hour i

p = hourly precipitation [mm]

s = hourly seepage water [mm]

w = lysimeter weight

2.2 Soils

Soil monoliths were collected in 2008 from arable land at three Swiss lowland sites: six each from Grafenried (Eutric Cambisol; FAO classification), Reckenholz (Gleyic Cambisol) and Schafisheim (Orthic Luvisol above gravel). The three soil types represent typical agricultural soils as they occur along the Swiss Central Plateau. Soil profile characteristics are summarized in Appendix D.

2.3 Experimental design

Treatments were chosen to represent conventional soil management with mouldboard plough (i.e. conventional tillage = CT) and a form of reduced tillage that is subsidized and widely implemented in Switzerland (i.e. ”Mulchsaat”). According to the Federal Office for Agriculture (FOAG) 32% of all arable land was under conservation soil management in 2019 (75% of that under ”Mulchsaat). The practice is equivalent to chisel ploughing. To align with the international literature, we term the “Mulchsaat” treatment NIT (= non-inversion tillage) in this publication.

The two treatments were introduced in autumn 2009 prior to sowing of winter wheat and they were implemented as follows. The conventional tillage treatment (CT) was simulated on the lysimeters by manually digging the soil to 20 cm depth using a

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spade. Thereby, the soil was subjected to complete inversion tillage, and all remaining crop residues were thoroughly incorporated into the topsoil. In secondary tillage before main and cover crops, harrowing was simulated using a hoe to 10 cm soil depth. In the non-inversion tillage (NIT) treatment, a chisel plough operation as mimicked by cutting/making 20 cm deep slots at 20 cm spacing with a spade. In this treatment, harvest residues partly remained on the soil surface, forming a mulch layer. Crop residues were chopped and retained in both treatments. During the experimental period investigated here, these were cover crops, sugar beet tops and straw of maize and wheat. The two treatments, each with three replicates per soil type, were allocated to the lysimeters of the three soil types in a completely randomized design. Each treatment and soil was represented once within the subset of weighable and sensor-equipped lysimeters.

While the treatment differences were introduced already in 2010, the analysis in this study focuses only on the treatment differences from 2013 to 2016 (data gaps prevented a robust analysis of the initial period). This implies that evaluated treatment differences relate to three-year established treatment effects (photos in Appendix B illustrate exemplary treatment difference on May 21st, 2014).

2.4 Crop rotation and management

Since the establishment of the lysimeter facility in 2009 all lysimeters considered in this study had the same crop rotation of grain maize (GM, Zea mays L.) - winter wheat (WW, Triticum aestivum L.) + cover crop (CC; Phacelia tanacetifolia Benth.) – field peas (FP, Pisum sativum L. convar. sativum) – oilseed rape (OR; Brassica napus L. var. napus) - winter barley (WB, Hordeum vulgare L. subsp. vulgare) + cover crop (phacelia) - sugar beet (SB, Beta vulgaris subsp. vulgaris var. altissima Döll.) - grain maize – winter wheat. During the experimental period analysed here, the lysimeters were cropped with phacelia (2013), sugar beet (2014), grain maize (2015) and winter wheat (2016). N mineral fertilizer was applied according to the official fertilizer recommendations of the Swiss Federal Agricultural Research Stations in force at the start of the experiment (Flisch et al., 2009).

2.5 Lab analyses

Samples of seepage water were collected every two weeks from sample bottles attached to tipping buckets. The samples were analysed colorimetrically for nitrate (NO3) and ammonium using segmented flow injection analysis (s-FIA). Nitrate concentrations of seepage water are reported as flow-weighted means.

For all harvested products removed from the lysimeters, dry matter (DM) yields and N removals by harvested products were determined. All plant samples were dried at 60 °C, ground and analysed for total N on a VarioMax CN elemental analyzer (Elementar, Langenselbold, Germany) following a dry combustion method based on the original method by (Dumas, 1831) (see also Bremner and Mulvaney, 1982).

2.6 Meteorological data

Interpretations of experimental results produced in the lysimeter station are supported by climatic data recorded at automated weather station Reckenholz operated by MeteoSwiss. The weather station is located 20 m next to the lysimeter station. We used average daily temperature and precipitation sums measured in 2 m height above ground.

3. Results

Figure 1 provides an overview of treatment impacts on daily actual evapotranspiration, N export with harvest, daily seepage water, daily NO3 concentrations in seepage water and daily N leaching loads. As no differences in any of these variables were observed between the three soil types in the lysimeter facility, all soil types were pooled for the analyses.

Actual evapotranspiration (Eta) varied mostly dependent on temperature and crop development stage but shows little differences depending on treatment. Differences between treatments are visible only during the sugar beet cropping period in June 2014, where Eta is higher in CT than in NIT. Cumulative ETa during the sugar beet cropping period was overall higher in CT (672.9 ± 17 mm) than in NIT (573.2 ± 29 mm). This treatment difference is in line with the treatment difference in exported N with sugar beet yield in 2014. N export and dry matter yields in 2014 were higher in CT than in NIT. During the bare soil period following sugar beet, cumulative evapotranspiration was largely unaffected by the treatment (140.3 ± 23.3 mm in CT; 150.5 ± 36.8 mm in NIT). Also, no differences in seasonal evapotranspiration with treatments could be identified for the maize cropping period in 2015 (497.2 ± 28 mm in CT vs. 501 ± 12.5 mm in NIT) or the winter wheat cropping period in 2015/2016 (506.3 ± 29.2 mm in CT vs. 460 ± 53.2 mm in NIT). In line with that, N exports with grain maize yield in 2015 and winter wheat yields in 2016 were similar in both treatments.

Seepage water was mainly generated during late autumn, winter and spring. It tended to be slightly higher under NIT than under CT, but the difference in cumulative seepage water between both treatments was not found to be significant (Mann-Whitney test p-value = 0.16, Figure 2).

During the experimental period, nitrate concentrations in seepage water under CT were often higher than under NIT. During the bare soil period and during the early growth of grain maize in 2015, nitrate concentrations were significantly higher in CT than NT. This period was also characterized by large amounts of precipitation (especially in spring 2015). The difference in nitrate concentrations persisted at the beginning of winter wheat establishment in 2016 but decreases thereafter. Nitrate leaching was thus also higher under CT than under NIT, during those periods with higher nitrate concentrations in CT. Treatment differences in nitrate leaching are thus clearly driven by concentration rather than seepage amount differences. It is striking that treatment differences predominantly occur under poor or no plant cover. During the cover cropping period with phacelia in autumn 2013 and the following sugar beet cultivation period in 2014, nitrate leaching was generally lowest.

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Recordings of soil water content, water tension and soil temperature are shown in Appendix E. These measurements could not confirm the hypotheses that soil temperature in spring and summer would be lower under the mulch layer in the NIT treatment than under CT and that soil moisture would be higher under NIT than under CT due to the mulch layer in NIT. Instead, small treatment differences in soil moisture and water tension can be attributed to differences in plant water uptake. Sugar beet developed more biomass in the CT than in NIT treatment and produced higher yields (Appendix F). The better plant development was associated with lower soil moisture in CT than in NIT in 2014. In 2015 this effect was inverse (i.e. slightly lower soil water content in NIT during grain maize growth in association with slightly higher grain maize yields in NIT).

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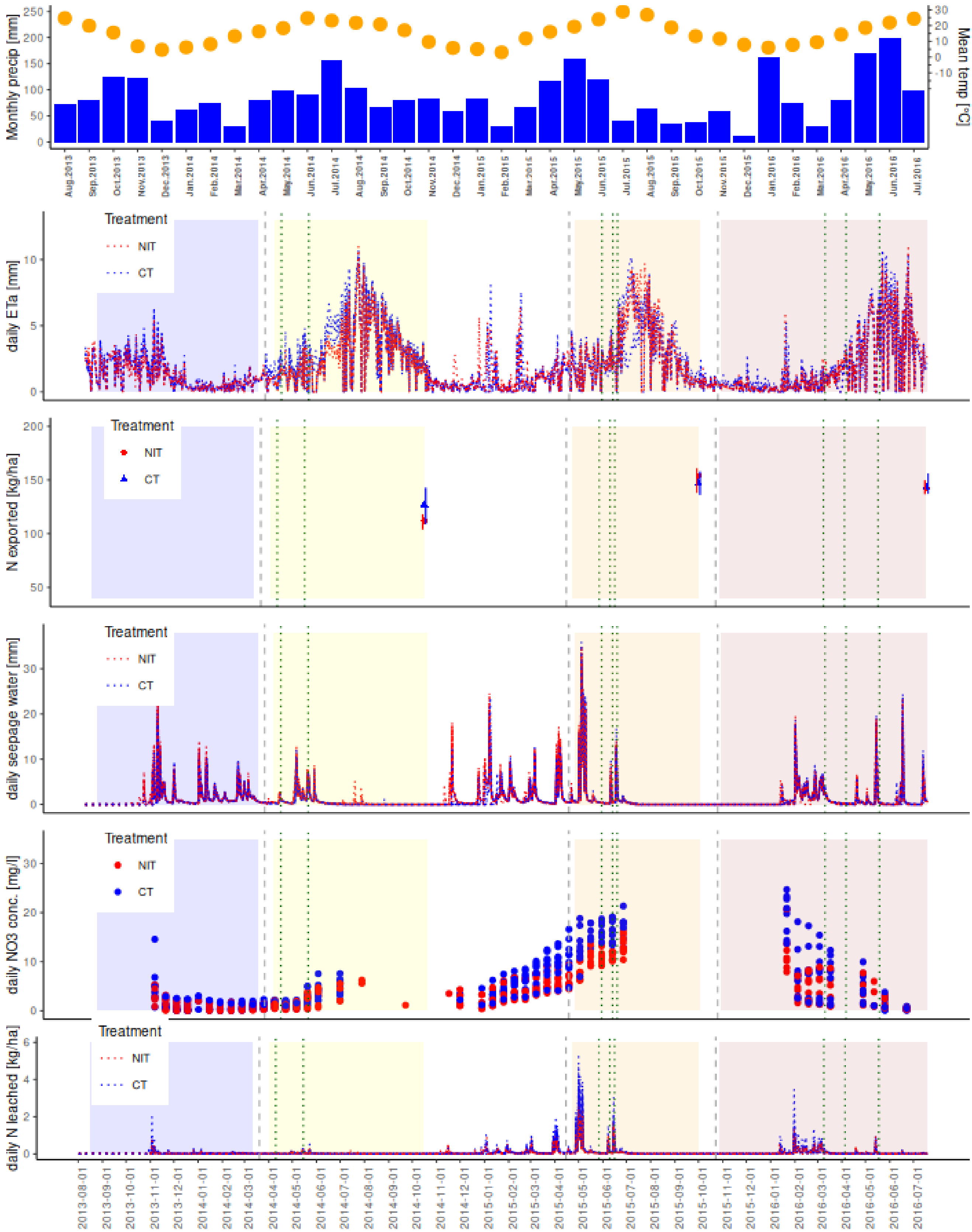

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Figure 1: Monthly mean temperature and monthly precipitation sums in comparison to time series of daily actual evapotranspiration, N exported with harvest (points indicate median values by treatment, while vertical bars indicate the 25th-75th percentile range), daily seepage water, bi-weekly nitrate concentrations in seepage water and daily N loads leached from lysimeters of both treatments (CT = conventional tillage, NIT = non-inversion tillage); coloured background shading = cropping periods: purple = phacelia, yellow = sugar beet, orange = grain maize, red = winter wheat; grey dashed vertical lines = ploughing times; green dotted vertical lines = fertilization times; n=9 data from 3 soil types.

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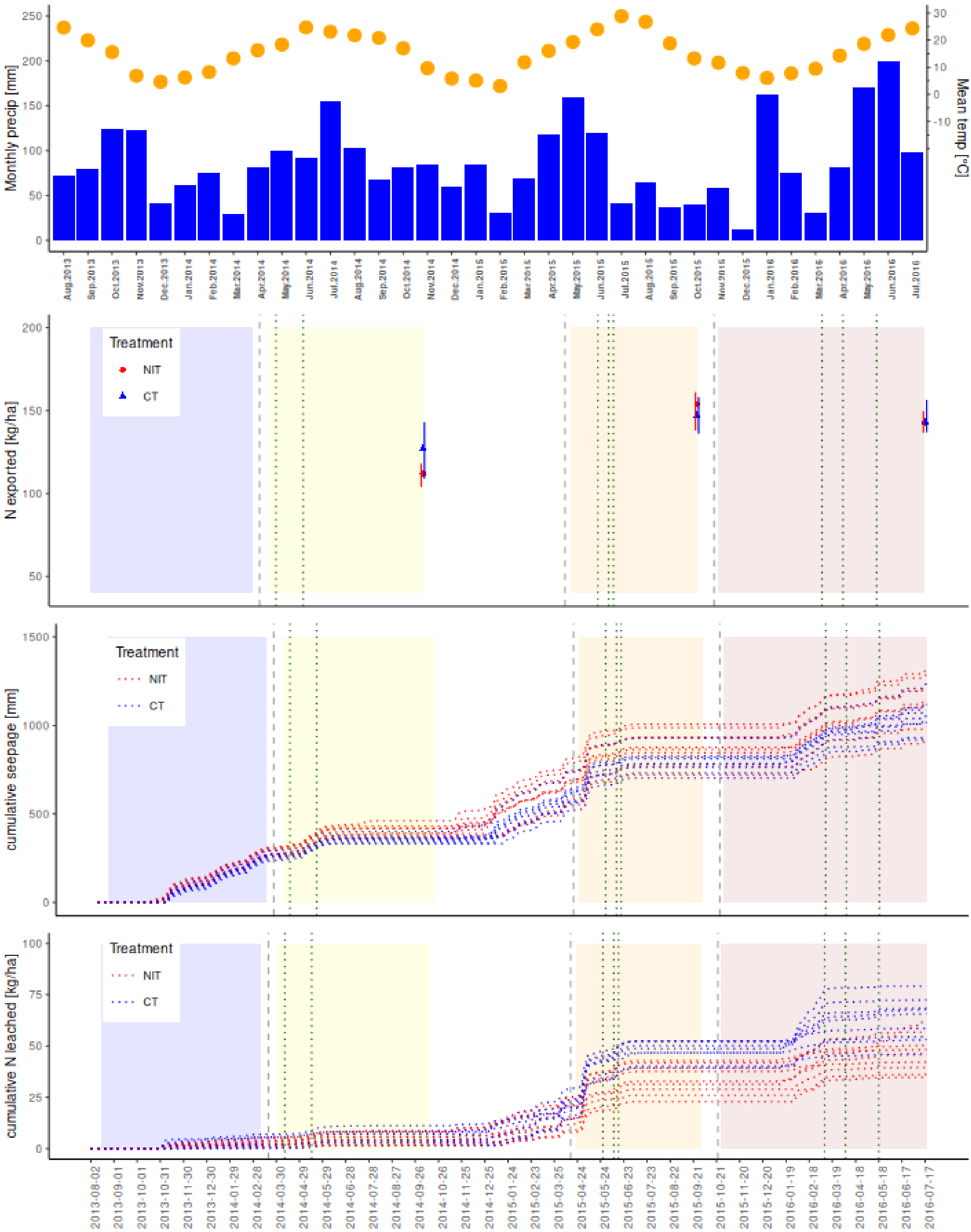

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Figure 2: Monthly mean temperature and monthly precipitation sums in comparison to N exported with harvest (points indicate median values by treatment, while vertical bars indicate the 25th-75th percentile range), cumulative seepage water and cumulative nitrate-N loads leached from lysimeters of both treatments (CT = conventional tillage, NIT = non-inversion tillage); coloured background shading = cropping periods: purple = phacelia, yellow = sugar beet, orange = grain maize, red = winter wheat; grey dashed vertical lines = ploughing times; green dotted vertical lines = fertilization times; n=9 data from 3 soil types.

Over the observation period between August 2013 and July 2016, significantly more nitrate was leached from lysimeters with CT than with NIT (+26%). Mean nitrate loads leached from NIT treatment lysimeters between August 2013 and July 2016 were 46±9 kg/ha NO_3-N, while 63±10 kg/ha NO_3-N leached from CT lysimeters (Fig. 3). The difference is significant with a p-value of 0.00399 (Mann-Whitney test).

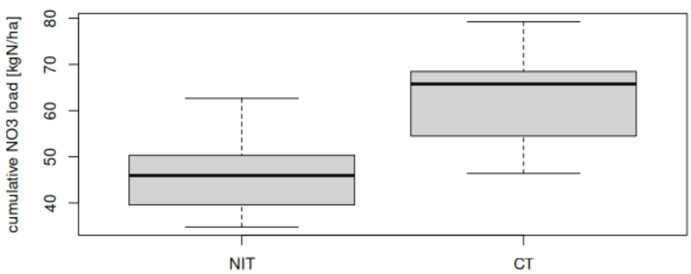

Figure 3: Boxplots of cumulative nitrate-N loads leached from lysimeters during the observation period between 2013-08-01 and 2016-07-19 distinguished by treatment (NIT = non-inversion tillage with chisel plough, CT = conventional tillage with mouldboard plough; n = 9 by treatment)

4. Discussion

4.1 Higher nitrate leaching under CT due to higher nitrate concentration in seepage water

Results presented in this study are generally in line with Li et al. (2023), who concluded from their global meta-analysis that the benefits of reduced tillage for nitrate leaching reduction tend to be higher on soils with medium texture and SOC contents >1% in temperate climate zones and with longer durations of reduced tillage practices. Following the lysimeter study of Spiess et al. (2020) who had found that nitrate leaching was slightly lower under no-till than under conventional tillage, our study comparing CT vs. NIT in a lysimeter setting shows a similar difference with higher N leaching under CT. In our study, nitrate concentrations were the driver of the treatment difference, rather than differences in the soil water balance as also in Spiess et al. (2020). Higher nitrate concentrations in seepage water under CT may be explained through soil structural differences in the topsoil between treatments that could have led to a higher share of matrix water flow in the CT treatment than in the NIT treatment. With more matrix water flow in CT, more nitrate would be carried through the soil profile in CT than in NIT, whereas a larger share of water would travel through macropores under NIT, solving less nitrate from the soil matrix. Such a bypass effect was also suggested by Bjorneberg et al. (1996), Shipitalo et al. (2000), Hess et al. (2020) and Miranda-Vélez et

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al. (2022). It was found by Roseberg and Mccoy (1992) and more recently by Chakraborty et al. (2022) that although tillage creates greater total porosity, macropore continuity can be reduced. This disruption of macropore continuity by tillage can reduce the contribution of macropores to the percolation flow. Higher aggregate stability under reduced tillage as often reported in studies investigating tillage effects on soil physical properties (e.g. Blanco-Canqui and Ruis, 2018; Weidhuner et al., 2021), could imply greater stabilization of organically bound nitrogen and thus a smaller risk of leaching. In our study, also larger amounts of sugar beet residues in CT (accompanied with the larger sugar beet yields in 2014) may have contributed to the treatment difference in nitrate leaching as it is an easily degradable source of N (Thomsen and Christensen, 1996). Higher denitrification as reported by Mkhabela et al. (2008) under no-till compared to CT might also have contributed to the observed effect. Another factor potentially contributing to the treatment difference observed here might have been accelerated soil organic N mineralization resulting from soil disturbance with CT, which led to higher amounts of mineral N in the soil after ploughing during early crop growth as also found by Zihlmann and Weisskopf (2006). However, the fact that in our experiment nitrate leaching was not significantly higher under CT than NIT during days directly after tillage, but only after the termination of sugar beet in 2014 suggests that ploughing effects on mineralization did not play a strong role here. It has to be noted, however, that with ploughing after sugar beet harvest in autumn (a common practice in agriculture) nitrate leaching would likely have been much higher under CT as documented in several previous studies (e.g. Hansen et al., 2010; Hansen and Djurhuus, 1997; Francis et al., 1995).

4.2 Peak nitrate leaching during wet bare soil period

The fact that nitrate leaching is highest during and shortly after the bare soil period following sugar beet cultivation highlights that plant cover and the continuity of N uptake by plants are strong leverages to reduce nitrate leaching. On the contrary, large amounts of precipitation during periods of low or no plant cover as experienced between January and May 2015 impose large risks of nitrate leaching. As climate projections for Switzerland suggest increasing winter and spring precipitation (CH2025), such risks are expected to increase in the future (e.g. Klein et al., 2013; Klein et al., 2014; Zarrineh et al., 2020). Results from this study suggest that reduced soil tillage could hold the potential to reduce nitrate leaching in such situations as also found by Hess et al. (2020), who showed that under an experimental regime with more intense but less frequent rain events, nitrate leaching increased in tilled systems but did not in no-till systems.

Even though our results align well with findings from other studies investigating soil tillage impacts on nitrate leaching in Switzerland and other temperate climate regions (e.g. Spiess et al., 2020; Norberg and Aronsson, 2025), it needs to be studied further to what extent the finding holds true on under changing climatic conditions and on different soil types / soil depths. According to studies identifying higher NO3-leaching under reduced tillage or no-till compared to conventional tillage, changes in soil water fluxes play a key role in determining this effect. Daryanto et al. (2017), Li et al. (2023) and Huang et al., (2024) attributed the effect to the presence of biopores (earthworm burrows, old root channels) under long-term no-tillage

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management, which led to more deep percolation in no-till than in conventionally ploughed fields. However, not all studies documenting an increase in deep percolation with reduced tillage also report increased leaching loads. For example, Randall and Iragavarapu (1995), Weed and Kanwar (1996) and Spiess et al. (2020) found that reduced tillage decreased N leaching slightly despite increasing deep percolation. This indicates that deep percolation per se cannot be the main driver of the treatment differences as also found in our study, where we measured higher nitrate leaching under CT than NIT with no significant difference between treatments in terms of seepage water generation. Li et al. (2023) identified soil organic carbon content as a strong explanatory variable driving the effect size of area-scaled NO3-leaching: In soils with low SOC content (<1%), no-till resulted in approximately 50% greater area- and yield-scaled NO3-leaching than inversion tillage. This may be explained by the fact that the possibilities to increase aggregate stability through reduced tillage or no till are limited in carbon-deprived soils. In a regional study on no-till impacts in the US Midwest, Blanco-Canqui et al. (2009) found that the soil organic carbon content was positively correlated with aggregate wettability and aggregate resistance to rain drops. Thus, with lower carbon content the bypass-effect connected to aggregate stability described in section 4.1 is likely to become less relevant. This would explain higher leaching of NO3 under no-till in carbon-poor soils. In a semi-arid region of China with low SOC content Huang et al. (2015) found 44.6% higher NO3-leaching under no-till than under conventional tillage. They attribute this to higher amount of deep percolation under no-till, but also higher NO3 concentrations in seepage water with no-till than with conventional tillage. It is notable that at their study site due to very dry winter conditions, the seasonality of seepage water generation differs substantially from conditions in temperate regions of Europe, where mostly no or opposing effects were observed (e.g. Norberg and Aronsson, 2025).

4.3 Unresolved links

The influences of climatic conditions and in particular precipitation regimes on changes of NO3-leaching under tillage reduction were not addressed in depth in any of the meta-analyses on the subject so far. Relationships between precipitation+irrigation and effects of no-till on NO3-leaching identified by Daryanto et al. (2017) and Li et al. (2023) are not conclusive. Daryanto et al. (2017) found that no-till increases nitrate leaching more in dry years than in wet years. Results from Li et al. (2023) suggest that both relatively low water inputs from precipitation and irrigation, but also relatively high water inputs were associated with greater NO3-leaching losses under no-till compared with inversion tillage. Further work is needed to investigate this linkage more in depth as the prospects of inducing increased NO3 leaching with no-till could shift with progressing climate change.

Besides climatic and soil structural drivers, other processes may add to increased NO3 leaching under NT. Hansen et al. (2010) for example, found some negative effects of reduced tillage intensity on nitrate leaching in Denmark (Flakkebjerg), which they attribute to poorer crop establishment with reduced tillage and thus reduced N plant uptake. This effect is expected to play a

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considerable role in general since it has often been reported that no-till can limit crop productivity due to higher surface compaction limiting root growth and slower soil warming under mulch layers (Pittelkow et al., 2015; Büchi et al., 2018). Meisinger et al. (2015) see a likely reason for lower nitrate losses in mouldboard plough treatment in comparison to NT in the higher decomposition of the carbon rich wheat straw residues incorporated into the ploughed soil. The faster decomposition and accompanying immobilization of NO3-N in CT is likely to have led to a smaller NO3-N pool in the CT soil.

Differences in earthworm communities between the treatments as for example reported by Maurer-Troxler et al. (2005) and Jossi et al. (2011) would also have significant implications on soil nitrogen dynamics. Worm casts contain nitrogen in plant-available forms (Singh, 2018). Differences in earthworm abundances also have implications on soil microbial communities as reported by Ma et al. (2022). Both earthworm and microbial activities would lead to faster decomposition of organic material, potentially increasing the risk of NO3-leaching with no-till. N mineralization on the soil surface and in the topsoil could potentially be higher in NT/NIT than in CT if the mulch layer induces more favourable temperature and moisture conditions for soil microbial activity during dry periods.

5. Conclusions

In this study we explored the impacts of non-inversion tillage (NIT) in comparison to conventional tillage (CT) on nitrate leaching after three years of treatment implementation in a lysimeter facility in Zurich, Switzerland. Our data suggest that between August 2013 and July 2016, significantly more nitrate was leached from lysimeters with CT than with NIT (+26%). The observed effect is driven by differences in nitrate concentrations in seepage water rather than seepage water amounts. We argue that the differences in nitrate concentrations in seepage could be attributed to soil structural differences induced by the treatments: greater aggregate stability in combination with macropore continuity is likely to have led to greater N retention in NIT than CT and thus less nitrate was dissolved from the soil matrix in NIT. Differences in pre-crop residues and denitrification may have contributed to the observed treatment effect on NO3 leaching. The beneficial effect of NIT is most prominent during a bare-soil period coinciding with a wet spell, which may suggest that NIT holds potential to buffer nitrate leaching risks, which are expected to increase with climate change (i.e. with projected increases in winter and spring precipitation).

According to our study results and in view of the broader literature on the subject, the risks of increased nitrate leaching through the adoption of no-till or NIT seem to be limited in temperate regions of Europe and mostly associated with the time since conversion to no-till/NIT. During early stages of no-till/NIT establishment crop productivity and thus plant N uptake is often reduced, and formation of macropore continuity and aggregate stability is limited. This applies especially to soils with low soil carbon content. Up to now the influences of climate drivers (i.e. precipitation regimes, temperature variations) on NT effects on NO3 leaching are not well understood. Further work is needed to investigate the influence of climate drivers on benefits and drawbacks of reduced soil management regarding nitrate leaching.

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Author contributions

AH: data curation; formal analysis; writing – original draft. **ES**: conceptualization; methodology; data curation; formal analysis; writing – review and editing. **CH**: investigation. **KMZ**: investigation. **OH**: writing – review and editing; **TK**: writing – review and editing. **VP**: conceptualization; methodology; formal analysis; writing – review and editing.

Competing interests

The authors declare that they have no conflict of interest.

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Appendices

Appendix A: Lysimeter station Reckenholz belowground

Figure A.1: Lysimeter station Reckenholz belowground (tipping buckets with sampling bottles).

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Appendix B: Photos illustrating treatment differences

Figure B.1: Lysimeter with sugar beet plants under conventional tillage (CT) treatment on May 21st, 2014

Figure B.2: Lysimeter with sugar beet plants under non-inversion tillage (NIT) treatment on May 21st, 2014

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Appendix C: Climatic conditions during observation period

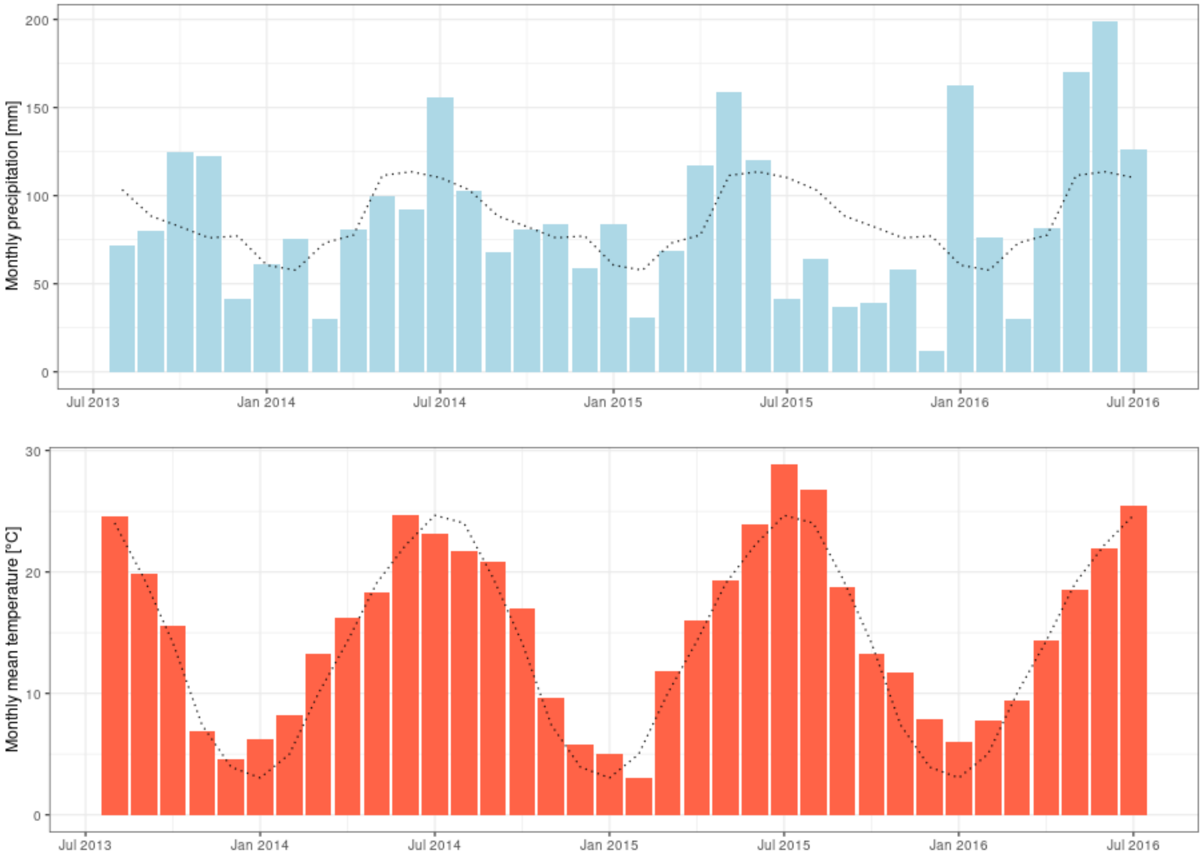

Figure C1: Top: Monthly precipitation sums recorded at MeteoSwiss station Zurich Reckenholz during the experimental period (blue bars) in comparison to long-term averages of monthly precipitation between 1981 and 2010 (dotted line). Bottom: Monthly mean temperatures recorded at MeteoSwiss station Zurich Reckenholz during the experimental period (red bars) in comparison to long-term averages of monthly mean temperatures between 1981 and 2010 (dotted line).

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Appendix D: Soil profile characteristics

Table D.1: Soil texture, pH, bulk density and porosity by layer for each of the three soils in the lysimeter.

	texture					Porosity*				
depth	clay	silt	sand	pH ($CaCl_2$)	bulk density	porosity	<pF 1.8	**pF 1.8 - 3.0**	**pF 3.0 - 4.2**	>pF 4.2
m	%w	%w	%w	- -	g cm^{-3}	%v	%v	**%v**	**%v**	%v
Soil Grafenried										
0 - 0.25	16	32	52	6.3	1.46	44.4	11.6	**3.7**	**11.6**	17.5
0.25-0.65	20	27	53	5.8	1.58	40.6	10.6	**3.2**	**7.7**	19.1
0.65-1.10	18	24	58	5.7	1.55	42.2	11.1	**3.4**	**8.2**	19.4
1.10-1.35	16	27	57	5.9	1.62	39.9	9.2	**3.9**	**8.1**	18.8
1.35-1.50	drainage layer									
Soil Reckenholz										
0-0.25	25	50	25	6.4	1.36	48.4	9.7	**2.7**	**10.8**	25.3
0.25-0.32	24	54	22	6.6	1.44	46.3	9.1	**3.0**	**8.5**	25.6
0.32-0.85	32	48	20	6.5	1.44	46.6	8.4	**2.6**	**7.9**	27.7
0.85-1.05	19	61	20	7.7	1.39	48.6	8.3	**2.9**	**8.7**	28.6
1.05-1.35	18	65	17	7.8	1.61	40.6	4.5	**4.1**	**16.9**	15.1
1.35-1.50	drainage layer									
Soil Schafisheim										
0-0.27	18	28	54	4.8	1.50	42.8	7.6	**2.6**	**10.0**	22.7
0.27-0.60	22	31	47	5.4	1.53	42.6	11.2	**2.5**	**7.4**	21.5
0.60-0.85	26	18	56	5.6	1.47	44.7	12.0	**3.2**	**6.5**	23.0
0.85-1.10	28	22	50	5.8	- -	- -	- -	- -		- -
1.10-1.35	25	21	54	7.2	- -	- -	- -	- -		- -
1.35-1.50	drainage layer									

*Porosities were determined following the procedure described in (Agroscope, 2020)

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Appendix E: Soil temperature, soil moisture and soil water tension

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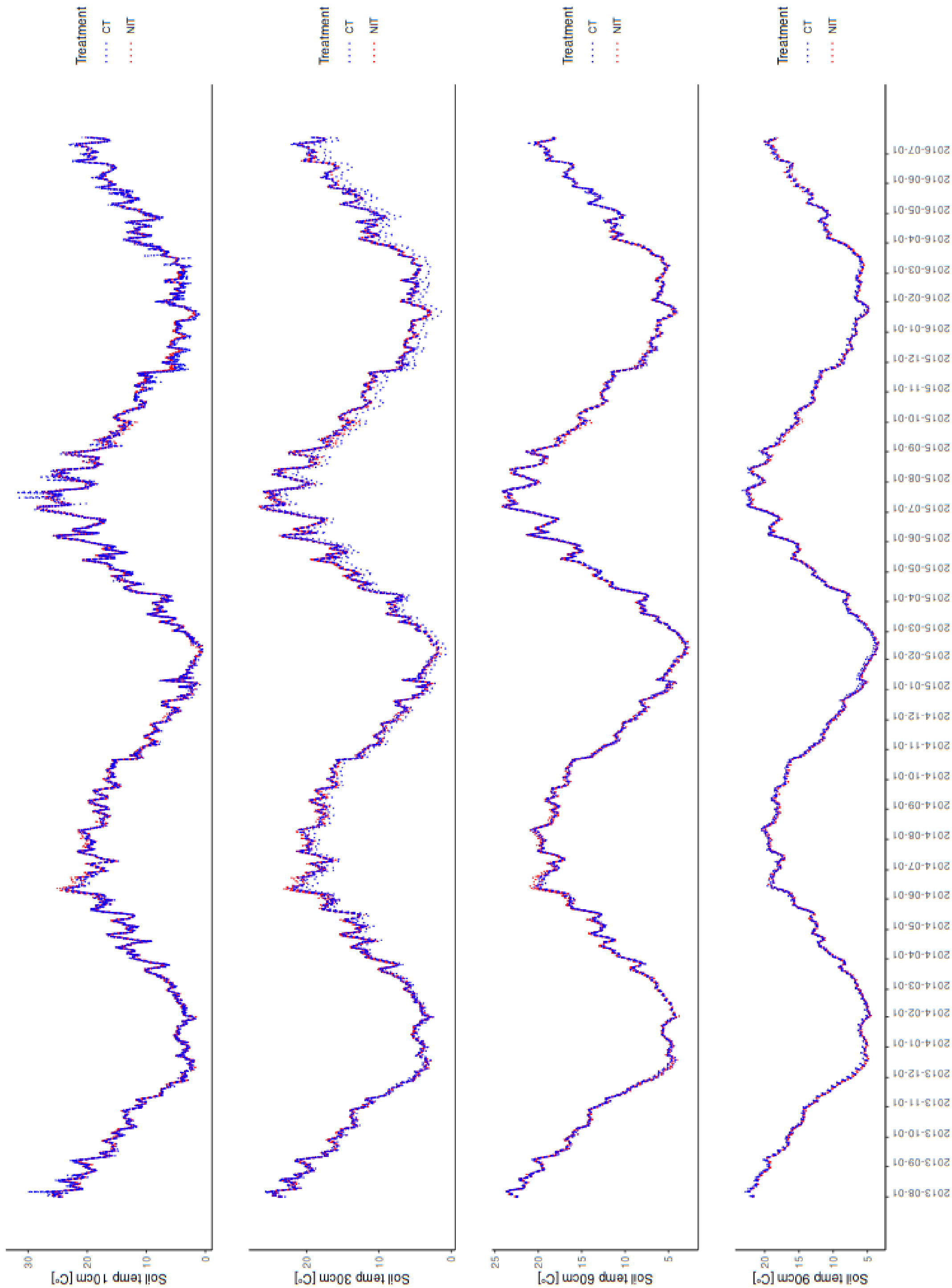

Figure E.1: Soil temperatures recorded in four depths in three lysimeters by treatment (NIT = non-inversion tillage, i.e. chisel plough; CT = conventional tillage, i.e. moldboard plough).

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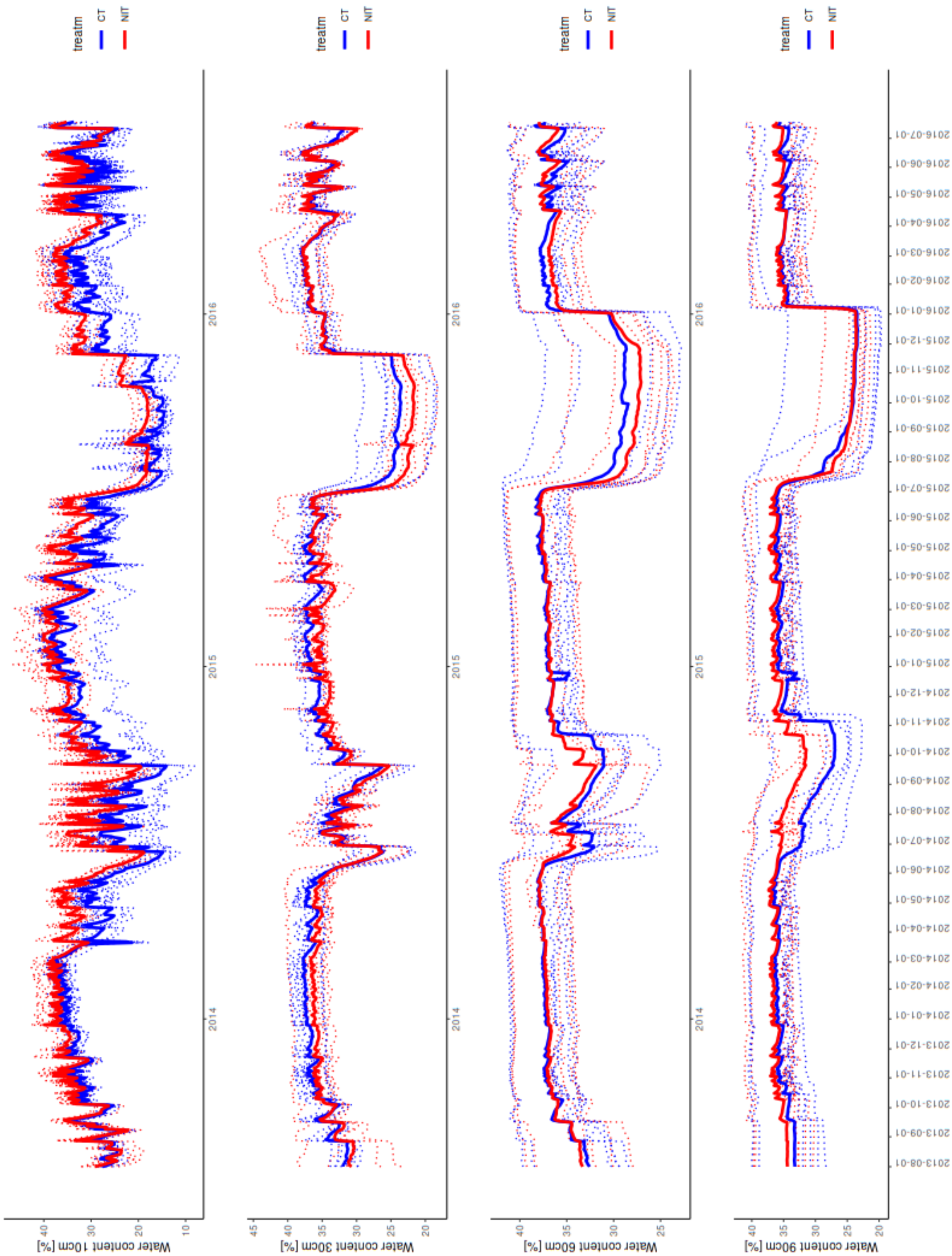

Figure E.2: Soil water contents recorded in four depths in three lysimeters by treatment (NIT = non-inversion tillage, i.e. chisel plough; CT = conventional tillage, i.e. moldboard plough; solid lines indicate mean values by treatment, dashed lines indicate single sensor values).

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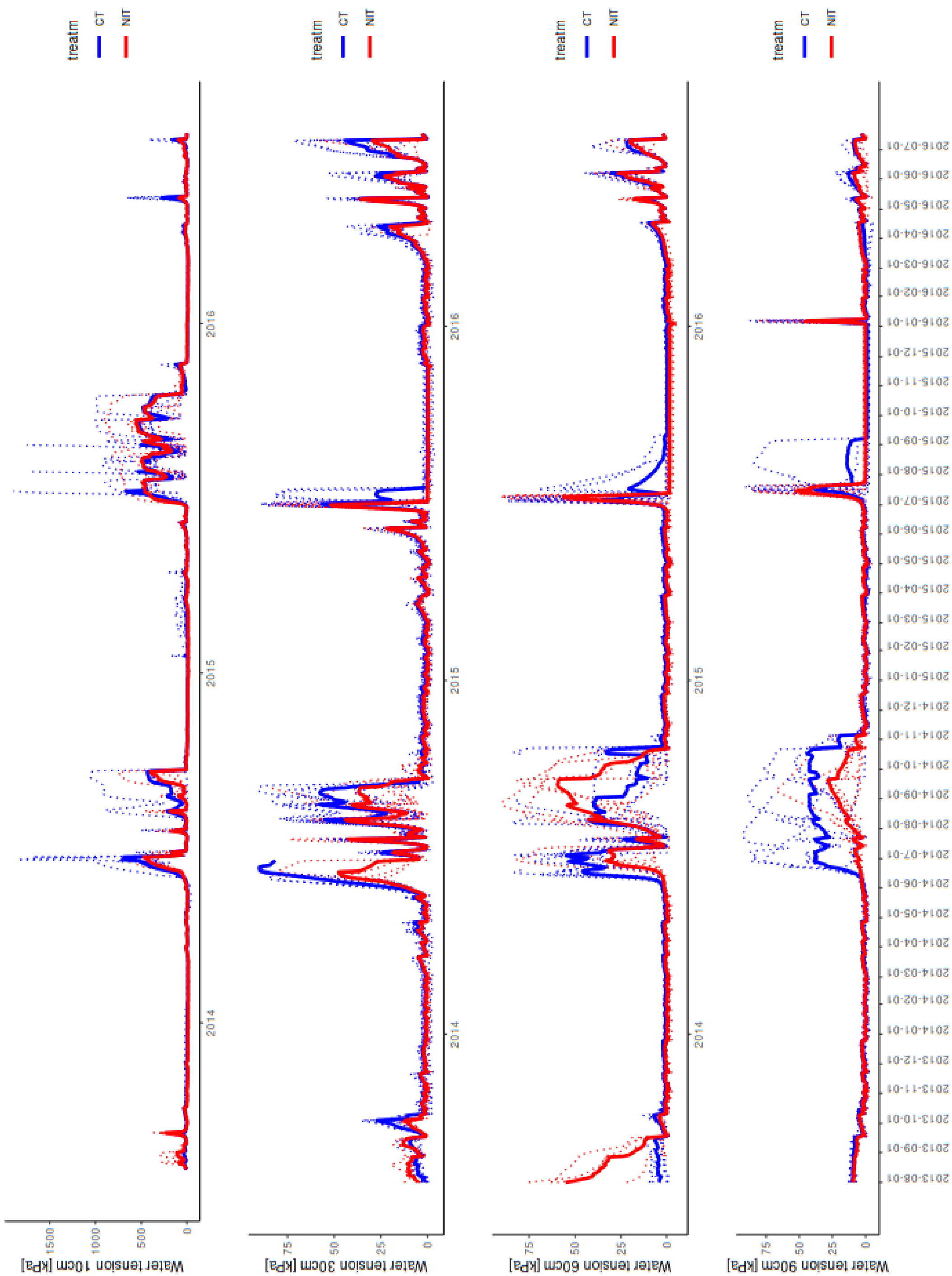

495 **Figure E.3: Soil water tensions recorded in four depths in three lysimeters by treatment (NIT = non-inversion tillage, i.e. chisel plough; CT = conventional tillage, i.e. moldboard plough; solid lines indicate mean values by treatment, dashed lines indicate single sensor values).**

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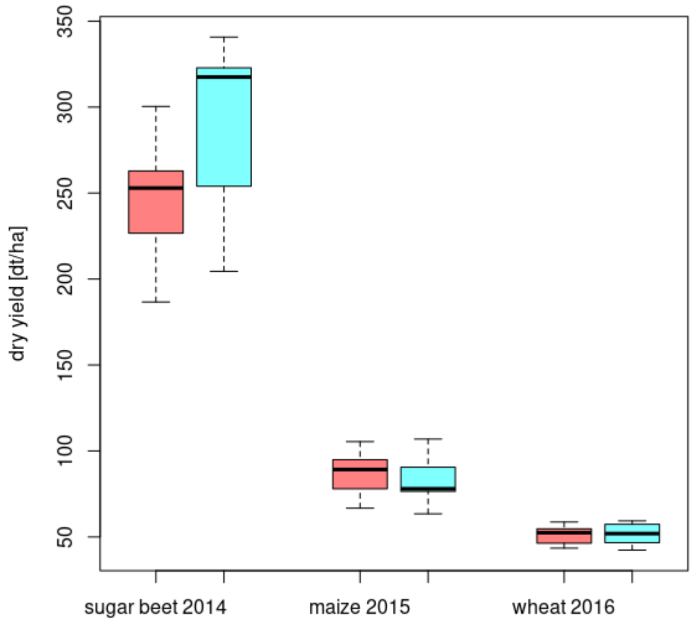
Appendix F: Crop yields



500

Figure F.1: Dry matter yields recorded on lysimeters depending on treatments (red = NIT, blue = CT).