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# Effect of soil warming and rainfall patterns on soil N cycling in Northern Europe

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ABSTRACT

With climate change northern Europe is expected to experience extreme increase in air temperatures, particularly during the winter months, influencing soil temperatures in these regions. Climate change is also projected to influence the rainfall amount, and its inter- and intra-annual variability. These changes may affect soil moisture regimes, soil water drainage, soil nitrogen (N) availability and N leaching to aquatic environment and $N_2O$ emissions to atmosphere. Thus it is important to study the effects of increased soil temperature and varying rainfall patterns on soil N cycling in arable land from temperate climates, which is a major source of N pollution. An open-field lysimeter study was carried out during 2008–2009 in Denmark on loamy sand soil (Typic Hapludult) with three factors: number of rainy days, rainfall amount and soil warming. Number of rainy days included the mean monthly rainy days for 1961–1990 as 'normal' and half the number of rainy days of former as 'reduced' treatments. Rainfall amount included mean monthly rainfall for 1961–1990 as 'present' and the projected change in mean monthly rainfall for 2071–2100 as 'future' treatments. Soil warming included increase in soil temperature by 5 °C at 0.1 m depth as 'heated' and non-heated as 'control' treatments. Automated mobile rain-out shelter and irrigation system, and insulated buried heating cables were used to impose the treatments.

Soil warming, compared with unheated control, advanced winter wheat crop development, and increased the above-ground biomass and N uptake only during vegetative stage, but shortened the total crop growing period by 12 days without reducing the total above-ground biomass. Rainfall amount and rainy days treatments increased the drainage, 46% and 10%, respectively, but did not have additive effect on the drainage. In contrast, soil warming increased crop evapotranspiration (18%) and reduced drainage (41%). The projected future rainfall amount increased $NO_3$-N leaching (289%) compared with present rainfall amount. The study showed significant interaction between soil warming and rainfall amount ($P < 0.001$) with heated plots reducing $NO_3$-N leaching both under present and future rainfall amount offsetting the adverse effect of increased future rainfall on $NO_3$-N leaching. Soil warming, compared to control, consistently increased the soil $NO_3$-N availability during the crop growing season and left higher levels of $NO_3$-N in the plough layer (19 kg N ha$^{-1}$) even after harvest of crop posing a potential risk of increased leaching in the following autumn/winter seasons. The results suggest that while the projected future rainfall patterns increase drainage and N leaching, warmer winters, on the contrary, seems to offset this effect through increased water and N removal by the advanced crop growth and development during winter.



## 1. Introduction

By the end of 21st century mean global surface temperatures are projected to increase between 1.8 and 4.0 °C due to anthropogenic warming (IPCC, 2007). This warming is expected to be most extreme at high latitudes and during the winter months influencing soil temperatures in these regions (Peng and Dang, 2003). Global warming is also expected to influence inter- and intra-annual variability of precipitation regimes (Christensen et al., 2007). Many climate change projections suggest that longer duration dry periods interspersed with extreme rainfall events will become more frequent (Mearns et al., 1995; Frederick and Major, 1997; Easterling et al., 2000). These changes under warmer climates result in extended periods of soil moisture deficit and larger variability in soil water content (Jackson et al., 2001; Hlavinka et al., 2009). Since both temperature and precipitation regimes are projected to change with climate change affecting not only crop water availability but also soil nitrogen (N) transformations and losses, and thus crop N supply, it becomes important to study their effects soil N dynamics (Wang et al., 2006).

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Temperature is a key factor that regulates many terrestrial biogeochemical processes (see Rustad et al., 2001). To demonstrate the effect of warmer climate on soil processes, soil warming experiments using heating cables have been conducted on perennial grasslands and forest tree species in temperate climates (see Lukewille and Wright, 1997). While some studies have shown increase in soil N availability (Van Cleve et al., 1990), $NO_3$-N concentrations (McHale et al., 1996; Lukewille and Wright, 1997), and nitrification and net N mineralisation (Verburg et al., 1999) in heated soils, other studies have shown either no change in the soluble N levels (Hantschel et al., 1995) or negligible increase in net N mineralisation and net N nitrification (Rustad et al., 1996). The range of increase in soil temperature (2.5–7.5 °C) and the depth at which heating cables were placed or buried in soil (0–0.05 m) varied among these studies, as did soil and above-ground vegetation type. Rustad et al. (2001) conducted meta-analysis of data from 32 experimental ecosystem warming projects, and reported significant increases in soil respiration, net N mineralization, and aboveground plant productivity. Most of these study sites (31 out of 32) sites represented perennial woody species under N-limited environments. However, little is known about the effects of soil warming on arable ecosystems from temperate climates (Ineson and Benham, 1991; Hillier et al., 1993; Kamp et al., 1998). Arable lands, generally in northern Europe, represent intensive and N-sufficient ecosystems, and are the major source of N pollution (Berntsen et al., 2006). If N mineralization under the influence of increased temperature exceeds immobilization by the soil microbial biomass and crop uptake, especially during the winter period, excess N can leach down beyond the crop root zone and may result in eutrophication of aquatic ecosystems (Verburg et al., 1999).

Few field studies carried out on soil warming in agriculture systems have only looked at the crop response and productivity reporting changes in plant growth, biomass accumulation and nutrient absorption rates to a small increase in soil temperature (Clarkson et al., 1992; Engels and Marschner, 1992; Gavito et al., 2001). Hartley et al. (2007) found no effect of soil warming on plant development for wheat (*Triticum aestivum*), but observed advanced flowering and lower specific leaf area in maize (*Zea mays*) without any significant effect on final biomass. Kamp et al. (1998), however, looked at soil N availability and found higher $NO_3$-N and lower $NH_4$-N content in heated plots at several sampling dates in both fallow and wheat fields.

Similarly, very few studies have reported the impact of greater intra-annual precipitation variability on arable land (e.g. Dickin et al., 2009). Hagedorn et al. (1997) observed fluctuation in soil moisture influencing net N mineralization, with the intensity and timing of rainfall at the start of crop season determining N availability during the cropping season. Elevated soil temperature is expected to stimulate microbial activity thereby increasing the N mineralisation and accelerate diffusion of soluble substrates in soil (MacDonald et al., 1995; Zak et al., 1999). However, it is uncertain how net N mineralisation, N uptake by vegetation, and N leaching will respond as a whole (Luxmoore et al., 1998) from N-rich arable crops ecosystems as both release of inorganic N from soil organic matter and subsequent nitrate movement in the soil profile are strongly affected by rainfall amount and distribution, through its effects on temporal soil water status and percolation (Hasegawa and Denison, 2005). Therefore, combining the projected rainfall patterns (amount and frequency) and soil warming to investigate the main and interactive effects of multiple climate change factors would help in quantifying and understanding the soil N cycling and $NO_3$-N leaching. This would help not only in optimising the input management and improving the crop yields under changing climates, but also in containing the $NO_3$-N pollution of surface and aquatic waterbodies. However, with the projected future (2071–2100) rainfall amount for northern Europe showing a significant increase during winter (Christensen and Christensen, 2007), we hypothesised that nitrate leaching losses increase further. We also hypothesised that increased rainfall amount and intensity will have additive effect on drainage and N leaching, whereas, increased soil temperatures increase the soil N availability.

Though several methods are available to assess drainage and nitrate leaching in field experimentation, lysimeters provide direct and accurate measure of water and nitrate fluxes (Beaudoin et al., 2005). Thus, a lysimeter experiment was carried out to evaluate the main and combined effects of varying rainfall frequency, rainfall amount and soil warming on: (a) temporal soil moisture regimes and drainage flux, (b) soil $NO_3$-N content, N leaching and $N_2O$ emission losses, and (c) their effect on winter wheat crop growth and N uptake on a loamy sand soil in Denmark.

## 2. Materials and methods

### 2.1. Lysimeter facility

The experiment was conducted in outdoor concrete lysimeters at Aarhus University, Faculty of Agricultural Sciences, Foulum, Denmark (56°29′N, 9°34′E). Each lysimeter had a volume of 1.5 $m^3$ (surface area = 1 × 1 m, depth = 1.5 m) filled with loamy sand soil (Typic Hapludult) (Table 1). These lysimeters were built and filled with soil in 1992, and since then are being regularly used for agronomic experimentations. The surface of the lysimeters was at the same level as the surrounding field. An automated mobile rain-out shelter (50 × 10 × 8 m; $L \times W \times H$) equipped with a rain sensor covered all the lysimeters only during precipitation. The two sides along its 50 m length and the top were covered with roofing material while the other two sides were open. This allowed ambient air to freely pass through it over lysimeters and crops were exposed to diffuse day light even when the rain-out shelter fully covered all the lysimeters while it rained. However, we did not record how much of the time the lysimeters were covered by rain-out shelter and its possible impact on light levels during the study period.

A computer controlled mobile irrigation system had four metal frames of the same size as surface area of lysimeters (1 × 1 m) and moved from one plot to other in their respective lysimeter rows. Each frame had eight rows of continuous plastic pipe (0.015 m diameter) mounted with drippers at a regular spacing to deliver water. These frames were also able to move vertically (up and down) as were equipped with sensors to locate crop height, which enabled the frames to hang just over the top of the crop. This allowed the automated irrigation system in locating any of the chosen lysimeter and applying a targeted amount of water (pH 7.5) at a required intensity to closely match that of natural rain. The water treatment schedule started on 1 November 2008 and continued until harvest.

In each heated lysimeter an insulated heating-cable was placed in the crop rows at 0.1 m depth during tillage and connected to a power supply, whereas soil in the unheated (control) lysimeters was also tilled, but no heating-cables were placed in them. A programmed computer controlled the soil warming set up and the soil temperature was monitored using sensors (Campbell Scientific Inc., Germany) placed horizontally in the middle between the heating cable rows at 0.05 m, 0.1 m and 0.25 m depths in heated plots and control plots. Sensors were connected to a data logger, which monitored temperature every 15 s, and a heater maintained the temperature at 0.1 m depth in heated plots at 5 °C above their respective control plots. Data were stored every 15 min and later averaged for each day.

**Table 1**
Physical properties of loamy sand soil in lysimeters.

| Depth (m) | Dry bulk density (Mg m$^{-3}$) | Organic matter (Mg m$^{-3}$) | Clay (%) | Silt (%) | Fine sand (%) | Coarse sand (%) |
|---|---|---|---|---|---|---|
| 0–0.3 | 1.5 | 2.5 | 9.0 | 11.0 | 45.0 | 35.0 |
| 0.3–0.6 | 1.5 | 0.5 | 12.0 | 11.0 | 45.0 | 32.0 |
| 0.6–0.9 | 1.6 | 0.2 | 14.0 | 11.0 | 44.0 | 31.0 |
| 0.9–1.4 | 1.6 | 0.1 | 16.0 | 11.0 | 43.0 | 30.0 |
| 1.4–1.5 | Filled with small pebbles and gravel for free drainage | | | | | |

### 2.2. Experimental design and treatments

The experiment was laid out in a split-split plot design with three factors and two levels in each factor: (i) number of rainy days (RD) assigned to main plots and levels were normal ($RD_0$) and reduced ($RD_1$) number of rainy days, (ii) rainfall amount (RF) assigned to sub plots and levels were present ($RF_0$) and future ($RF_1$) rainfall amounts, and (iii) soil warming (SW) assigned to sub–sub plots and levels were unheated as control ($SW_0$) and soil warming ($SW_1$) at 5 °C above control at 0.1 m depth. The total of eight treatment combinations was replicated four times using 32 lysimeters.

Rainfall data for the period 1961–1990 from the local weather station was considered as the reference for defining the rainfall treatment. A day (0–24 h) with a minimum of 1 mm rainfall was counted as one rainy day, while anything less than that was added to the rainfall of its nearest rainy day to have at least 1 mm day$^{-1}$ or more as the automatic irrigation system was programmed to apply a minimum of 1 mm water (1 l m$^{-2}$) or more.

The average monthly number of rainy days for the reference period (1961–1990) was taken as normal number of rainy days ($RD_0$) and the treatment with 50% fewer rainy days was regarded as the reduced number of rainy days ($RD_1$). Both $RD_0$ and $RD_1$ treatments received the same amount of rainfall, but $RD_1$ represented heavy rainfall on each event with a longer dry period in between (Table 2). Many climate change predictions suggest that long dry periods and extreme rainfall events will become more frequent in the future (Mearns et al., 1995; Frederick and Major, 1997; Easterling et al., 2000), though no study has predicted expected changes in rainfall intensity or number of rainy days. Therefore, 50% reduction in number of rainy days with $RD_1$ treatment was not based on any climate change scenarios, but considered to achieve significant increase in rainfall intensity of each rainfall event (mm day$^{-1}$) to study its effect on drainage and leaching flux.

The average annual rainfall amount of 627 mm for the reference period (1961–1990) was regarded as the present rainfall amount ($RF_0$) and the projections made for Denmark for the period 2071–2100 (658 mm) under the IPCC A2 emission scenario (Christensen and Christensen, 2007) was regarded as the future rainfall amount ($RF_1$). Though the increase in projected annual rainfall amount ($RF_1$) is only 5%, there is a significant variation between seasons with increased rainfall during winter and less in summer (Table 2).

Soil warming set up was turned on 13 days after sowing (23 October) and the soil temperature in all the heated plots ($SW_1$) was maintained at 5 °C above the temperature of control plots ($SW_0$) at 0.1 m depth throughout the study period.

### 2.3. Wheat crop management

Winter wheat (*Triticum aestivum* L. cv. Ambition) seeds were sown (300 seeds m$^{-2}$) on 10 October 2008 at a row spacing of 0.13 m accommodating eight rows in each plot. Since sowing coincided with a sudden drop in air temperatures, the germination of seeds and seedling emergence was severely reduced. Gaps due to failed germination were filled with wheat seedlings raised in soil trays under controlled conditions, which at full emergence of the first leaf were transplanted to obtain a final plant stand of 150 plants m$^{-2}$. Inorganic fertilizer in granular form was applied on the soil surface to supply 170 kg N ha$^{-1}$, which contained 91 g kg$^{-1}$ $NO_3$-N, 115 g kg$^{-1}$ $NH_4$-N, 26 g kg$^{-1}$ P, 96 g kg$^{-1}$ K, 36 g kg$^{-1}$ S, 11 g kg$^{-1}$ Mg and 0.2 g kg$^{-1}$ Bo. On both 27 February and 21 March, 10 kg N ha$^{-1}$ was applied, while the remaining 150 kg N ha$^{-1}$ was divided equally and applied on 3 April and 1 May 2009. Lucerne (alfalfa) had been grown in all lysimeters for two years as the pre-crop without applying fertilizers. During this period the lucerne was cut at regular intervals and residues were removed. On 1 October 2008 the above-ground vegetative part of lucerne was cut for the last time and removed from the plots, including stubble. Major roots from the plough layer were also removed to allow a uniform seed bed preparation and to place the heating cables accurately. Tillage was performed manually by inverting the top 0.2 m of soil. Pest and weed control measures followed recommended agronomic practices.

### 2.4. Measurements

Volumetric soil water contents (%) in 0–1 m soil layer were measured in all the treatments from two replicates, on average three times a week from 7 November 2008 until the crop was harvested, using segmented (0–0.2, 0–0.5 and 0–1 m) time domain reflec-

**Table 2**
Mean monthly soil temperature at 0.1 m depth and air temperature (°C) at 2 m above surface in heated ($SW_1$) and control ($SW_0$) treatments, monthly rainfall amount (mm) under present ($RF_0$) and future ($RF_1$) rainfall amount treatments, and monthly change (%) in rainfall of $RF_1$ over $RF_0$ imposed in the study.

| Month | Soil temp. (°C) at 0.1 m depth | | Air temp. (°C) at 2 m height | Rainfall amount (mm) | | Monthly change (%) in $RF_1$ over $RF_0$ |
|---|---|---|---|---|---|---|
| | $SW_0$ | $SW_1$ | | $RF_0$ | $RF_1$ | |
| October | 7.6 | 12.5 | 8.7 | 67 | 82 | +22 |
| November | 5.1 | 10.2 | 4.9 | 68 | 77 | +13 |
| December | 3.0 | 8.0 | 1.7 | 51 | 66 | +29 |
| January | 1.3 | 6.3 | 0.6 | 36 | 54 | +50 |
| February | 1.0 | 6.0 | 0.3 | 29 | 43 | +48 |
| March | 4.3 | 9.3 | 3.6 | 41 | 50 | +22 |
| April | 10.3 | 15.3 | 9.4 | 35 | 33 | −6 |
| May | 12.3 | 17.3 | 10.8 | 45 | 45 | 0 |
| June | 15.3 | 20.3 | 13.4 | 53 | 54 | +2 |
| July | 18.8 | 23.7 | 16.4 | 67 | 62 | −7 |
| August | 19.5 | 24.6 | 16.5 | 66 | 41 | -38 |

tometry (TDR) probes (Campbell Scientific Inc., Germany). These daily soil moisture data were used to calculate monthly average soil moisture deficit (SMD; in mm) as the difference between soil moisture at field capacity and the actual soil moisture recorded on each measurement and averaged for each month during the study period.

Crop phenology during the study period was recorded using the BBCH scale for cereals (Lancashire et al., 1991). Destructive above-ground biomass sampling was done on four dates; 28 April, 15 June, 15 July and at maturity (27 July and 7 August in $SW_1$ and $SW_0$, respectively), by cutting the plants at the soil surface ($0.1\,m^{-2}$) from two replicates. The total above-ground biomass and its partitioning into various plant parts were recorded on an oven dry basis (80 °C for 48 h). A representative sample from the partitioned plant parts was ground to fine powder and analysed for plant N concentration ($mg\,N\,g^{-1}$) using a LECO CNS-1000 Elemental Analyser (LECO Corporation, USA). The N concentration ($mg\,N\,g^{-1}$) in various plant parts was multiplied with their respective oven dried biomass ($g\,m^{-2}$) to calculate the total N amount in above-ground plant parts ($mg\,N\,m^{-2}$) and presented in $kg\,N\,ha^{-1}$.

Soil mineral N content ($NO_3$-N and $NH_4$-N) was measured at 0–0.3 m depth in each treatment once per month from four replicates at the start (9 October 2008) and end of the study (18 August 2009), and from only two replicates during the study period (November 2008 to July 2009). Three soil cores per lysimeter were pooled to derive a composite sample for each lysimeter. The sampled holes were immediately filled with the local Foulum soil and were thereafter unused. Each month, soon after sampling, the sieved soil (2 mm size) was analyzed for inorganic N concentrations ($NO_3$-N and $NH_4$-N) using a 10 g sub-sample of each composite soil sample in 40 mL 1 M KCl extraction solution. The soil-KCl solution was shaken for 30 min and extraction was filtered into sample vials and frozen (−20 °C) for later analysis on a Bran+Luebbe-AutoAnalyzer3 (SPX Process Equipment, Norderstedt, Germany). The amount of $NO_3$-N and $NH_4$-N was added to derive total mineral N and was transformed to $kg\,N\,ha^{-1}$ using average bulk density of the soil at 0–0.3 m layer and the gravimetric water content measured after each sampling.

Each lysimeter had a hole at its bottom which was connected with a polyethylene pipe to a plastic can to collect drainage water under zero tension. The drainage volume (mm) from each lysimeter (four replicates) was measured on a weekly basis, and a sub-sample from each lysimeter was analysed for $NO_3$-N and $NH_4$-N leaching concentrations ($mg\,L^{-1}$) on a Bran+Luebbe-AutoAnalyzer3. Total drainage (mm) and total $NO_3$-N and $NH_4$-N leaching losses ($kg\,N\,ha^{-1}$) were calculated using the collected drainage volume ($L\,m^{-2}$), and the measured $NO_3$-N and $NH_4$-N concentrations ($mg\,N\,L^{-2}$) on weekly basis. The total drainage flow-weighted $NO_3$-N leaching concentrations ($mg\,N\,L^{-1}$) were calculated representing weighted averages for the study period based on total drainage flux ($L\,ha^{-1}$) and $NO_3$-N leaching losses ($kg\,N\,ha^{-1}$) during the sampling period. Evapotranspiration (sum of evaporation and transpiration) was not directly measured in this study but calculated as the difference between rainfall (irrigation input), drainage water collected and the total change in soil water storage during the study period. Similarly, the amount of active pore volumes leached was calculated using average soil moisture at field capacity (pF 2) and the total soil volume (1 × 1 × 1.4 m).

Fluxes of $N_2O$ from the soil were measured using closed static chambers. Each chamber of 1 $m^3$ size (1 × 1 × 1 m) was built using white polyvinyl chloride sheets (5 mm thick) and aluminium frames leaving the bottom side open. The white colour of the chambers minimised heating due to solar radiation during the period of gas collection. A battery operated fan was fixed inside the chamber to ensure mixing of the gas. Each lysimeter had concrete collars (25 mm thick) and rubber cushion patches to enable the chambers to rest firmly on the concrete collars of lysimeters. Gas samples were collected with an accumulation time of 60 min and 45 min between two samples during winter and spring, respectively. Gas measurements were done, on average, once a week between February and May. Each chamber was equipped with 10 mm hole on top side in which a rubber stopper was inserted. Gas sample was collected using a 20 mL nylon syringe with a needle by sampling through the stopper. The syringe plunger was slowly drawn in and out a couple of times to insure against sample heterogeneity, and a 20 mL sample was taken and stored in 20 mL capacity evacuated vials (Labco Limited High Wycombe, UK). The height of the chambers was 1 m, and as plants grew taller it became difficult to move chambers between lysimeters and place them on concrete collars without damaging plants growing inside the lysimeters. Hence, we had to stop gas measurements at the end of May.

### *2.5. Statistical analyses*

Data were subjected to analysis of variance using split–split-plot design with the Genstat, version 8.1 (Lawes Agricultural Trust, Rothamsted Experimental Station, UK). Where significant, differences between means of main factor effects and their interactions were compared by determining the values of the least significant difference at $P < 0.05$ when presenting the results. A lysimeter plot, the smallest unit in the experiment within each replication, was treated as 'covariate' as each lysimeter soil column was considered independent. Interactions are presented in the results only when found to be significant.

## 3. Results

### *3.1. Soil temperature and rainfall patterns*

During the study period, the daily mean temperature differences at 0.1 m depth between heated and control plots were $5.0 \pm 0.005$ °C ($n = 277$ days). At a depth of 0.05 m and 0.25 m the mean soil temperature for the study period in heated plot was 4 °C and 2.5 °C higher compared with that in control plots at corresponding depths, suggesting that soil warming through buried heating-cables affected a large part of the plough layer soil volume. The monthly mean soil temperatures at 0.1 m depth in control and heated treatments are presented in Table 2.

Rainfall treatments imposed in this study altered both the amount and timing of precipitation (Table 3). Future rainfall ($RF_1$) treatment received approximately 60 mm more rainfall during winter (November–March), while total rainfall during spring/summer (April–July) did not differ between RF treatments (Table 3). The protocol for simulating reduced rainfall frequency with $RD_1$ treatment by reducing the number of rainy days by half led to increase in mean rainfall event size ($7.5\,mm\,day^{-1}$) during the study period compared with $RD_0$ treatment ($4\,mm\,day^{-1}$). This also reduced the number of small rain events ($\geq 9\,mm\,day^{-1}$) by more than half in $RD_1$ treatment compared to $RD_0$, whereas the number of heavy rainfall events ($>10\,mm\,day^{-1}$) was not affected (Table 3). Despite altering the rainfall frequency, majority of dry periods (number of days without rainfall) were short in nature (<6 days) making up 86% and 70% of the total dry periods in $RD_0$ and $RD_1$ treatments, respectively.

### *3.2. Soil moisture regime and drainage*

Soil moisture at the start of imposing rainfall treatments (1 November) was not significantly different between various treatments (Fig. 1). During the whole study period the monthly average soil moisture deficit (SMD) calculated for 0–1.0 m depth showed no significant effect of RF and RD treatments (Fig. 2b and c). In

**Table 3**
Total rainfall amount (mm) applied during winter (November–March) and thereafter until the harvest of crop (April–July), and the characteristics of rainfall frequency imposed during the study period in different rainfall pattern (RF and RD) treatments.

| | Present rainfall ($RF_0$) | | Future rainfall ($RF_1$) | |
|---|---|---|---|---|
| | Normal rainy days ($RD_0$) | Reduced rainy days ($RD_1$) | Normal rainy day ($RD_0$) | Reduced rainy days ($RD_1$) |
| Rainfall applied (mm) | | | | |
| November–March | 200 | 202 | 256 | 263 |
| April–July | 200 | 200 | 194 | 193 |
| Total | 400 | 402 | 450 | 456 |
| Number of rain events | | | | |
| <5 mm | 70 | 28 | 76 | 30 |
| 5–9 mm | 21 | 12 | 16 | 9 |
| 10–19 mm | 8 | 12 | 13 | 14 |
| >20 mm | 1 | 4 | 1 | 6 |
| Number of dry periods | | | | |
| ≤3 days | 38 | 23 | 40 | 26 |
| <6 days | 7 | 7 | 6 | 9 |
| 6–9 days | 4 | 11 | 6 | 10 |
| ≥10 days | 3 | 4 | 2 | 3 |

contrast, soil warming ($SW_1$) significantly increased SMD for January ($P = 0.044$), February ($P = 0.039$), April ($P = 0.035$) and May ($P = 0.013$): the latter month coincided with the peak growing period of crop (Fig. 2a). However, no factor had significant effect on total change in soil water ($\Delta S$) for the whole study period in 0–1 m soil layer (Table 4).

Both the rainfall amount (RF) and number of rainy days (RD) treatments showed significant effects on total drainage (Table 4). Reduced number of rainy days ($RD_1$) marginally increased the total drainage by 10% compared with normal number of rainy days ($RD_0$). Future rainfall amount ($RF_1$) significantly increased the drainage by 46% compared with present rainfall amount ($RF_0$). Soil warming ($SW_1$), on the contrary, significantly reduced the drainage ($P < 0.001$), and the reduction was equivalent to 41% compared with drainage in control ($SW_0$) (Table 4). None of the interactions were significant.

### 3.3. *Nitrate leaching concentrations*

As the total $NH_4$-N leaching losses recorded (0.05 kg N ha$^{-1}$) made up less than 0.01% of total N leaching losses, only $NO_3$-N leaching concentrations and losses are presented in this paper. The total drainage flow-weighted average $NO_3$-N leaching concentration was significantly increased by future rainfall amount ($RF_1$) compared with present rainfall amount ($RF_0$), while the number of rainy days (RD) treatments showed no effect. On the contrary, soil warming ($SW_1$) significantly reduced the weighted average $NO_3$-N leaching concentrations compared with control (Table 4). Interactions between rainfall amount (RF) and soil warming (SW) were found significant with the treatment combinations of $RF_1 \times SW_0$ and $RF_0 \times SW_1$ recording significantly the highest (10.1 mg N L$^{-1}$) and the lowest (0.5 mg N L$^{-1}$) concentrations, respectively (Table 4).

**Table 4**
Total crop evapotranspiration (ET), total change in soil water ($\Delta S$) between start and end of study period and total drainage (all in mm), and total $NO_3$-N leaching (kg N ha$^{-1}$) and the total drainage flow-weighted $NO_3$-N leaching concentrations (mg N L$^{-1}$) during the study period.

| Treatments | Crop ET (mm) | $\Delta S$ (mm) | Total drainage (mm) | Total $NO_3$-N leaching (kg N ha$^{-1}$) | Drainage flow-weighted $NO_3$-N leaching concentrations (mg N L$^{-1}$) |
|---|---|---|---|---|---|
| Rainy days | | | | | |
| $RD_0$ | 462 | −136 | 129 | 6.4 | 3.9 |
| $RD_1$ | 448 | −135 | 142 | 7.9 | 4.5 |
| *P*-value (<0.05) | NS | NS | 0.037 | NS | NS |
| Rainfall amount | | | | | |
| $RF_0$ | 442 | −130 | 110 | 2.9 | 2.1 |
| $RF_1$ | 468 | −141 | 161 | 11.3 | 6.3 |
| *P*-value (<0.05) | NS | NS | <0.001 | <0.001 | <0.001 |
| Soil warming | | | | | |
| $SW_0$ | 417 | −133 | 170 | 12.4 | 6.9 |
| $SW_1$ | 492 | −138 | 101 | 1.8 | 1.5 |
| *P*-value (<0.05) | <0.001 | NS | <0.001 | <0.001 | <0.001 |
| Interactions | | | | | |
| $RD_0 \times SW_0$ | – | – | – | 11.3 | – |
| $RD_0 \times SW_1$ | – | – | – | 1.4 | – |
| $RD_1 \times SW_0$ | – | – | – | 13.6 | – |
| $RD_1 \times SW_1$ | – | – | – | 2.2 | – |
| *P*-value (<0.05) | NS | NS | NS | 0.034 | NS |
| $RF_0 \times SW_0$ | – | – | – | 5.4 | 3.7 |
| $RF_0 \times SW_1$ | – | – | – | 0.4 | 0.5 |
| $RF_1 \times SW_0$ | – | – | – | 19.4 | 10.1 |
| $RF_1 \times SW_1$ | – | – | – | 3.3 | 2.5 |
| *P*-value (<0.05) | NS | NS | NS | <0.001 | <0.001 |

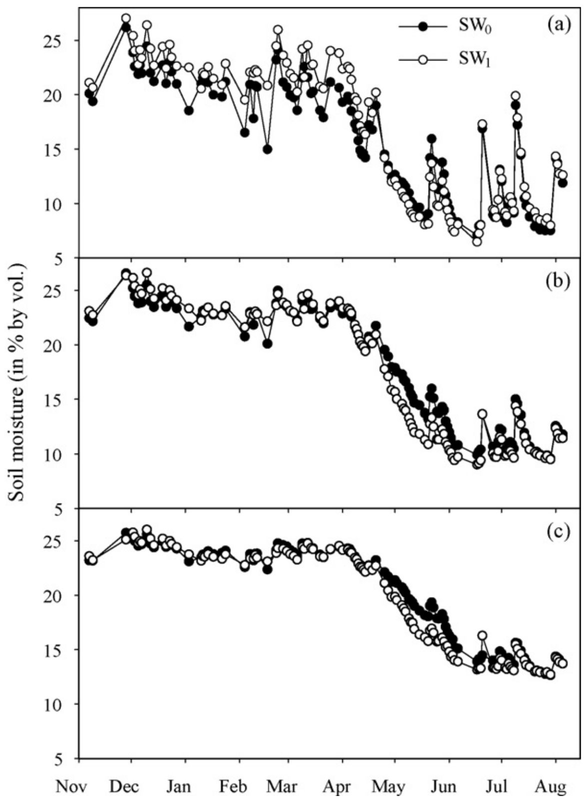


**Fig. 1.** Daily mean ($n = 8$) soil moisture (% by vol.) in (a) 0–0.2 m, (b) 0–0.5 m and (c) 0–1 m soil layer under control ($SW_0$) and heated ($SW_1$) treatments.

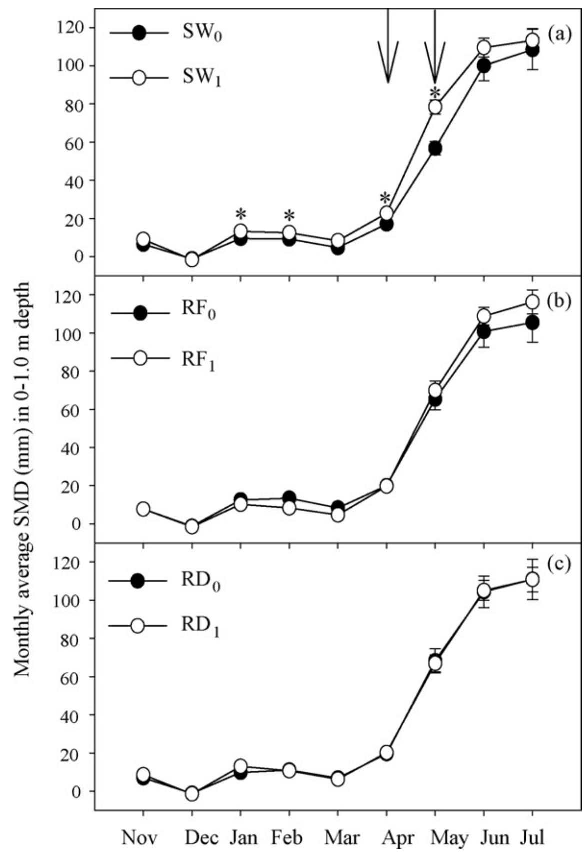


**Fig. 2.** Monthly average soil moisture deficit (mm) in 0–1 m depth as influenced by (a) control ($SW_0$) and heated ($SW_1$), (b) present ($RF_0$) and future ($RF_1$) rainfall amount, and (c) normal ($RD_0$) and reduced ($RD_1$) number of rainy days treatments during the crop growing period. Vertical bars show ±S.E. with $n = 8$. Arrows and asterisks indicate time of fertilizer application and significant at $P < 0.05$, respectively.

### 3.4. Total $NO_3$-N leaching losses

Future rainfall amount ($RF_1$) significantly increased total $NO_3$-N leaching losses compared with present rainfall amount ($RF_0$), while soil warming ($SW_1$) significantly reduced the total $NO_3$-N leaching losses. However, the number of rainy days (RD) treatments showed no significant effect (Table 4). The total $NO_3$-N leached with future rainfall amount ($RF_1$) was equivalent to 289% compared with present rainfall amount ($RF_0$) treatment. With soil warming ($SW_1$) the extent of reduction in $NO_3$-N leaching was 85% compared with leaching in control ($SW_0$). Among the interactions, RD × SW and RF × SW were found statistically significant. While $RD_0 \times SW_1$ followed by $RD_1 \times SW_1$ resulted in significantly lower $NO_3$-N leaching losses, $RF_1 \times SW_0$ recorded significantly the highest $NO_3$-N leaching losses (Table 4).

### 3.5. Soil mineral N content

Soil $NO_3$-N content in top 0.3 m layer was not significantly influenced by rainfall amounts (RF), even though the future rainfall amount ($RF_1$) treatment periodically resulted in lower $NO_3$-N content during the study period (Fig. 3d). The rainfall frequency (RD) treatments showed no effect on soil $NO_3$-N content. In contrast, soil warming significantly increased the soil $NO_3$-N content during winter (January–March) and in summer (June–August), while the effect of soil warming in spring (April–May) was masked by the application of 150 kg N $ha^{-1}$ in two equal splits on 3 April and 1 May (Fig. 3a). None of the factors had any effect on soil $NH_4$-N content (Fig. 3b and e). The analysis of total mineral N (SMN) content showed no effect of rainfall amount (RF) and frequency (RD) treatments, but soil warming ($SW_1$) significantly increased the total mineral N content in winter (January–February) and later in summer (July–August) closely following the variation in soil $NO_3$-N content (Fig. 3c and f).

### 3.6. Soil $N_2O$-N fluxes

Cumulative fluxes of $N_2O$-N between two sampling dates from heated and control plots varied over time from an uptake of 11.7 $N_2O$-N g $ha^{-1}$ to emission of 35.7 g $N_2O$-N $ha^{-1}$ (Fig. 4). None of the negative fluxes were significant, and overall fluxes were very low and highly variable. However, a clearer temporal pattern existed with fluxes from heated plots being consistently higher than from control during winter, while it varied with no pattern during spring time. None of the factors had any significant effect on the total accumulated $N_2O$-N fluxes, though soil warming recorded a total of 52 (±1.8) g $N_2O$-N $ha^{-1}$ emissions compared with 16 (±3.1) g $N_2O$-N $ha^{-1}$ from control for the measurement period.

### 3.7. Crop phenology, above-ground biomass and N uptake

Soil warming advanced the crop phenology during vegetative stages (i.e. until end of tillering), but did not affect later development stages until harvest. However, this shortened the whole crop growing season by 12 days compared to the crop in control plots (Table 5). At the 28 April biomass sampling, the crop in heated plots was at stem elongation (GS 31) and had accumulated significantly higher biomass ($P < 0.001$) compared with the crop in control plots (tillering; GS 27) (Table 5; Fig. 5a). Similarly on 15 June sampling, the crop in heated plots were at 'end of flowering'

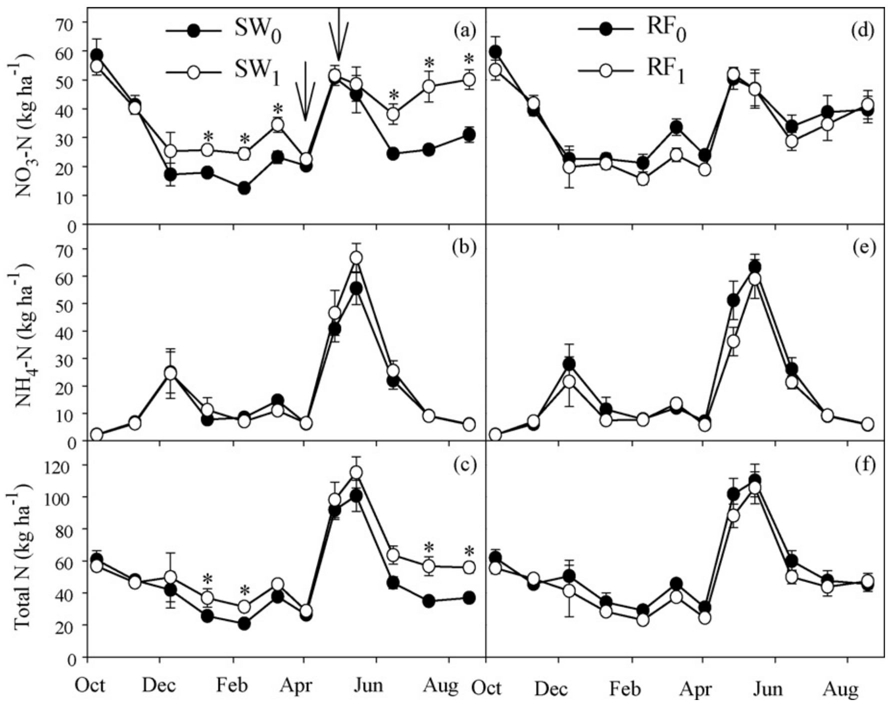


**Fig. 3.** Soil available (a) $NO_3$-N, (b) $NH_4$-N and (c) total mineral N in kg ha$^{-1}$ under control ($SW_0$) and heated ($SW_1$) treatments, and soil available (d) $NO_3$-N, (e) $NH_4$-N and (f) total mineral N in kg ha$^{-1}$ under present ($RF_0$) and future ($RF_1$) rainfall amount treatments. Vertical bars show ±S.E. with $n$ = 8. Vertical bars show ±S.E. with $n$ = 8. Arrows and asterisks indicate time of fertilizer application and significant at $P$ < 0.05, respectively.

**Table 5**
Crop phenology in heated and control plots monitored on BBCH scaling from sowing (GS 0) to harvest (GS 92) (Lancashire et al., 1991) (sowing date: 10 October 2008).

| Development stages (BBCH Scale GS number) | Date of reaching end of principal growth stages | | Days taken for each principal growth stage to complete | |
|---|---|---|---|---|
| | Heated ($SW_1$) | Control ($SW_0$) | Heated ($SW_1$) | Control ($SW_0$) |
| Nine or more leaves (19) | 04 February | 20 March | 107 | 151 |
| End of tillering (29) | 22 April | 05 May | 77 | 46 |
| Flag leaf (39) | 15 May | 26 May | 23 | 21 |
| First awn visible (49) | 27 May | 04 June | 12 | 9 |
| End of heading (59) | 04 June | 13 June | 8 | 9 |
| End of flowering (69) | 16 June | 24 June | 12 | 11 |
| Late milk grain filling (77) | 30 June | 06 July | 14 | 13 |
| Fully ripe (89) | 24 July | 04 August | 24 | 29 |
| Hard grain harvested (92) | 27 July | 07 August | 3 | 3 |

(GS 68) stage and had still maintained significantly higher biomass ($P$ = 0.004) compared with the crop in control plots (end of heading; GS 27). However, on 15 July and at harvest the biomass in heated and control plots did not differ statistically (Table 5; Fig. 5a).

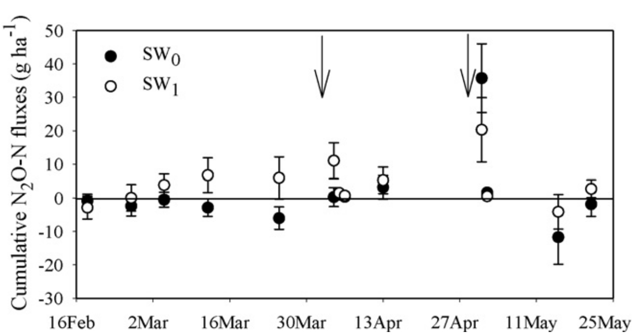


**Fig. 4.** Cumulative $N_2O$-N fluxes (g ha$^{-1}$) between two sampling times during the period from February to May 2009 under control ($SW_0$) and heated ($SW_1$) treatments. Vertical bars show ±S.E. with $n$ = 8. Vertical bars show ±S.E. with $n$ = 8. Arrows indicate time of fertilizer application.

Neither the rainfall amount (RF) nor the rainfall frequency (RD) treatments had any effect on above-ground biomass. Similarly neither did they have any effect on the total N amount accumulated in above-ground biomass across sampling dates (data not shown). However, soil warming significantly increased the accumulated N amount in biomass by 28 April ($P$ < 0.001) and marginally by 15 June ($P$ = 0.08), but not during the latter two samplings (Fig. 5b).

## 4. Discussion

With the wider acceptance of global warming predictions amongst the scientific community, large numbers of temperature (air and/or soil) manipulation experiments have been carried out using different techniques: electrical heat-resistance heating cables (see Lukewille and Wright, 1997), fluid heat pipes (Chapin and Bloom, 1976), greenhouses (see Kennedy, 1995), vented and unvented field chambers (Marion et al., 1997) and overhead infrared lamps (Harte and Shaw, 1995). While no single technique is found to be perfect, we used insulated heating-cables and buried method to manipulate soil temperature because (i) our main objective was to increase the soil temperature and study its effect on soil

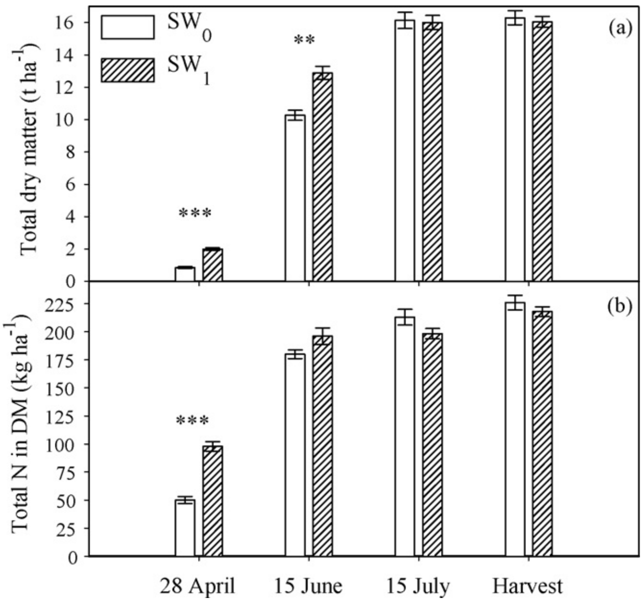


**Fig. 5.** Total (a) above-ground dry matter (t DM $ha^{-1}$) and (b) N amount in total above-ground dry matter (kg N $ha^{-1}$) measured on four sampling dates during the crop growing period. Vertical bars show ±S.E. with $n = 8$. ***,**Significant differences at $P < 0.001$ and $P < 0.01$ levels, respectively.

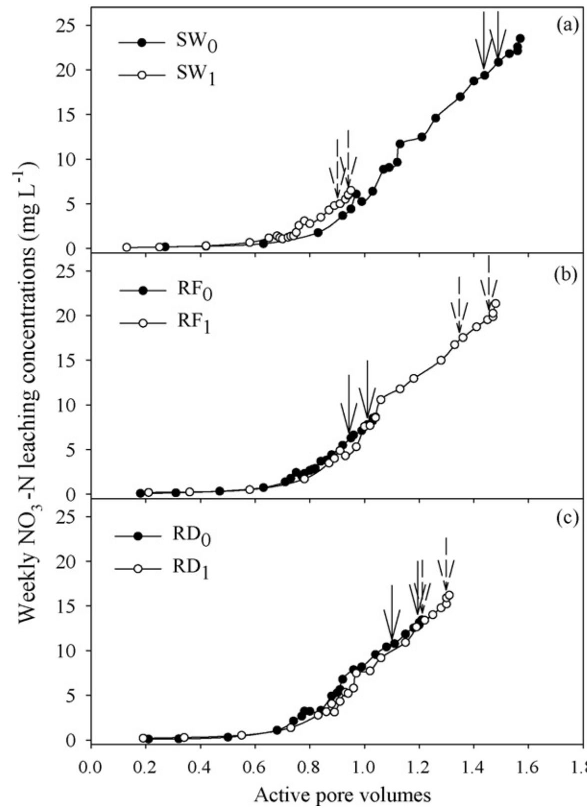


**Fig. 6.** Weekly $NO_3$-N leaching concentrations (mg $L^{-1}$) against active pore volumes under (a) control ($SW_0$) and heated ($SW_1$) treatments, (b) present ($RF_0$) and future ($RF_1$) rainfall amount treatments, and (c) normal ($RD_0$) and reduced ($RD_1$) number of rainy days treatments. Two solid arrows in (a), (b), and (c) indicate the timing of fertilizer application (two equal splits) in $SW_1$, $RF_1$ and $RD_1$ treatments, respectively. Similarly, two dotted arrows in (a), (b) and (c) indicate the timing of fertilizer application (two equal splits) in $SW_0$, $RF_0$ and $RD_0$ treatments, respectively.

moisture regime and N availability, (ii) heating-cable method was found to be as effective as other techniques (Rustad et al., 2001), and (iii) heating-cables are more robust and reliable under field conditions, and relatively cheaper (Verburg et al., 1999). In this study burying heating cables at deeper soil layer (0.1 m) and increasing the temperature by 5 °C, compared with control at corresponding depth, provided a more even and significant increase in mean soil temperature (3.8 °C) in plough layer (0–0.25 m depth). Advantage of placing heating cables at deeper layers than on or near the soil surface has been reported elsewhere (Peterjohn et al., 1993). The increase in soil temperature targeted in this study was on higher side that what is expected for 21st century, but we assumed such a degree of warming can provide a unique and valuable data set which could be used in calibrating and testing agroecosystem models and help in understanding how they will respond to global warming (Hagedorn et al., 1997).

### *4.1. Soil $NO_3$-N leaching*

Agricultural land is a major source of N leaching around the world (Di et al., 2009) and is a serious environmental problem in Europe (Berntsen et al., 2006). Even though the average annual N leaching losses from arable land vary a lot between years as they are greatly influenced by the rainfall during the growing season (Errebhi et al., 1998), weather, soil and crop management history (Goulding et al., 2000; Stopes et al., 2002; Beaudoin et al., 2005), most N leaching occurs as nitrate (Owens et al., 2000) during the cold winter period when crop growth and N uptake are minimal, evapotranspiration is low and drainage is high (Di and Cameron, 2002).

In this study, the reduced number of rainy days ($RD_1$), compared with normal number of rainy days ($RD_0$) treatment, showed no effect on the total $NO_3$-N leached (Table 4) though it marginally increased the drainage flux (10%). However, higher $NO_3$-N leaching losses with future rainfall amount ($RF_1$) was mainly driven by increased rainfall during winter period (Table 2) leading to significantly higher drainage, thus carrying more $NO_3$-N compared with present rainfall amount ($RF_0$) treatment (Table 4). Thorup-Kristensen et al. (2009) reported that N leaching during autumn and winter depends on soil water holding capacity of soil and precipitation, and we assume that the freely drainable characteristic of loamy sand soil used in this study may have enabled faster percolation of excess water, thus, with it, soil $NO_3$-N under future rainfall treatment. The much lower amount of N leached in the $RF_0$ treatment compared to $RF_1$ was mainly due to the large difference in drainage. The leached concentrations with respect to the amount of drained active pore volumes were similar (Fig. 6) showing that the amount of percolating water rather than N transformation processes in the soil and crop uptake was mainly controlling the amount of $NO_3$-N leached. The same can be seen for the SW treatments also. The mean residence time for water in soil profile under unheated (control; $SW_0$) and future rainfall amount ($RF_1$) was much lesser compared with heated ($SW_1$) and present rainfall amount ($RF_0$) treatments, respectively (Fig. 6a and b). This may have drained the $NO_3$-N from top layer resulting in higher leaching concentrations in former treatments. However, it also indicates that mineral N (150 kg N $ha^{-1}$) applied to soil surface in two equal splits in spring (3 April and 1 May) was not part of the N leachates collected in drainage during this study period (Fig. 6) in any of the treatments. However, the significant reductions in drainage and total $NO_3$-N leaching losses observed from heated plots, compared with control, may also have been influenced by (i) advanced crop growth leading to increased crop biomass and N removal from the soil until early spring (Fig. 5a), and (ii) significantly higher crop ET (Table 4), particularly during winter and early spring. The significant interaction between soil warming and rainfall amount showed that elevated soil temperatures not only reduced the $NO_3$-N leaching under present rainfall amount, but also under future rainfall amount (Table 4). This suggests that the negative environmental impacts of increased winter rainfall under future projected rainfall patterns could be offset by the effects of warmer winters on crop growth and N uptake. Ineson et al. (1998) while studying the effect of soil temperature and varying rainfall amount on upland grassland soils in Cambria, UK had also observed increased N uptake by the grassland vegetation and reduction in $NO_3$-N leaching in response to increased soil temperature.

### 4.2. Soil moisture regime and drainage

Projected changes in future rainfall amount and its frequency are important aspects of regional climate change, which can affect water infiltration and drainage through soil profile, and dynamics of soil water content (Harper et al., 2005). However, in this study on freely drainable loamy sand soil, the rainfall pattern (amount and number of rainy days) treatments had very little effect on the temporal soil water regime (Fig. 2b and c), but the future rainfall amount ($RF_1$) and reduced number of rainy days ($RD_1$) significantly increased the drainage (Table 4). As all the increased rainfall with the $RF_1$ treatment occurred during winter period (November–March); the period when crop growth is minimal and evapotranspiration is low (Di and Cameron, 2002), the drainage from this treatment increased correspondingly (Table 4). Whereas, the increased drainage with $RD_1$ treatment could be attributed to fewer (50% less) but larger rainfall events (mean size of 7.5 mm $day^{-1}$) under $RD_1$ treatment compared with $RD_0$ treatment.

Harper et al. (2005) reported that large rainfall events after longer dry periods help rewet deeper layers or if received in excess may drain out of rooting zone, while small rainfall events received at frequent intervals replenish the shallow top layer and our findings seemed to fall in line with their observations. On the contrary, an increased SMD at deeper layers during the peak growing period of wheat crop (Fig. 1b and c) and the significant reduction in drainage volume with $SW_1$ treatment may have been due to increased crop ET extracting significantly more soil water (18%) compared with the crop in the $SW_1$ (control) (Table 4). However, contrary to what one would expect, lower soil moisture in top layers of $SW_0$ treatment, compared with $SW_1$ treatment, was observed during the winter period (Fig. 1a and b). This could be attributed to measurement errors using TDR when soil water exists in both liquid and frozen conditions as it did in $SW_0$ plots on many occasions and each time several days. The TDR is dependent on the dielectric constant of the media (soil) and measures only the unfrozen water content of the soil (Kahimba and Sri Ranjan, 2007). Evett (2003) also noted that freezing of soil water decreases the permittivity of water and affects the accuracy of TDR measurements.

### 4.3. Soil mineral N content

As hypothesised, soil warming significantly increased the soil $NO_3$-N content in top 0.3 m layer during the study period; though in spring the effect of soil warming was masked by surface application of 150 kg N $ha^{-1}$ (Fig. 3). We argue this was most likely due to increased N mineralisation in the plough layer of $SW_1$ plots at elevated soil temperature compared with $SW_0$ plots. Kamp et al. (1998) also periodically observed higher $NO_3$-N content in fallow and wheat fields with soil warming and they attributed this to increased mineralisation. However, the higher $NO_3$-N left in the top 0.3 m soil layer of heated plots (19 kg $NO_3$-N $ha^{-1}$), compared with control, even after the harvest of wheat crop poses a potential risk of more leaching in the following autumn and winter seasons (Macdonald et al., 1989). This risk, however, can be reduced by growing crops during autumn and winter or by keeping the soil covered with catch crops (Lewan, 1994; Wyland et al., 1996; Thorup-Kristensen et al., 2003) or catch crops (e.g. perennial ryegrass) under-sown in the main crop (Hansen and Djurhuus, 1997; Aronsson and Torstensson, 1998; Macdonald et al., 2005). Cover crops, if sown early in autumn (Francis, 1995) or during winter (Schroder et al., 1992) are found to be effective in reducing $NO_3$-N leaching by removing mineral N from the soil profile before the drainage starts in autumn or by reducing the drainage with increased evapotranspiration losses. Therefore, our findings suggest that regular integration of catch or cover crops in cereal based cropping systems would help to reduce $NO_3$-N leaching under future warmer climates without affecting the yield of main crops (Kirchmann and Thorvaldsson, 2000; Schweigert et al., 2004). Another option could well be incorporation of cereal straw after harvest, which has been reported to immobilise soil N in the range of 10–25 kg N $ha^{-1}$ and decrease mineralisation during the autumn (Beaudoin et al., 2005).

This study showed that under warmer climates, simulated through increased soil temperatures, soil N availability is increased, but the crop growth and development was advanced during vegetative stages shortening its growing cycle by 12 days. This advanced development and shortened growing period may have stopped N uptake by the wheat crop much earlier leaving more N in soil, compared with the crop in control. However, wheat genotypes which respond to warmer winter temperature by extending their vegetative period without advancing later developmental stages are likely to be better adapted to take advantage of higher soil N availability under warmer winters. It is, however, possible that the observed increases in soil N content in response to short-term soil warming are enhanced by faster decay of only the most labile soil C pool (Peterjohn et al., 1994) and with time most of the soil processes are reported to decline (Rustad et al., 2001; Hartley et al., 2007). Hence, further research on the longer-term response of soil N cycling to warming is required.

### 4.4. Soil $N_2O$-N fluxes

The production of $N_2O$ in soils is controlled not only by soil properties (Groffman and Tiedje, 1991; Hansen et al., 1992) and management practices (Bouwman, 1990; Burton et al., 1997), but also by the factors influencing microbial activity: soil temperature and moisture (Malhi et al., 1990; Bandibas et al., 1994), which are expected to be influenced by changing climate (Kamp et al., 1998). With rising temperatures $N_2O$ gas fluxes are expected to increase (Peterjohn et al., 1993) and may result in a positive feedback to global warming in the future (McHale et al., 1998).

Our $N_2O$ flux measurements suggest that total $N_2O$ emissions may increase if the soil temperature increases, though the emissions were very low (Fig. 5). Kamp et al. (1998) while studying the effect of soil warming on fallow and wheat fields found no difference in $N_2O$ emissions for the whole study period of 21 months, but between the seasons. However, those seasonal differences were linked to catch crops vegetation and N fertilization rate. Highly variable (Peterjohn et al., 1993) and low levels of $N_2O$ fluxes (Bowden et al., 1990; Peterjohn et al., 1993) under elevated soil temperature were also reported from forest ecosystem, but no correlation with soil temperature was found (Peterjohn et al., 1993) as soil heating did not consistently increase $N_2O$ fluxes. The highly variable and low fluxes observed in this study could partly be attributed to the complexity of below-ground N cycling (Bowden et al., 1990; McHale et al., 1998) and the effect of environmental processes on the formation, transport and oxidation of $N_2O$. However, the responses of the wheat crop and soil N cycling observed in this study were due only to increased soil temperature. However, under future climates both air and soil temperatures increase concurrently affecting degree of cloudiness, solar radiation, humidity and evapotranspiration besides reducing the duration of all growth stages of crops (Craufurd and Wheeler, 2009). The findings of this study did not take into account of these weather parameters.

Though this study covered one full growing season of wheat crop, soil N cycling and leaching fluxes are greatly influenced by management of N cycle during crop rotations history (Beaudoin et al., 2005). Goulding et al. (2000) opined that such studies need to be carried out for a minimum of three to five years to have reliable results taken to decision support system. Another limitation in our approach was that below-ground root biomass, rooting depth and its role in soil water and N extraction pattern was not monitored. Hence, longer-term whole agroecosystem studies are needed in order to understand the response of entire ecosystem(s) to altered temperature and rainfall regimes.

## 5. Conclusions

Soil warming advanced wheat crop development, and increased the above-ground biomass and N uptake only during vegetative stage, but shortened the total crop growing period by 12 days without reducing the total above-ground biomass. Future rainfall amount and reduced frequency treatments increased the drainage, but their combined effects did not have additive effect on the drainage. In contrast, soil warming increased the crop ET and reduced the drainage.

This study also showed that the future rainfall amount increased the $NO_3$-N leaching, while soil warming reduced $NO_3$-N leaching both under present and future rainfall amounts. Neither the soil warming nor the rainfall pattern treatments showed any significant effect on the $N_2O$ fluxes. Soil warming not only increased the $NO_3$-N availability during the crop growing season, but also left significantly higher levels of $NO_3$-N in the plough layer after harvest posing a potential risk of increased leaching in the following autumn/winter seasons. This underlines the importance of growing catch/cover crops during autumn/winter or integrating them into cereal based cropping systems to contain $NO_3$-N leaching under future warmer climates.

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