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ABSTRACT

Irrigation is, on one hand, expected to increase the risk of nitrate leaching through increased rates of percolation, but, on the other hand, enhances plant nutrient uptake and growth, thereby limiting the risk of leaching. To investigate this dichotomy, we analysed the effects of irrigation at three nitrogen (N)-application rates in spring barley (*Hordeum distichum* L., two experiments with 50, 100, and 150 kg N ha^{-1}) and winter oilseed rape (*Brassica napus* L., one experiment with 50, 150, and 250 kg N ha^{-1}) on a coarse sandy soil in Denmark in a humid climate, which facilitates nitrate leaching. Analyses comprised grain/seed dry matter yield, N-uptake, nitrogen use efficiency (partial nitrogen budget, PNB, and partial-factor productivity, PFP) and nitrate leaching. For both crops, increasing N-application without consideration of the crops' drought-stress responses lead to a relatively lower N-uptake in grain, lower yield, lower PNB and PFP and higher nitrate leaching, although responses were not proportionally to increasing N-application. The effect of irrigation at the lowest N-rates was limited. The non-irrigated treatments with the highest N-rates had a grain/seed yield of 3.2, 2.3 and 0.7 t ha^{-1} and nitrate leaching rates of 64, 72 and 127 kg N ha^{-1} compared to a grain/seed yield of 5.3, 5.0 and 2.6 kg N ha^{-1} and nitrate leaching rates of 61, 42 and 85 kg N ha^{-1} (for spring barley, spring barley and winter oilseed rape, respectively). These results show that synchronised management of both irrigation and N-application are essential for reducing the risk of nitrate leaching and to promote efficient crop N-uptake in periods of droughts.

Introduction

Are the effects of irrigation on nitrate (NO$_3^-$) leaching losses good or bad? Shepherd (1992) already asked this question in 1992. Since then, many publications have shown that irrigation can indeed be bad and lead to increased nitrate leaching losses, often when combined with over-fertilisation (Rong and Xuefeng 2011; Yang 2011; Perego 2012). For example, Rong and Xuefeng (2011) found that traditional irrigation rates caused the highest rates of nitrate leaching for maize and cotton and could be reduced to 75% without significantly reducing crop yields on a coarse sandy soil in China. Perego (2012) quantified nitrate leaching on different farms in the Po Valley in Italy, grown with grain or maize and managed according to local practices. The authors observed high water drainage in summer due to large water supply by irrigation and often high N surpluses leading to high leaching losses.

Increased leaching losses with irrigation are largely explained by the fact that irrigation increases the soil water content, thereby promoting percolation, and enhancing the risk of nutrient transport through the soil profile. The importance of soil water content was highlighted by Powlson (1992), who found that the loss of fertiliser-N from the crop-soil-system was influenced most by the amount of percolating water following fertiliser application, rather than by soil type or previous cropping.

On the other hand, the extra water supply can increase both bulk flow and diffusion of N towards roots, which promotes plant-nutrient uptake. A crop under drought stress is not able to grow to its potential (Gehl 2006), and an increased level of nitrate in the soil is left after harvest. Irrigation may then decrease nitrate leaching in comparison to non-irrigated situations by limiting plant-stress responses, increasing the

availability of nutrients to the plants (Gallo 2014), and by enhancing denitrification (Di and Cameron 2002).

The nitrate that is not denitrified, immobilised or taken up by crops, has the potential to leach into ground and surface waters. The risk of nitrate leaching is greatest when both surplus nitrate and surplus water are present. Overlap of surplus nitrate and surplus water often occurs in autumn, in particular after periods of drought (Van Metre 2016), and in early spring due to mineralisation, especially after early ploughing (Di and Cameron 2002). An overlap may also occur during summer – especially in irrigated crops when fertiliser application and irrigation are not properly managed (Perego 2012). Where precipitation is high, and soil water holding capacity is low, for example in Denmark (Askegaard and Eriksen 2007), the risk of diffuse nitrate pollution from agriculture to ground – and surface-waters is high (Neal 2006; Van Metre 2016). This pollution may cause health risks when present in drinking water (Ward 2005; Schullehner 2018) and may cause eutrophication in aquatic ecosystems (Baldock et al. 2000; Romanelli 2020).

The importance of careful irrigation management to minimise nitrate contamination of groundwater and thereby protect the environment and water resources was emphasised by, among others, Daudén et al. (2010) and Gehl (2006). If properly irrigated, i.e. correct amount and timing, increased levels of fertiliser N may not result in increased losses through leaching but may instead bring about higher yields. Irrigation decision support systems can be used as a tool for tactical irrigation planning. In Denmark, *Markvand* (Thysen and Detlefsen 2006), now called Vandregnskab Online (SEGES Innovation P/S 2022), calculates the soil water balance of fields including a five-day meteorological forecast period. Practical precision in applying the right amount of water is, however, limited by both the reliability of weather forecasts and the on-farm irrigation facilities. Moreover, crops are typically fertilised in the beginning of the growing season before the risk of dry weather conditions and drought is known, meaning that the N-rate cannot be adjusted accordingly.

In this study, we investigated whether or not irrigation is bad and increases the risk of nitrate leaching,

when combined with different fertiliser rates in spring barley (*Hordeum distichum* L.) and winter oilseed rape (*Brassica napus* L.) in a humid temperate climate where soil conditions facilitate nitrate leaching (Hansen and Djurhuus 1997; Hansen 2012). Compared to winter barley, spring barley is grown more widely in Europe, however, it is also more vulnerable under dry conditions (Daničić 2019). In northern Europe, winter oilseed rape is grown as an important oilseed crop. To improve its seed yield and N-efficiency, integrated N management strategies are required (Rathke et al. 2006). Within the study region, the average gross irrigation water requirement 1990–2015 was 104 and 95 mm for spring barley and winter oilseed rape, respectively (ten Damme and Andersen 2018). Current recommended N-rates are 159 and 202 kg N ha^{-1} for spring barley and winter oilseed rape, respectively. The aim of this study was to measure the effect of irrigation management and different N-fertiliser rates, as well as their interaction, on crop yield and nitrate leaching.

Materials and methods

Experimental design

The experimental data was collected at Jyndevad Experimental Station in Denmark (54°54′N, 09°07′E, 16 m above sea-level), on a melt water sand from the Weichselian glacial age. The soil is a coarse sandy soil, classified as an Orthic Haplohumod according to the USDA Soil Taxonomy System. Root growth is restricted by the coarse texture; in previous studies very few roots were observed below the depth of 0.6 m (Andersen et al. 1992; Askegaard and Eriksen 2007). The coarse soil of the experimental site is characterised by a low water holding capacity (Table 1); in the top 0.6 m, the plant available water is about 67 mm (Hansen 1976). A low water holding capacity means that nitrate leaches quickly through the soil profile. It is commonly observed that nitrate concentrations around Jyndevad decrease during winter to a rather low level (Hansen and Djurhuus 1997; Hansen 2012).

The experiments were conducted with two types of crop: spring barley for the two seasons of 1988 (*Hordeum distichum* L., cv. Lina) and 1989 (*Hordeum*

Table 1. Soil characteristics from the experimental site (Hansen 1976).

Depth (m)	Clay, %	Silt, %	Fine sand, %	Coarse sand, %	Organic matter, %	PAW (mm) 0–0.6 m depth	PAW (mm) 0–1.0 m depth
0-0.2	3.9	4.1	12.2	76.8	3.0	66.5	90.7
0.21-0.25	3.9	3.6	10.9	78.4	3.2		
0.26-0.3	4.4	3.6	6.8	8.1	4.1		
0.31-0.75	4.0	2.9	4.7	85.8	2.6		
0.76-1.0	1.6	1.1	14.9	82.0	0.4	-	-

Clay < 0.002 mm, silt 0.002-0.02 mm, fine sand 0.2-2.0 mm, coarse sand 0.2-2.0 mm, PAW: plant available water.

Table 2. Climatic data from Jyndevad Research Station.

Year	Month	J	F	M	A	M	J	J	A	S	O	N	D	Average	Sum
1988	Temp	3.8	2.6	2.4	6.0	12.0	14.8	15.7	14.9	12.9	8.8	4.2	4.3	8.6	
	Prec	179	146	139	23	61	76	174	87	142	95	64	93		1279
	PET	4	10	25	54	103	93	86	74	45	22	10	5		528
1989	Temp	4.5	4.4	6.1	6.0	11.7	14.6	16.2	15.1	14.0	10.3	3.5	2.7	9.1	
	Prec	28	67	113	69	15	63	76	76	35	118	29	91		778
	PET	5	12	29	46	107	112	95	73	54	22	10	5		569
1992	Temp	2.7	4.0	4.8	6.7	13.1	17.2	17.5	16.2	13.3	6.6	5.5	3.2	9.2	
	Prec	57	70	102	76	34	3	63	134	65	116	209	79		1008
	PET	7	11	29	47	115	131	111	77	51	25	10	5		618
$\bar{x}$	Temp	1.8	1.8	3.9	7.7	11.6	14.4	17.0	16.8	13.6	9.5	5.5	2.5	8.9	
	Prec	95	77	65	45	64	82	92	116	102	107	100	106		1051
	PET	7	13	33	62	92	99	105	85	50	26	9	5		586

Temp: temperature (average per day, °C), Prec: precipitation (sum, mm) measured at height of 1.5 m and corrected to the soil surface according to Allerup and Madsen (1979), PET: potential evapotranspiration (sum, mm), $\bar{x}$: normal values (average 1990–2015).

distichum L., cv. Alis), hereafter SB1 and SB2, respectively, and; winter oilseed rape (Brassica napus L., cv. Ceres) during one season of 1992, hereafter WR. The crops were sown with a row spacing of 12 cm. The seeding rates were 170 kg ha^{-1} for SB1 and SB2 and 3 kg ha^{-1} for WR. Each experiment consisted of six treatments, which were placed within four replicate blocks in a randomised complete block design. The gross plot size, i.e. for each treatment, was 7 m by 3 m. In all experiments, spring barley was grown as a pre-crop. The plots were sprayed with pesticides to control weeds, insects and pathogenic fungi. For the Figures and Tables, the treatments within each experiment are designated with the letters 'I' for irrigated, 'NI' for non-irrigated plus a number (50–250) in subscript for the fertiliser N-rate.

Precipitation and temperature (Table 2) were measured at the Danish Meteorological Institute's weather station at Jyndevad Research Station, within one kilometre from the experimental fields. The values for precipitation (mm) were corrected from the rain gauge at 1.5 m to the soil surface following Allerup and Madsen (1979). Potential evapotranspiration (mm) was calculated according to the modification of Makkink (1957) as described by Plauborg (2002). Compared to the long-term average, SB1 was carried out in a cooler and wetter year, while the conditions during SB2 were dry but cool, particularly throughout the growing season. Precipitation from April until August was 421 and 229 mm in 1988 and 1989,

respectively, compared with the 25-year average of 399 mm. The temperature averaged 12.7°C for both years, compared with the 25-year average of 13.5°C. WR was carried out in near average climatic conditions, although at the start of the year temperature and precipitation were relatively high, whilst May and June were very dry.

In SB1 and SB2, spring barley was sown on 15 April 1988 and 18 April 1989, respectively. In WR, winter oilseed rape was sown on 22 August 1991. The harvest dates were 15 August 1988, 15 September 1989, and from 3–5 July 1992 for SB1, SB2, and WR respectively, after which the fields were left with stubble. Table 3 depicts the three N-rates and two irrigation regimes (irrigated and non-irrigated) for the three experiments. All crops received the recommended rates of phosphorus and potassium. Winter oilseed rape was also given solubor and magnesium sulphate to prevent boron and magnesium deficiency.

Irrigation was performed using a trickle irrigation system mounted on mobile aluminium frames with the drip nozzles with a discharge rate of 1.2 L h^{-1} forming a 20$^{×}$20 cm-pattern. The frames were placed over the (7 by 3 m) gross plots during irrigation, with water passing a water metre with a readout precision of 0.1 L per irrigation. Thus, irrigation doses of typically 30 mm were controlled manually and supplied within approximately one hour. The amount of irrigation needed was defined using tensiometers, which were placed at 0.22

Table 3. Nitrogen (N)-application rate and irrigation treatments of the three experiments SB1: spring barley, 1988; SB2: spring barley, 1989 and WR: winter oilseed rape, 1992.

		SB1			SB2			WR[a]		
N-rate (kg ha^{-1})		50	100	150	50	100	150	50	150	250
Irrigation (sum)	I (mm)[b]	24	24	24	105	105	105	121	165	221
	Ni (mm)	-	-	-	15[c]	15[c]	15[c]	-	-	-

[a]The N-application includes 48 kg N ha^{-1} applied September 10, 1991 for all treatments. [b]Dates and millimetres applied with each irrigation are mentioned in the text. [c] Irrigated to dissolve mineral fertiliser.

and 0.40 m depth. The irrigated treatments were re-watered to field capacity when the tensiometers indicated a deficit of 25–30 mm according to a calibration curve between tension and water content for the soil. This corresponded roughly to a tension of 0.08 MPa at the 0.22 m depth. The irrigated treatments in SB1 were irrigated once on 14 June 1988 (24 mm). In SB2 both irrigated and non-irrigated treatments were irrigated on 26 May 1989 (15 mm) in order to dissolve applied mineral fertiliser and afterwards the irrigated treatments were irrigated on June 16 (30 mm), June 26 (30 mm) and July 11 (30 mm). In WR, treatments with different N-rates were irrigated differently: treatment I_{50}: June 1 (36 mm), June 9 (25 mm), June 16 (30 mm), June 29 (30 mm); treatment I_{150}: May 26 (30 mm), June 1 (35 mm), June 9 (40 mm), June 16 (30 mm), June 23 (30 mm) and treatment I_{250}: May 19 (25 mm), May 25 (31 mm), June 1 (35 mm), June 9 (40 mm), June 16 (30 mm), June 23 (30 mm), June 29 (30 mm).

Measurements of yield

Net plots of 2.40 by 3.40 m were harvested with a plot combine harvester. The grain/seed was weighed and the dry matter content (t ha^{-1}) determined in the laboratory. The total N-uptake in grain/seeds and straw (kg N ha^{-1}) at harvest was determined by the Kjeldahl analysis, which uses a digestion of the sample to convert organic-N to ammonium-N, after which the ammonia is measured (Bremner and Mulvaney 1982). The yield of winter oilseed rape was presented previously by Andersen et al. (1996) comprising treatments not included in this study.

Measurements of nitrate leaching

Nitrate leaching (kg N ha^{-1}) was calculated from the NO_3^--N concentration (mg L^{-1}) measured in the soil water, extracted with suction cups, and estimated percolation (mm). Each plot contained two suction cups resulting in eight suction cups per treatment. They were installed at 0.8 m depth, i.e. below the rootzone as described in Djurhuus and Jacobsen (1995). The soil water was sampled and analysed on an auto-analyser according to the methods described in Hansen and Djurhuus (1997). This method assumes that the nitrate concentrations in the suction cups represents flux-average conditions (Djurhuus and Jacobsen 1995), which seems reasonable for the coarse sandy soil at Jyndevad soil (Lord and Sherperd 1993; Webster 1993; Djurhuus and Jacobsen 1995). Percolation was calculated with the use of the model *Evacrop*, as described in Olesen and Heidmann (2002).

Statistical analyses

First, analysis of variance for the effects of the six treatments were carried out for each year and each experiment according to a randomised block design with four replications. Significant differences between mean values were separated according to LSD$_{.05.}$ Second, analyses of variance for the combined effect of irrigation treatment, N-application rate and their interactions were performed. In both cases, we used SAS® software's general linear model procedure GLM.

The partial nitrogen budget (PNB) was calculated with Equation (1), to analyse the total N-uptake in grain/seed and straw per kg N applied in each treatment of the experiments. A PNB > 1 indicates that more nitrogen is harvested than supplied in fertiliser, i.e. soil mining, whereas a PNB < 1 indicates that more nitrogen is applied than recovered in the crop. The partial-factor productivity (PFP, kg kg^{-1}) was calculated with Equation (2), to analyse the treatment effect on the dry matter (DM) grain/seed yield per kg N applied.
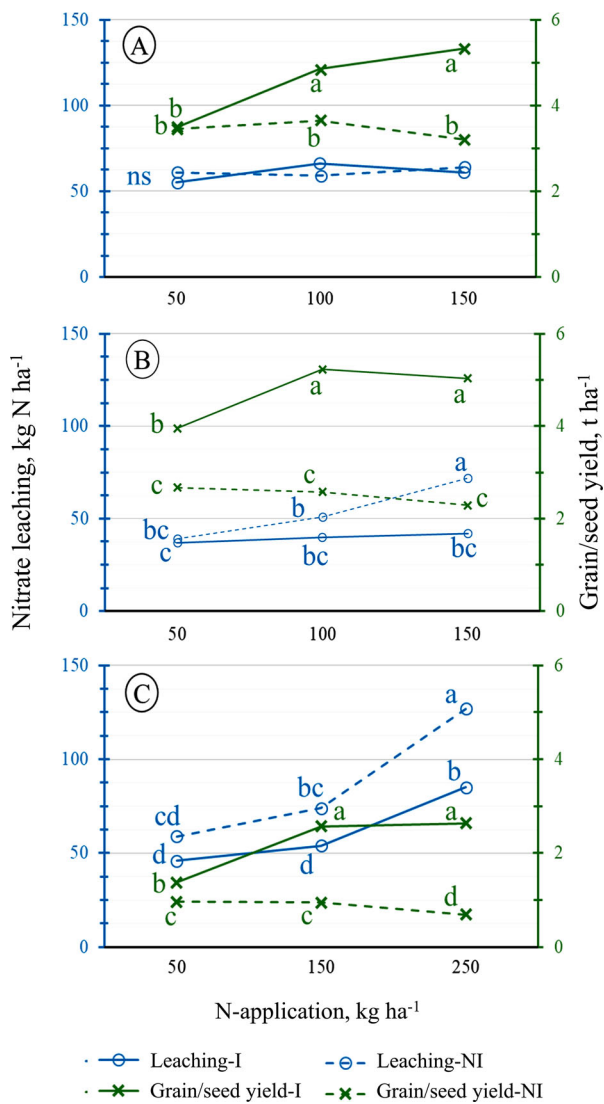
$$PNB = \frac{\Sigma \, N - uptake \, (kg \, ha^{-1})}{N \, applied \, (kg \, ha^{-1})} \quad (1)$$

$$PFP = \frac{Grain/seed \, yield \, (kg \, DM \, ha^{-1})}{N \, applied \, (kg \, ha^{-1})} \quad (2)$$

Results

Dry matter yield and nitrogen-uptake

In all three experiments, the interaction between irrigation and N-rate on the grain/seed yield was significant (Supplementary 1). In the irrigated treatments of SB1 and SB2, grain yield increased from N_{50} to N_{100} application (from 3.5–4.9 t ha^{-1} and from 4.0–5.2 t ha^{-1} for SB1 and SB2, respectively), but an application rate of N_{150} did not result in a further increase (5.3 and 5.0 t ha^{-1}, Figure 1). The non-irrigated treatments of SB1 showed no noteworthy response to an increased N-rate; the application of N_{150} yielded approximately as much as the irrigated treatment with N_{50} application (3.2 and 3.5 t ha^{-1}, respectively). The grain yields in the non-irrigated treatments of SB2 did not differ between different levels of N-application (2.3–2.7 t ha^{-1}) but were lower than any of the irrigated treatments (4.0–5.2 t ha^{-1}). In WR the same response as in SB1 and SB2 was seen; with irrigation the seed yield increased when N-rate first increased (from 1.4 t ha^{-1} for N_{50} to 2.6 t ha^{-1} for N_{150}), but not further, i.e. the highest application rate of N_{250} did not result in a further increase of seed yield (Figure 1). In the non-irrigated treatments of WR,

seed yields were lower than in the irrigated treatments at each N-rate (0.7–1.0 t ha^{-1}), being the lowest overall in the N$_{250}$ treatment.

Differences in total N-uptake were explained by the variance in N-rates alone in SB1, while we found an interaction of irrigation and N-rate in SB2 and WR (Supplementary 1). Total N-uptake increased with increasing N-rates in all experiments (Table 4), but in SB2 and WR higher N-rates increased total N-uptake more for the irrigated than the non-irrigated treatments. Generally, grain and seeds contained more N than straw, except for the non-irrigated treatment in WR with the highest N-application (250 kg ha^{-1}), where seeds contained only 27 kg N ha^{-1} and straw more than 50 kg N ha^{-1} (Table 4). The interaction of irrigation and N-rate on N-uptake in grain/seed were highly significant in all experiments (Supplementary 1). The N-uptake of grain/seed tended to be higher in the irrigated treatments compared to the non-irrigated treatments, mostly at the higher N-rates (Table 4). At the highest N-rate, the grain/seed yields were 5.3, 5.0 and 2.6 kg N ha^{-1} for the irrigated treatments, compared to 3.2, 2.3 and 0.7 t ha^{-1} for the non-irrigated treatments, in SB1, SB2 and WR, respectively. The interaction between irrigation and N-rate was also significant for the N-uptake in straw in SB1 and WR (Supplementary 1). In WR, the N-uptake in straw increased for increasing N-rates and with irrigation (Table 4). In SB1, the interaction effect on N-uptake in straw resulted in a larger increase in N-uptake for the irrigated compared to the non-irrigated treatments at the highest N-rate. At the same time, a high occurrence of green shoots was observed (Table 4).

Both the partial nitrogen budget (PNB) and the partial-factor productivity (PFP) were higher in the irrigated treatments compared to the non-irrigated treatments at similar N-rate, and decreased with increasing N-rates, in SB2 and WR (Table 5). However, we only found a significant effect of the interaction of irrigation and N-rate on the PFP in SB2. In SB1, no different PNB

Figure 1. Nitrate leaching and grain/seed yield of SB1 (spring barley, 1988), SB2 (spring barley, 1989) and WR (winter oilseed rape, 1992). Within each experiment, the same letter in same colour shows no significant difference between the treatments according to LSD$_{.05}$, while ns indicates no significant difference. The grain yield in SB1 and SB2 are at 85% dry matter, the seed yield in WR at 91% dry matter.

Table 4. Nitrogen (N) uptake in grain/seed and straw in six treatments of SB1: spring barley, 1988; SB2: spring barley, 1989; WR: winter oilseed rape, 1992. 'I' is irrigated and 'Ni' is non-irrigated.

		SB1			SB2		WR	
		N-uptake (kg ha^{-1})			N-uptake (kg ha^{-1})		N-uptake (kg ha^{-1})	
Irrigation and N-rate		Grain	Straw	GS[1]	Grain	Straw	Seed	Straw
I	50	38 c	7 d	0	47 de	5 c	33 c	8 f
	100[2]/150[3]	61 b	11 c	0	73 b	7 bc	65 b	20 d
	150[4]/250[5]	83 a	20 b	10	88 a	13 a	81 a	30 b
Ni	50	42 c	7 d	0	40 e	4 c	24 d	13 e
	100[2]/150[3]	56 b	11 c	10	54 cd	10 ab	33 c	25 c
	150[4]/250[5]	64 b	33 a	80	58 c	13 a	27 cd	51 a

GS: green shoots; In both the columns for N-uptake (grain/seed and straw), different letters indicate significant difference between treatments (according to LSD$_{.05}$); [1]Amount of green shoots estimated on 05 August 1988 on a scale from 0–100; [2]100 kg N ha^{-1} for SB1 and SB2, [3]150 kg N ha^{-1} for WR; [4]150 kg N ha^{-1} for SB1 and SB2, [5]250 kg N ha^{-1} for WR.

Table 5. Nitrogen (N) use efficiency indices in SB1: spring barley, 1988; SB2: spring barley, 1989; WR: winter oilseed rape, 1992. 'I' is irrigated and 'Ni' is non-irrigated.

Irrigation and N-rate		SB1		SB2		WR	
		PNB	PFP (kg DM kg N^{-1})	PNB	PFP (kg DM kg N^{-1})	PNB	PFP (kg DM kg N^{-1})
I	50	0.90 a	59 a	1.03 a	67 a	0.82 a	25 a
I	$100^2/150^3$	0.73 b	41 b	0.80 c	45 b	0.57 c	16 c
I	$150^4/250^5$	0.69 b	30 c	0.67 d	28 c	0.44 d	10 d
Ni	50	0.97 a	59 a	0.89 b	45 b	0.72 b	18 b
Ni	$100^2/150^3$	0.67 b	31 c	0.63 d	22 d	0.39 d	6 e
Ni	$150^4/250^5$	0.65 b	18 d	0.48 e	13 e	0.31 e	3 f

PNB: partial nitrogen budget (Equation 1); PFP: partial-factor productivity (Equation 2); Within each experiment, different letters indicate significant difference between treatments (according to LSD.₀₅); [1]100 kg N ha^{-1} for SB1 and SB2, [2]150 kg N ha^{-1} for WR; [3]150 kg N ha^{-1} for SB1 and SB2, [4]250 kg N ha^{-1} for WR.

and PFP were measured between the irrigated and non-irrigated treatments with the lowest level of N-application, and while the PNB was higher at the lowest N-rate, the PNB differed not significantly between the intermediate and high levels of N-application. The PNB ranged 0.9–0.65, 1.03–0.48 and 0.82–0.31 in SB1, SB2 and WR, respectively. The PFP, the conversion of the applied nitrogen into DM grain/seed yield, ranged 59–18, 67–13 and 25–3 kg DM kg N^{-1} for SB1, SB2 and WR, respectively, with the lowest values recorded in the unirrigated treatments at the highest N-level.

Nitrate leaching

Percolation increased with irrigation; with 11 mm in SB1, 15 mm in SB2, and in WR with 8, 9, and 50 mm for N_{50}, N_{150}, and N_{250} respectively (data not shown). The nitrate concentrations fluctuated with water percolating through the soil profile, as can be seen from Figure 2. Nitrate concentrations in the soil water increased after crop harvest, peaked before the end of the year and were, in SB2 and WR, at a minimum at the latest in spring (Figure 2). In SB1, no such minimum was observed, even in the following spring. In WR, the nitrate concentration in the soil water was clearly higher for higher N-applications throughout the season, whereas this was less obvious in SB2, and not observed in SB1 (Figure 2).

There were no significant differences in nitrate leaching between the treatments in SB1 (55–66 kg N ha^{-1}, Figure 1). In SB2, the effect of the interaction between irrigation and N-rate on nitrate leaching was significant (Supplementary 1). This resulted in lower nitrate leaching in the irrigated than in the non-irrigated treatments at the highest N-rate (42 and 72 kg N ha^{-1}, respectively, Figure 1). This difference existed even though the nitrate concentrations in the non-irrigated treatments showed a pronounced variation between the eight suction cups, with one suction cup in particular showing much higher concentrations than the others. In WR, no significant effect of the interaction between irrigation and N-rate was

found (Supplementary 1), but the non-irrigated treatments leached more than the irrigated treatments for N_{150} (74 compared to 54 kg N ha^{-1}) and N_{250} (127 compared to 85 kg N ha^{-1}). In WR, both irrigated and non-irrigated treatments showed increased nitrate leaching with increasing levels of N-application (Figure 1).

Discussion

It is well known that irrigation can increase grain and seed yield at various N-rates (e.g. Lord and Mitchell 1998). This was also observed in the present study, where the grain/seed yield was generally higher for the irrigated treatments at a given N-rate (significant effect of the interaction between irrigation and N-rate). Irrigation also enabled an increase in grain/seed yield with increasing N-rate, but this manifested only from the lowest to the intermediate level of N-rate (Figure 1). Figure 1 shows, in other words, that the highest level of N-application was above what could be utilised by the plants to produce additional seed/grain yield, even in the irrigated treatments. This is a common response for cereal yield, i.e. to increase with N-application until a maximum utilisation. At N-application levels higher than maximum utilisation, yield is maintained and then decreases (Hay and Walker 1989; Zhu 2011; Delin and Stenberg 2014). The seed yield we obtained from WR was below 3 t ha^{-1} (Figure 1), which is lower than the 3–4 t ha^{-1} that is normal for winter oilseed rape in Europe (Rathke et al. 2006). This relatively low yield was earlier discussed by Andersen et al. (1996), who pointed out that some of the seeds and pods may have been lost before the harvest in 1992. The authors assumed that a relative comparison between the treatments remains valid.

The significant lower grain and seed yields in the non-irrigated treatments in SB2 and WR compared with the irrigated treatments for a given N-rate reflect the impact of irrigation for crop production (Figure 1). The irrigated treatments were irrigated four, and four to seven times, respectively (Figure 2), with the total
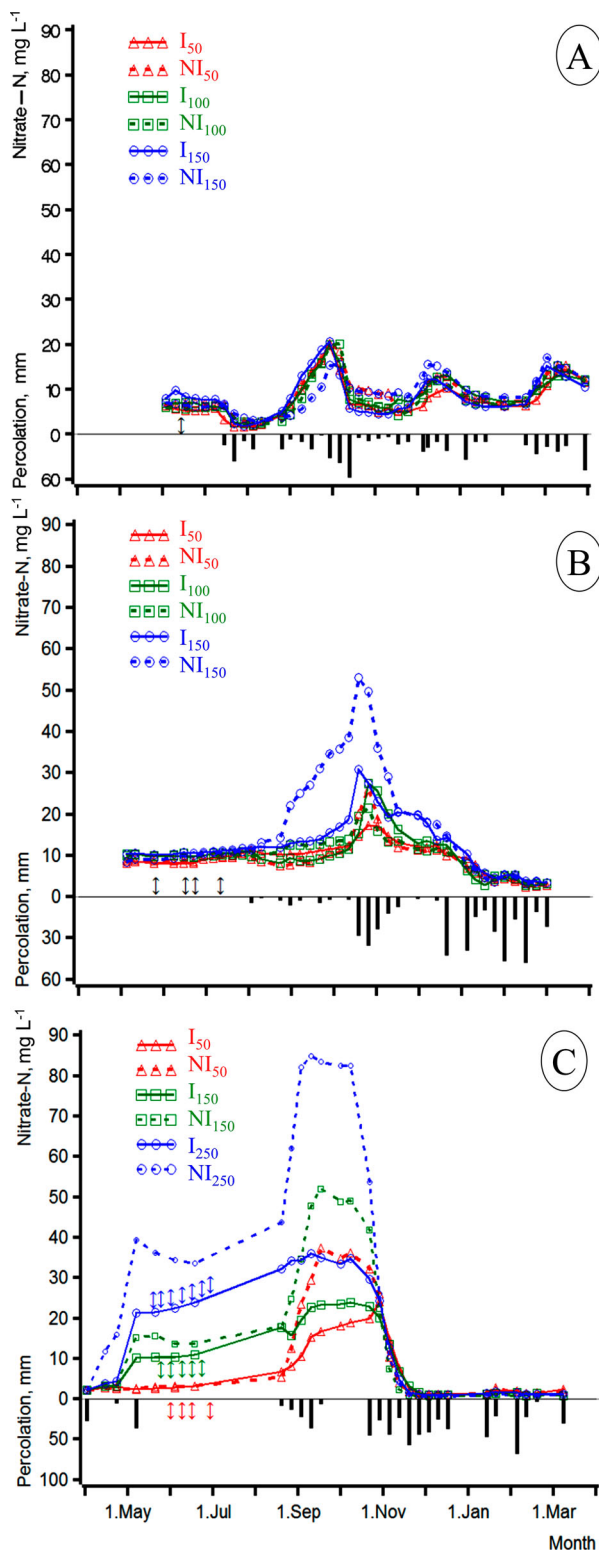
Figure 2. Nitrate leaching and percolation of SB1 (spring barley, 1988), SB2 (spring barley, 1989) and WR (winter oilseed rape, 1992) over time. I-: irrigated, NI-: non-irrigated. 50, 100, 150 and 250 are the N-application rates (kg ha^{-1}). The percolation in all graphs is of the irrigated treatments at 50 kg N-application. Arrows indicate days of irrigation.

amount given in Table 3. The negligible difference in grain yield at the two lowest N-rates between the two irrigation strategies in SB1 (Figure 1) is a result of the irrigation need in that year being low (Table 3). However, the yield response at the highest N-rate was surprisingly high (Figure 1), in particular given the low irrigation need. The lower yields in the non-irrigated treatments in SB2 and WR (Figure 1) indicate that the crops there suffered some level of drought stress. Namely, in response to drought stress, premature senescence, decreased photosynthesis efficiency, increased respiratory losses, and stomatal closure could occur (Legg 1979). Crop drought stress can be worsened with increasing N-application rates, as higher N-rates may result in a larger leaf area, which exacerbates water losses (Andersen et al. 1996). In other words, the irrigation demand increases at higher N-rates, to prevent crop yield losses. This is supported by the irrigation strategy applied in WR (Table 3).

Despite the stagnating grain/seed yield (Figure 1), we observed an increasing plant N-uptake with increasing N-rates (Table 4). This increase was most pronounced for the irrigated treatments, for which the N-uptake increased significantly, not only from the lowest to the intermediate, but also from the intermediate to the highest level of N-application (Table 4). The N-uptake that is not required for immediate growth is referred to as luxury N-uptake (e.g. Lipson et al. 1996) and can influence the quality of grain/seed. For example, Bulman and Smith (1993) found higher grain protein concentration for higher N-application rates, and Andersen et al. (1996) found, for oilseed rape, that the concentration of oil is negatively correlated with the N-concentration in the seed. For the farmer, utilisation of N-applied may then be of relevance for managing the quality of the final product to attract a premium price.

The notable increased N-uptake by the straw in the non-irrigated treatment in SB1, and to a lesser extent in the irrigated treatment, could be explained by the production of new green shoots (also called green tillers) of the barley crop, late in the season. These green shoots have earlier been associated with multiple applications of fertilisers throughout the season (Haastrup 2008) and when conditions suddenly change from dry to wet (Chaturvedi 1981). The presence of green shoots can cause problems at harvest (Mogensen 1980). The fact that many more green shoots were observed in the non-irrigated treatments compared to the irrigated treatments demonstrate how irrigation can be used to promote an even crop development.

The nitrogen use efficiency (NUE)-indices (Table 5) indicate that irrigation improved the NUE while increasing levels of N-application reduced the NUE, as expressed in terms of the partial N budget (BNP) and partial-factor productivity (PFP). Namely, less N was recovered by the crops (in grain/seed and straw) relative to the amount of N applied for the non-irrigated treatments compared to the irrigated treatments in SB2 and WR, but not in SB1, (where the need for irrigation was small) as indicated by the smaller PNB (Table 3). Moreover, the decreasing PNBs with increasing N-application (from 0.82–1.03–0.44–0.69 and from 0.72–0.97–0.31–0.65 for the irrigated and non-irrigated treatments, respectively, Table 5) showed clearly that most surplus N was applied in the treatments with the highest N-application. The decreasing PFP with increasing levels of N-application could be a financial concern for farmers, as they should balance the cost of N with the DM yield. The fact that the PFP was higher for irrigated compared to the non-irrigated treatments at equal levels of N-application (with exception of the lowest level of N-application in SB1, for which difference was not significant), indicates that irrigation is an important tool in managing NUE. In the non-irrigated treatments at the highest N-rate (150/250 kg N ha^{-1}), the PFP was only 13 kg DM grain yield per kg N applied to spring barley and 3 kg DM seed yield per kg N applied to oilseed-rape.

The observed lack of increase in grain and seed yield and the strongly reduced PNB in response to the increasing N-applications meant that more N remained in the soil and was therefore at risk of leaching at the higher N-rates. This excess N could explain the leaching at the higher N-rates (Figure 1), particularly considering the field and climatic conditions of the trials. Moreover, occurrences of droughts during the growing season, following wet conditions, can trigger nitrate leaching from agricultural fields (Van Metre 2016). This can explain the nitrate leaching in the non-irrigated treatments at the higher N-rates in SB2 and WR, during which drought conditions occurred since irrigation was triggered. Irrigation had, in these treatments, a significant effect on the reduction of nitrate leaching. The significant interaction between irrigation and N-rate in SB2, where the reduction due to irrigation was higher at the higher N-rates (Figure 1), is in agreement with Lord and Mitchell (1998), who also showed that irrigation can reduce nitrate leaching at a large N-application rate, but that the effect of irrigation is smaller at lower N-rates. In SB1, where the need for irrigation was small (Table 3), the differences in nitrate leaching between treatments were negligible. In this experiment, the lack of increased nitrate leaching with higher N-rates could be explained by the N-uptake of the green shoots (Table 4).

The critical importance of weather conditions in relation to nitrate leaching is further confirmed by the results from five experiments comparable to the ones presented in this study, performed on the same experimental station. In those experiments, winter wheat (*Triticum aestivum L.*) or spring oilseed rape were grown (Supplementary 2). They were fertilised according to normal practice. The nitrate leaching was not significantly different between irrigated and non-irrigated treatments in four out of the five experiments where the need for irrigation was limited. Only in the experiment with winter wheat in 1989 (the same, relatively dry year as SB2, with eight irrigations in winter wheat), was nitrate leaching significantly different. As in the present study, nitrate leaching was significantly higher (with 17 kg N ha^{-1}) in the treatments without irrigation than in the treatments with irrigation. Thus, irrigation did not increase nitrate leaching; in contrast, it reduced nitrate leaching in a year with periods of drought.

The experiments included in this study showed that irrigation does not need to increase the risk of nitrate leaching, despite it increasing the soil water content and percolation. Synchronised management of irrigation and N-application is key for managing the risk of nitrate leaching. Our results show that balancing irrigation and N-application is an important, delicate matter which influences crop yield, N-uptake, grain/seed quality and risk of nitrate leaching. More specifically, we observed that increasing N-application without considering drought-stress responses brought little gain to grain and seed yield, resulted in a relatively lower N-uptake (particularly in the grain), and higher amounts of nitrate leaching. However, at the lowest N-rates, irrigation had a relatively limited effect on N-uptake in grain/seed and on N-leaching compared to the higher N-rates.

Balancing irrigation and N-application is particularly important for sandy soils, as was also pointed out by Gehl (2006). Delin and Stenberg (2014) examined fertiliser responses in spring oat (*Avena sativa L.*) and found that if the yield response per kg of N-fertiliser (the partial-factor productivity) was at least 10 kg grain, nitrate leaching would not be affected by the increase in fertiliser use. However, during the growing season it is difficult to predict final yield and predict how much fertiliser a crop will be able to utilise. Careful irrigation scheduling could then increase N-utilisation, and thereby reduce the risk of nitrate leaching in a dry growing season. In this respect, reliable weather forecasts are equally important, especially in humid climates where unforeseen rainfall can disturb irrigation management; events that did not occur during the experiments discussed.

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