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Site-specific effects of variable water supply and nitrogen fertilisation on winter wheat

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Abstract

The plant-available soil water, amount and distribution of rainfall or irrigation are primary factors that may affect yield and quality of winter wheat in heterogeneous fields. The objective of this 2-y study was to vary N application and water supply in order to achieve a more mechanistic insight into the effects of underlying differences in the site-specific productivity on heterogeneous fields. Two N fertilizer rates (120 and 180 kg N ha^{-1}) and three different water supply treatments (rain sheltering, irrigation, rain-fed) were compared on field sites with lower or higher plant available soil water capacities. On the whole, the site, rather than rainfall or N fertilisation, was the primary factor that accounted for variability in grain yield. Rainfall distribution during the growing season affected the overall yield level in a given year. The sites characterised by lower plant available water capacity did not show higher grain yield and improved quality with the increased N rate. This suggests that the reduced N rate should be recommended on these sites to take into account the environmental sustainability of N fertilisation. With respect to the higher N application at sites of high plant available soil water capacity, although the already high yield levels were not increased further, the protein quality was significantly improved in the first season within all treatments and in the second season in the irrigated treatments. Therefore, a higher N-rate proved to be advantageous, especially considering that the residual nitrate levels after harvest were low. The study demonstrated that the response of winter wheat to water shortage or abundance and N fertilisation is site-specific and dependent on the availability of soil water.

Key words: nitrogen management / precision agriculture / site-specific N rates / soil mineral N / soil water / wheat yield variability / water use efficiency

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1 Introduction

In many areas of the world, available soil water, rainfall or irrigation amounts and distribution are among the primary factors that determine winter wheat yields (*Stephens* and *Lyons*, 1998; *Eitzinger* et al., 2003; *Lithourgidis* et al., 2006). Fields frequently consist of several soil types, both with different nitrogen (N) and plant available water capacities for crop growth. The spatial distribution of soil properties interacts differently with weather conditions, thus determining the productivity potential from one year to another (*Mzuku* et al., 2005; *Schmidhalter* et al., 2006). The effect of the rainfall variability on the yield of wheat crops can be more considerable than the soil spatial variability (*Diacono* et al., 2012). In particular, for winter wheat the impact on yield of the plant-available soil water and precipitation differs depending on the area under consideration. As a consequence of the variability in plant-available soil water, site-specific N rate management is required to obtain economically and ecologically reasonable yields (*Schmidhalter* et al., 2008). According to *Wong* and *Asseng* (2006), the main cause of temporal and spatial yield variability within the field is the interaction of seasonal rainfall, soil storage capacity for plant available water and N fertiliser applications.

Precision farming has created a critical need for spatial data on crop yield and related soil characteristics. Soil resource variability is a result of interactions among soil parent material, climate, and local processes. Since the introduction of precision farming, substantial progress has been made in

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identifying the spatial variability of crops and soils by non-destructive methods that allow to retrieve information about soil textural differences, *e.g.*, by EM-38 mapping (*Heil* and *Schmidhalter*, 2012), plant available water capacities (*Selige* and *Schmidhalter*, 2001), and C and N contents (*Selige* et al., 2006) by remote sensing. Tractor mounted active or passive remote sensing allows detecting on-the-go variations in vegetative crop growth as well as in the N nutritional status (*Mistele* and *Schmidhalter*, 2008, 2010; *Erdle* et al., 2011). Crop yield maps either obtained by destructive (*Blackmore*, 2000) or non-destructive ways (*Schmidhalter* et al., 2001) contain a wealth of corollary information about spatial variability of soil properties that affect yield.

However, the variability of crop growth, revealed by the various approaches reported above, results from the integration of all the factors responsible for crop growth and development, and the interpretation is not straightforward. Examination of sequences of yield maps has revealed not only large variations in yield in a given season, but also lack of consistency in the pattern of variability from season to season within fields (*Blackmore*, 2000). In part, this is due to the fact that historical information does not anticipate the actual or future situation, and on-the-go information is restricted to the actual status disregarding future or possible past scenarios. Notwithstanding that the collection of information is advanced, the assembling and translating of such information in management action is still rather in its infancy. Even though numerous algorithms have been suggested, there is a lack of studies demonstrating their long-term validity with regard to improved management actions (*Samborski* et al., 2009). The causes for variability must be adequately understood before variable rate fertilisation can safely be used to optimise N side-dressing in cereals (*Zillmann* et al., 2006).

Ultimately a lack of information regarding multifactorial influences becomes evident in differently targeted actions for the site-specific application of N fertilisers. This is also the case in the high yielding situation in W Europe. Contrasting views exist whether or not increased or decreased N inputs should be directed to lower yielding sites as well as with regard to the resulting consequences embracing not only yield and quality aspects but also environmental effects (*Ebertseder* et al., 2005; *Berntsen* et al., 2006; *Zillmann* et al., 2006; *Schmidhalter* et al., 2008). Divergent opinions also exist whether or not a homogenisation on heterogeneous site should be attempted.

Most of the information so far has been gained from correlative attempts linking heterogeneity to growth, yield, or quality. On the other hand, very few studies exist which aim to manipulate N and water inputs on heterogeneous field sites to arrive at a more mechanistic understanding of the causal factors contributing to the heterogeneous nature of crop growth.

This research was, therefore, undertaken to test various scenarios including varied N supply by fertilisation together with varied water supply scenarios. Whereas the individual information already might be collected from previous experimentation done under homogeneous site conditions, the withdrawal of such information depicting heterogeneous sites is challenging, and faces limits when further considering the varying influence of the annual climate. Knowledge of these variables and of their effect on the observed variations in the response to fertilizer is necessary when planning sustainable and site-specific management actions.

2 Material and Methods

2.1 Site description

The trials were conducted for 2 y in the tertiary foothills of the Bavarian Alps, S Germany. In this area, fields with heterogeneous soil texture are frequent. Prior to the study, two adjacent fields (Sieblerfeld and Krohberg) were carefully texture-mapped according to the guidelines of the German Soil Science Society (*Finnern* et al., 1996) to a depth of 90 cm, and the plant available soil water capacities were mapped across the entire fields (Fig. 1). Contrasting sites were selected for the targeted variation of water and N application on the field Sieblerfeld in 2000 and on the field Krohberg in 2001. Both fields were adequately supplied with P and K as evidenced by a detailed nutrient status survey on the fields (data not shown). Therefore, it could be postulated that N and water supply were the growth limiting factors.

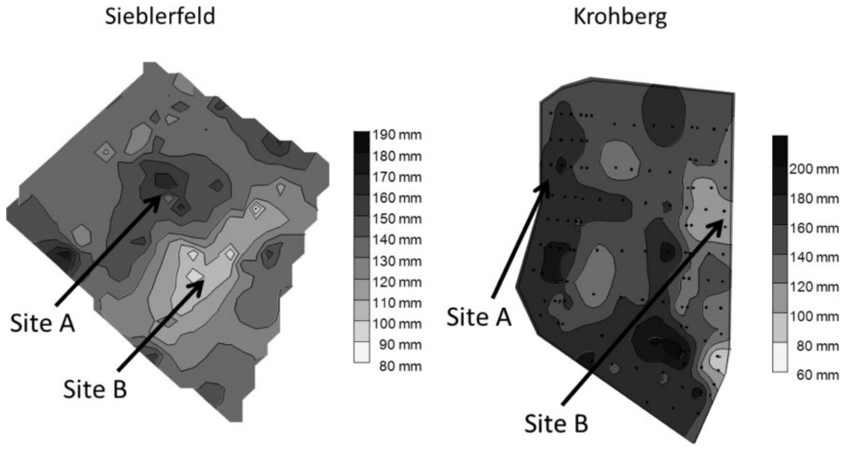

Figure 1: Plant available soil water capacities in 0–90 cm soil depth on the field sites Sieblerfeld and Krohberg. Locations on both fields, within higher (A) and lower (B) plant available soil water capacity zones (PASW), are indicated where completely randomised two factorial designs were set up with two N fertilizer treatments (120 and 180 kg N ha^{-1}) and three different water supply treatments (stress by rain sheltering, irrigation by T-Tape trickle irrigation, control being rain-fed) on the respective sites characterized by lower and higher plant available soil water capacities.

Within the Sieblerfeld field, a loamy Cambisol (*"Braunerde"*) (site A, characterised by a plant available soil water capacity of ≈160 mm down to 90 cm soil depth) and a loam-sandy Cambisol (site B, characterised by a plant available soil water capacity of ≈100 mm down to 90 cm soil depth) site were selected for the first trial year in 2000. A silt-loamy Cambisol (site A, characterised by a plant available soil water capacity of ≈170 mm down to 90 cm soil depth) and a loam-sandy Cambisol (site B, characterised by a plant available soil water capacity of ≈100 mm down to 90 cm soil depth) site were selected for the second trial within the Krohberg field in 2001. In general, on both fields the A (higher grade) sites showed increased plant available soil water capacities as compared to the B (lower grade) sites. In these fields, the groundwater level was > 2 m deep.

2.2 Experimental design, sampling, and measurements

At selected sites of lower and higher soil water capacities of each of the two heterogeneous fields, a completely randomised two-factorial design with three replications was set up with two N fertiliser treatments (NT) and three different water supply treatments (WT). The winter wheat (*Triticum aestivum* L.) variety "Pegassos" was sown at a row distance of 13.2 cm. In both years, the preceding crops were maize and mustard (as a catch crop).

Each experimental plot consisted of two subplots of 1.85 m × 6 m. One subplot was used for the installation of soil water measurement devices (*Geesing* et al., 2004) and, in the second trial year, for additional soil sampling and pre-harvest aboveground biomass sampling. The second subplot was used for the final harvest. The following NT treatments were compared: (1) 120 kg N ha^{-1} and (2) 180 kg N ha^{-1} in both sites, representing a decreased and a conventional fertiliser application in this region at the expected yield. The fertiliser (Ca/NH_4-nitrate) was split-applied in four applications as 60/40/40/40 kg ha^{-1} and 30/30/30/30 kg ha^{-1} for (1) and (2), respectively. The application times were the beginning of the growing season (Growth Stage (GS) 10; *Zadoks*, 1974), beginning of stem elongation (GS 30), two-node stage (GS 32), and beginning of heading (GS 50).

The WT treatments were as follows: (1) stress by rain sheltering, (2) irrigation by T-Tape trickle irrigation (T-Systems Europe Ltd., Toulouse, France), and (3) control (rain-fed only). The mobile rain shelter consisted of timber frames that were covered with a 0.5 mm transparent polyethylene sheet supported (to give a 0.3 m pitch) by 2 m and 2.3 m vertical stakes set 0.5 m into the ground. Drainage from the roof was discharged away from the site. Driving rain was kept out by side curtains that were lowered if necessary. Border rows were excluded at biomass and harvest samplings to exclude possible small effects from water infiltrating sideways into the rain-starved plots from below the soil level. The temperature under the shelter was somewhat higher than outside, particularly at night and on days with clear skies. Therefore, plots were covered immediately before rains and the cover was removed shortly after. The plots never stayed covered longer than four consecutive days to avoid masking side effects. Irrigation and rain sheltering were applied depending upon weather conditions between the two-node stage to the flag leaf stage (GS 37) in the first year, and between the three-node stage (GS 33) and the first visible appearance of the awns (GS 49) in the second year. Nitrogen applications decisions are mainly either done shortly before or occur within this period, thus the interactive effects of varied N application and water supply can best be studied within this period.

Once a week, soil water was measured from 10 to 100 cm soil depth in 10 cm increments by using a portable Diviner capacitance probe (Sentek Pty Ltd., South Australia). This probe was lowered into PVC access tubes that were inserted into hand augered holes. The capacitance probe method measures the soil-water-air mixture and the water content at different electromagnetic field frequencies. The frequency collected by the instrument was converted into volumetric water contents by using a customised calibration. The calibration was obtained by simultaneous soil core sampling and by relating the soil water content to the electromagnetic field frequency of the capacitance probes (*Geesing* et al., 2004).

In addition, during the field trial soil core samples were taken weekly from each plot to determine the gravimetric soil water from 0–30 cm and 31–60 cm soil depths. The samples were taken with an auger of 4-cm inner diameter (two samples per depth), 50 cm away from the access tube. Then, the two samples per depth and plot were bulked, put into a plastic bag, and immediately placed into an ice box. For the determination of the gravimetric soil water content, soil samples were weighed, dried in an oven at 105°C for 24 h, and then reweighed.

Bulk density was derived from data obtained from three soil profiles inside the trial field and two soil profiles in a neighbouring field. At site A in the first trial year, the bulk density was 1.51 and 1.55 g cm^{-3} at soil depths of 20 and 50 cm, respectively, whereas in the second trial year, it was 1.52 and 1.55 g cm^{-3}, respectively. In 2000 at site B, the bulk density was 1.64 and 1.68 g cm^{-3} at soil depths of 20 and 50 cm, respectively, whereas in 2001, it was 1.64 and 1.65 g cm^{-3}, respectively.

Not all plots could be equipped with capacitance probes in the first trial year due to the restricted availability of probes. Thus, soil water measurements for the low- and high-N treatments were not taken separately. In the second trial year, all plots were equipped with capacitance probes, and thus, separate soil water measurements for the two N treatments were obtained. In addition, at each site one irrigated plot, one control, and one rain-sheltered plot within each NT were equipped with an EnviroScan capacitive multisensor probe system (Sentek Pty Ltd., South Australia). The capacitance sensors were located within the root zone, in 20 cm increments to a depth of 100 cm. These sensors remained permanently *in situ* during the trial and were logged hourly.

Soil core samples, obtained from one soil profile made at each site, were placed on a ceramic plate in a pressure chamber to determine the water retention function. Therefore, they were subjected to gas pressures of 60 hPa, 300 hPa, 1000 hPa, 5000 hPa, and 15000 hPa, and reweighed after each pressure step. The freely draining equilibrium water content was 60 hPa for the coarse-textured soils and 300 hPa for the loamy soils. This content was considered to be the field capacity (θ_{vFC}), whereas the equilibrium water content at 15,000 hPa was considered to be the wilting point (θ_{vWP}) (*Cassel* and *Nielsen*, 1986). Four horizons were sampled on average. The plant-available soil water (PASW) was calculated as the difference between the soil water content at field capacity and at the wilting point. The PASW of the rooting zone was computed by summing the PASW of the different soil horizons. Depletion of PASW was calculated using Eq. (1), with θ_v being the volumetric water content determined from capacitive sensor readings:

$$(\theta_v - \theta_{vWP} / \theta_{vFC} - \theta_{vWP}) \times 100. \quad (1)$$

The median value from 4–5 measurements per month (per 10 cm increments) was used to describe the monthly depletion status of PASW. A maximum monthly depletion (MMD) of an increment layer was then defined as the highest depletion value among the months April through July.

During the field trial in 2001, soil core samples were regularly taken from each plot to determine the soil mineral N content (N_{min}) from 0–30 cm and 31–60 cm soil depths. Soil samples were extracted with 0.1 N $CaCl_2$ and analysed for soil nitrate content by high-performance liquid chromatography (HPLC) and for ammonium-N by the indophenol blue method (*Barth* et al., 2008).

2.3 Biomass and yield data

In the second trial year, pre-harvest samples were taken from an area of 1.5 m^2 at the beginning of stem elongation (GS 30), at the beginning of flowering (GS 60), at the end of flowering (GS 69), and at the medium milk stage (75). From the beginning of flowering on, ears were manually clipped for a separate analysis.

At the end of the trial, each subplot that was fixed for harvest was separately hand-harvested. The yield per plot was weighed, and the number of ears per square meter was estimated from a subsample. This number was related to the weight of the yield of the respective plot. The grain was then threshed with a nursery thresher, and the straw yield was determined to be the difference between the total dry matter and grain yield. Subsamples of grain and straw were oven-dried at 65°C to constant weight, thereafter they were ground for an analysis of the total N by the Dumas technique in a macro-N-analyser. Grain samples for 1000-grain weight determinations were air-dried, counted with an electronic seed counter, and then weighed. The water use efficiency in grain production was determined by dividing the grain yield by the cubic meter of water used (soil water use *plus* precipitation for the same period).

2.4 Statistical analysis

Statistical analysis was performed using a general linear model (SAS, 2010). When significant differences were found ($P = 0.05$), the least significant differences (LSD) were calculated. For testing differences between the soil water content under high- and low-N applications, a Wilcoxon rank-sum test was performed (SAS, 2010). The available soil water capacity data (Fig. 1) were interpolated using the geostatistical package GS+ (version 3.1.7, 1998). Continuous maps were obtained using experimental omnidirectional semivariograms and ordinary kriging of residuals.

3 Results

3.1 Meteorological conditions and water supply

The average daily temperature, precipitation, irrigation amount, and withheld precipitation for each growing spring and summer season are given in Table 1. In April and May 2000, the temperature and precipitation were above average followed by a relatively hot and dry June and a relatively cold and rainy July. The temperature and precipitation in the growing spring season of 2001 were near average, except for May and July, which were both warmer and drier than the average.

The difference in the external water supply between the irrigated plots and the rain-shelter plots was 244 mm in 2000 and 214 mm in 2001.

3.2 Depletion of plant available soil water

In the first trial year, the amount of PASW to a soil depth of 90 cm was ≈160 and ≈100 mm at sites A and B, respectively. In the second trial year, at the same soil depth, the PASW was ≈170 and ≈100 mm for sites A and B, respectively.

Figures 2 and 3 compare the monthly depletion of PASW of the two sites during the growing period of winter wheat in the two trial years. At both sites, the depletion of PASW was slowed down by irrigation or accelerated by the rain-shelter treatment compared to the control. After the water supply treatment (WT) was terminated in the beginning of June, PASW depletion quickly reached similar levels in all treatments.

As for the pattern of depletion in the soil profile, a substantial difference between the two sites could be recognised. At site B, depletion was more pronounced above 50 cm in the soil profile than below this depth. In contrast, at site A, PASW was depleted to a comparable extent in all depths throughout the soil profile. At a depth of 90 cm, PASW depletion continuously increased from May to July at site A, whereas at site B, there was little difference in depletion between May, June and July, particularly in the first year.

A maximum monthly depletion (MMD) of > 70% of the PASW of the first 50 cm soil depth was observed at site B. In contrast, at site A the MMD of the PASW at the same depth was

Table 1: Monthly average maximum and minimum temperature, precipitation, amount of irrigated water and of rainwater withheld by sheltering during the 2000 and 2001 growing seasons, and the 30-y average.

2000	**April**	**May**	**June**	**July**
Temperature				
Average Maximum (°C)	15.8	20.7	23.4	20.9
Average Minimum (°C)	4.0	8.6	10.2	10.9
Precipitation (mm)	74	104.3	60.9	137.1
Irrigation (mm)		150		
Withheld rainwater (mm)		94.3		
2001				
Temperature				
Average Maximum (°C)	11.8	20.8	19.5	23.8
Average Minimum (°C)	2.4	8.9	8.9	11.6
Precipitation (mm)	52.6	60.2	104.5	57.7
Irrigation (mm)		160		
Withheld rainwater (mm)		54.9	10.2	
1981–2010				
Temperature				
Average Maximum (°C)	13.5	18.6	21.2	23.7
Average Minimum (°C)	2.5	7.3	10.2	12.1
Precipitation (mm)	55.6	82.9	88.9	107.8

always < 75%. The difference between the two sites in MMD from 60 to 90 cm was less pronounced than from 0 to 50 cm. This difference ranged from 36 to 57% at site B and from 54 to 65% at site A. The MMD was higher on the rain-sheltered treatment than on the control one, which in turn was higher than the maximum depletion of the irrigation treatment.

The plant available soil water depletion did not remarkably differ between the two N treatments at site B and below a 30 cm soil depth at site A (data not shown). However, in the topsoil of site A (especially under the irrigation treatment) depletion of PASW was higher in the low-N treatment than on the high-N treatment. Moreover, significant differences (> 10%) between the two N treatments were often found.

3.3 Grain yield

From 2000 to 2001, a yield increase was observed on both sites within all treatments. In 2001, the average grain yield of site A was 10.8 t ha^{-1}. This outcome was markedly higher than in the 2000 cropping season (7.4 t ha^{-1}) (Table 2, Fig. 4). However, the absolute difference in grain yield between the two sites had a similar magnitude in both years when compared within each treatment.

The high-N treatment generally yielded more than the low-N treatment, except in the rain-shelter treatment at site B in 2000. The differences were always significant when the WT data were pooled, but only in a few cases within each WT. The highest yield increase, from 2000 to 2001, was obtained for the rain-shelter treatments (*i.e.*, when the water supply was reduced during stem elongation and heading). This increase was 61.4 and 113.6% at sites A and B, respectively. In addition, the high-N treatment showed average yield increases of 40.9 and 61.4% at sites A and B, respectively.

At site A, an increased external water supply did not benefit grain yield (*i.e.*, in the irrigated low-N treatment). Irrigation was beneficial on the sandy soils, although it occurred during a less-critical water demand period.

The effect of the factor site on grain yield interacted with the WT treatments (Table 3). The significant difference between the two sites with respect to the rain-shelter treatment (3.8 dt ha^{-1} in 2000 and 4.6 dt ha^{-1} in 2001) was not significant when examining the irrigation treatment (0.6 dt ha^{-1} in 2000 and 1.2 dt ha^{-1} in 2001). At the A sites, in 2000, the difference in grain yield between the rain-shelter and irrigation treatments was similar in value to the grain yield difference due to NT (*i.e.*, ≈1 dt ha^{-1}). In 2001, small differences between the two WT and of ≈ 0.5 dt ha^{-1} between the two NT were found. At the B sites, the difference between the rain-shelter and irrigation treatment was far more important (4.2 dt ha^{-1} and 3.4 dt ha^{-1} in 2000 and 2001, respectively) than the average increase resulting from a higher N application (amounting to 0.3 dt ha^{-1} and 0.8 dt ha^{-1} in 2000 and 2001, respectively).

Increment efficiency was obtained by dividing the 60 kg N ha^{-1} increment by the yield increase (in kg). The maximum efficiency for each kg of N applied at the A sites was found in the rain-shelter treatments (21.0 and 12.8 kg kg^{-1} in 2000 and 2001, respectively). At the B sites in 2000, the maximum grain yield increase for each kg of the N increment applied

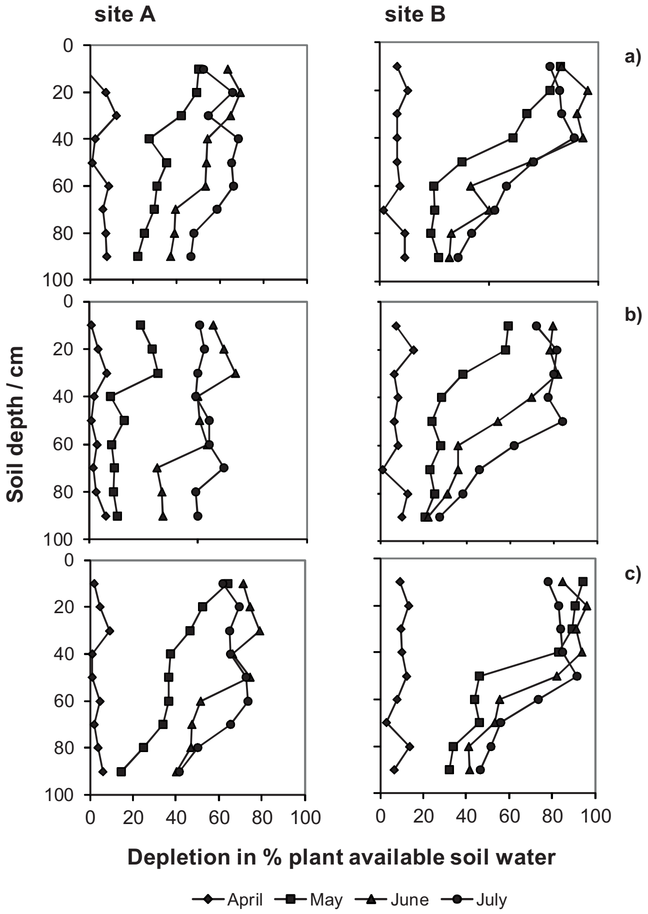

Figure 2: Depletion of plant-available soil water (%) at different soil depths at two sites (A characterized by a higher PASW, and B characterised by a lower PASW) in 2000, for three different water supply regimes: a) control, rain-fed; b) irrigation; c) rain-sheltering. Values are the median depletion of plant-available soil water for each month during the 2000 growing season.

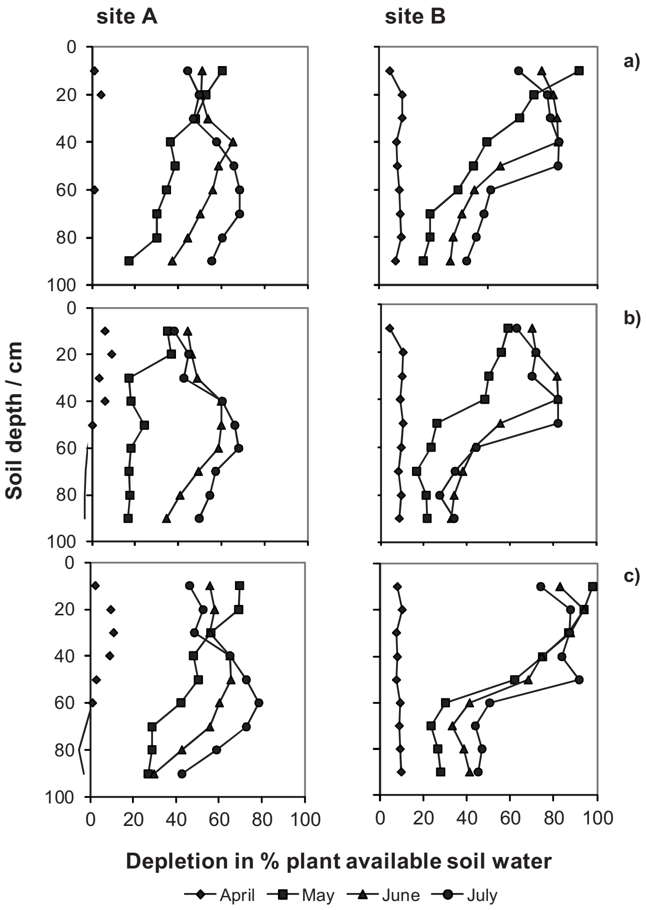

Figure 3: Depletion of plant-available soil water (%) at different soil depths at two sites (A, higher PASW, and B, lower PASW) in 2001, for three different water supply regimes: a) control, rain-fed; b) irrigation; c) rain-sheltering. Values are the median depletion of plant-available soil water for each month during the 2001 growing season.

was obtained on the irrigation treatment (12.7 kg). In 2001, the maximum efficiency for each kg of N applied was obtained in the irrigation treatment and, surprisingly, in the rain-shelter treatment (both 18.0 kg kg^{-1}). In 2000, on average across the WT, the N increment was more efficiently used at site A (16.5 kg kg^{-1}) than at site B (5.3 kg kg^{-1}). However, the opposite occurred in 2001, when the N increment was more efficiently used at site B (12.5 kg kg^{-1}) than at site A (8.7 kg kg^{-1}).

3.4 Straw yield and harvest index

The straw yield was generally higher on the high-N plots than on the low-N plots, but no significant differences were found within each WT (Table 3). At the B sites and at the A site in 2000, the effect of NT on straw yield was always stronger within the irrigation treatment than within the other WT. Moreover, significant differences in straw yield between the WT were found at the B sites. At the A sites, a steady increase of straw yield from rain-shelter to irrigation treatment could be observed on the high-N plots. The differences between the two sites in straw yield were much larger in 2001 than in 2000. In both years, the smallest differences between the two sites were found in the irrigation treatment.

Because the effect of NT on straw yield was comparable to its effect on grain yield, the harvest index (HI) was little influenced by NT. However, the effect of WT and of the factor “site” on grain yield differed from their respective effect on straw yield. We found the following different interacting effects: (1) site and WT on grain and straw yield in both experimental years, (2) site and WT on HI in 2000, and (3) NT and WT on HI in 2001 (Table 3). Thus, the response of HI to WT and site was quite erratic.

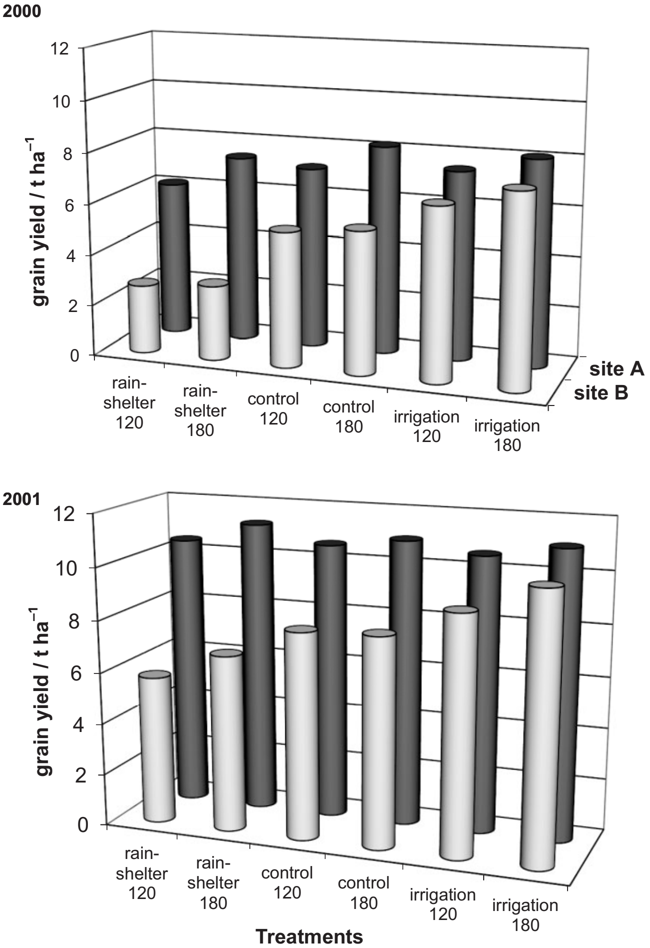

Figure 4: Effect of fertilizer treatments (120 and 180 kg N ha^{-1}), water supply treatments (control, rain-fed; irrigation; rain-sheltering) and site (A and B, characterized by higher and lower PASW, respectively) on grain yield in 2000 and 2001.

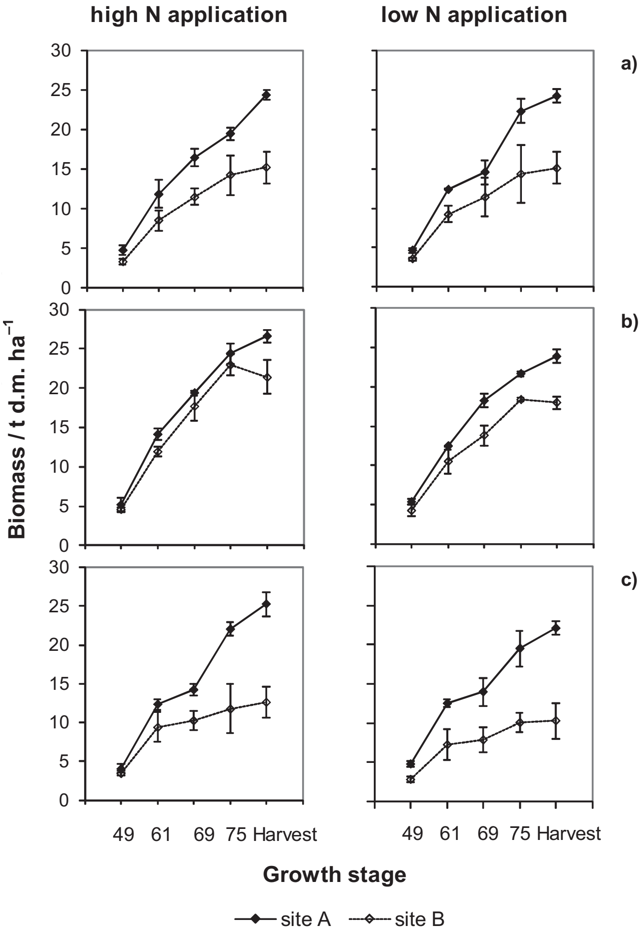

Figure 5: Effects of fertilizer treatments (high N: 180 kg N ha^{-1}; low N: 120 kg N ha^{-1}) and water supply treatments [a) control, rain-fed; b) irrigation; c) rain-sheltering] on aboveground biomass growth (tonnes on dry matter basis, d.m., with S.E.) in 2001, at site A (higher PASW) and B (lower PASW). The growth stages are based on (*Zadoks*, 1974).

3.5 Biomass development, ears per square meter and seed weight

Pre-harvest biomass data were only available for the second trial year. The biomass growth curve of the rain-shelter treatment of site A was flattened during anthesis (GS 60 to 69) compared to the curve of the irrigation treatment. The biomass growth curve of the rain-shelter treatment of site B, however, stayed flattened beyond anthesis, in comparison with the irrigation treatment and all treatments at site A (Fig. 5).

At the A sites, more ears per square meter on the low-N treatment than on the high-N treatment were found, except for the rain-shelter treatment in 2001 (Table 4). At the B sites, the response to NT was more erratic. At both sites, the number of ears generally increased from the rain-shelter treatment to the control and the irrigation treatments. The number of ears at site A was higher than at site B, except on the irrigation treatment in 2000 when the number was similar at both sites.

Seed weight was higher on the high-N treatment than on the low-N treatment, except in the irrigation treatment at site A and on the rain-shelter treatment at site B in 2000. On the whole, WT did not consistently affect seed weight. The seed weight was significantly higher at site A than at site B within WT in 2001. In 2000, seed weight was significantly higher at site A only within the rain-shelter treatment or when pooled across WT.

3.6 Grain N content

Grain N content (gN in g kg^{-1}) was generally higher on the high-N treatment than on the low-N treatment (Table 5). For both years at site B, gN decreased from the rain-shelter to control to irrigation treatment. This decrease could not entirely compensate for the biomass increase (except within the low-N treatment in 2001). In 2000, gN from the rain-shelter treatments was notably high at both sites. At the sites of low plant-available soil water, gN was particularly low on the irrigation treatment with low N.

Table 2: Grain yield, straw yield, and harvest index as affected by site (A and B characterised by higher and lower PASW, respectively), fertiliser treatments (120 and 180 kg N ha^{-1}), and water supply treatments (control, rain-fed; irrigation; and rain-sheltering) in the 2000 and 2001 seasons (ns: not significant at $P = 0.05$; † least significant difference between two sites).

Fertilizer	**Grain yield / Mg ha^{-1}**					**Straw yield / Mg ha^{-1}**					**Harvest index**				
/ kg ha^{-1}	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD
2000, site A															
120	7.12	7.42	6.10	6.88	ns	8.03	7.80	5.96	7.26	ns	0.47	0.49	0.50	0.49	ns
180	8.18	8.08	7.36	7.87	ns	8.63	8.78	6.48	7.96	1.89	0.49	0.48	0.53	0.50	ns
average	7.66	7.75	6.73	7.38	ns	8.33	8.29	6.22	7.61	1.26	0.48	0.48	0.52	0.49	0.03
LSD	ns	ns	ns	0.93		ns	ns	ns	ns		ns	ns	ns	ns	
2000, site B															
120	5.28	6.73	2.96	4.86	0.66	5.42	6.76	3.51	5.12	0.59	0.49	0.50	0.45	0.48	0.02
180	5.56	7.49	2.93	5.18	0.87	5.57	8.30	3.35	5.59	1.08	0.50	0.48	0.47	0.48	ns
average	5.42	7.11	2.94	5.02	0.52	5.50	7.53	3.43	5.36	0.78	0.50	0.49	0.46	0.48	0.02
LSD	ns	0.67	ns	1.38		ns	1.32	ns	ns		ns	ns	ns	ns	
LSD †	0.93	ns	0.97	0.97		0.97	ns	0.77	1.04		ns	ns	0.04	ns	
2001, site A															
120	10.63	10.60	10.47	10.57	ns	13.67	13.27	11.60	12.85	ns	0.44	0.44	0.48	0.45	0.03
180	10.97	11.05	11.24	11.09	ns	13.44	15.54	13.98	14.32	ns	0.45	0.42	0.44	0.44	ns
average	10.80	10.83	10.86	10.83	ns	13.55	14.40	12.79	13.58	ns	0.44	0.43	0.46	0.44	0.03
LSD	ns	ns	ns	0.65		ns	ns	ns	1.34		ns	ns	ns	ns	
2001, site B															
120	7.96	9.12	5.74	7.61	3.29	7.16	8.87	4.55	6.86	3.09	0.53	0.51	0.56	0.53	0.03
180	8.05	10.20	6.82	8.36	ns	7.17	11.20	5.81	8.06	3.70	0.53	0.48	0.54	0.52	0.02
average	8.01	9.66	6.28	7.98	1.95	7.17	10.03	5.18	7.46	2.14	0.53	0.49	0.55	0.52	0.02
LSD	ns	ns	ns	2.08		ns	ns	ns	ns		ns	0.03	0.01	ns	
LSD †	1.42	ns	2.05	1.04		1.70	2.30	2.10	1.45		0.02	0.03	0.02	0.02	

Table 3: Variance ratios (*F*) of the interaction effect of site, N fertilizer application (NT) and water supply treatment (WT) on yield, plant characteristics, grain quality, and N uptake of winter wheat (* significant at $P = 0.05$; ** significant at $P = 0.01$).

2000								
Source	D.F.	Grain yield	Straw yield	Harvest index	Ears / m^2	Seed weight	N grain	N uptake
site X NT	1	2.09	0.13	0.81	0.44	0.89	0.04	3.62
site X WT	2	16.32**	7.01**	8.16**	0.66	1.52	7.85**	6.42**
NT X WT	2	0.02	1.66	1.96	0.70	0.43	0.93	0.06
site X WT X NT	2	0.82	0.54	0.02	0.26	4.33*	0.07	0.71
(WT X NT) / site A	2	0.18	0.08	0.86	0.40	1.35	0.68	0.14
(WT X NT) / site B	2	0.90	3.59*	1.20	0.66	4.04*	0.74	0.86
2001								
Source	D.F.	Grain yield	Straw yield	Harvest index	Ears / m^2	Seed weight	N grain	N uptake
site X NT	1	0.07	2.38	0.00	0.35	0.04	0.00	0.63
site X WT	2	5.11**	3.90**	2.72	1.50	0.75	0.02	2.18
NT X WT	2	0.25	2.38	4.74*	0.21	0.05	0.11	2.81
site X WT X NT	2	0.09	0.20	0.40	2.12	1.04	0.00	0.19
(WT X NT) / site A	2	0.14	2.72	2.82	3.21	0.86	0.04	0.61
(WT X NT) / site B	2	0.17	0.69	2.13	0.63	0.45	0.07	3.12**

Table 4: Ears per square meter and seed weight as affected by site (A and B characterised by higher and lower PASW, respectively), fertilizer treatments (120 and 180 kg N ha^{-1}), and water supply treatments (control, rain-fed; irrigation; and rain-sheltering) in the 2000 and 2001 seasons (ns: not significant at $P = 0.05$; † least significant difference between two sites).

Fertiliser	**Ears / m^2**					**Seed weight / g 1000-grain^{-1}**				
/ kg ha $^{-1}$	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD
2000, site A										
120	421.4	443.9	410.5	425.2	ns	38.0	48.8	42.1	41.0	ns
180	392.3	399.3	322.8	371.5	ns	41.1	45.4	51.2	45.9	7.9
average	406.8	421.6	366.7	398.3	ns	39.6	44.1	46.7	43.4	5.7
LSD	ns	ns	ns	ns		ns	ns	ns	4.8	
2000, site B										
120	364.4	398.2	315.0	356.4	76.3	36.3	36.7	40.5	38.0	ns
180	353.2	455.9	352.2	384.9	93.7	38.5	44.1	40.0	40.8	3.5
average	358.8	427.1	333.6	370.7	57.2	37.4	40.4	40.3	39.4	ns
LSD	ns	ns	ns	ns		ns	3.6	ns	ns	
LSD †	42.6	ns	ns	ns		ns	ns	5.0	2.7	
2001, site A										
120	632.4	647.6	479.7	586.6	72.7	47.2	47.4	47.4	47.3	ns
180	609.2	628.0	557.7	598.3	ns	48.9	49.9	52.0	50.2	ns
average	620.8	637.8	518.7	592.4	54.1	48.0	48.7	49.7	48.8	ns
LSD	ns	ns	ns	ns		ns	ns	ns	2.0	
2001, site B										
120	440.0	500.2	440.3	460.2	ns	37.2	39.6	43.2	40.0	4.0
180	474.1	586.4	427.7	496.0	ns	41.4	44.2	44.2	43.3	ns
average	457.1	543.3	434.0	478.1	91.7	39.3	41.9	43.7	41.6	ns
LSD	ns	ns	ns	ns		7.0	10.5	6.3	3.8	
LSD †	63.7	ns	57.6	52.2		3.5	4.8	3.9	2.3	

3.7 Nitrogen uptake

The increase in grain and straw yield and the higher grain and straw N concentrations (data not shown) with the high-N treatment compared to the low-N treatment were also reflected in an increased N uptake. Uptake of N was more substantial at site A than at site B (Table 5). At site B, N uptake increased from the rain-shelter to the control and to the irrigation treatments. In most cases, and in particular at site A, the N removed by the plants exceeded the amount of applied N fertilizer.

3.8 Water use efficiency (WUE)

Soil water use was initially assumed to be similar for both NT and, thus, soil water monitoring devices were shared in 2000. In 2001, soil water use was monitored on each NT. As mentioned before, differences in soil water use between the NT were in some cases substantial when single soil layers were considered over a limited period of time. However, when estimated for the entire growing season and for the rooting zone, these differences were relatively small (< 6%) and had little effect on the WUE calculation. Thus, the two different approaches in 2000 and in 2001 did not exclude a comparison between the two experimental years.

The WUE was ≈ 90% higher in 2001 than in 2000 (Table 7). Water was more efficiently used at site A than at site B, with similar absolute differences between the two sites in both years (0.5 kg grain m^{-3} in 2000, and 0.57 kg grain m^{-3} in 2001).

More efficient use of soil water was observed on the high-N treatment compared to the low-N treatment within WT, every time in which a yield increase occurred. The rain-shelter treatment resulted in the largest WUE at the A sites. Irrigation reduced the WUE compared to control at both sites, but to a lesser extent at site B than at site A. Thus, the differences in WUE between the two sites were smaller in the irrigation treatment than on the other WT.

Because the soil water depletion data suggested water extraction at the A sites below the monitored 90 cm, the difference in WUE between the two sites are most likely smaller than that presented in Table 6. Water use efficiency consid-

Table 5: Nitrogen content in grain and N uptake (aboveground) as affected by site (A and B characterised by higher and lower PASW, respectively), fertiliser treatments (120 and 180 kg N ha^{-1}), and water supply treatments (control, rain-fed; irrigation; and rain-sheltering) in the 2000 and 2001 seasons (ns: not significant at $P = 0.05$; † least significant difference between two sites).

Fertiliser	**Grain N content / g kg^{-1}**					**N uptake**				
/ kg ha $^{-1}$	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD
2000, site A										
120	21.4	20.9	24.5	22.3	1.6	191.6	193.3	181.7	188.9	ns
180	23.5	23.9	27.6	25.0	1.5	246.4	250.8	255.2	250.8	ns
Average	22.5	22.4	26.1	23.6	2.0	219.0	222.0	218.4	219.8	ns
LSD	1.3	1.6	2.2	2.0		ns	ns	ns	28.7	
2000, site B										
120	21.7	19.6	27.1	23.1	2.0	133.9	162.1	97.7	129.1	9.2
180	25.1	22.1	29.0	25.6	1.9	167.8	202.8	108.4	156.4	12.5
Average	23.4	20.8	28.1	24.3	2.0	150.8	182.4	103.0	142.8	8.0
LSD	0.7	ns	1.7	2.5		ns	ns	ns	ns	
LSD †	ns	ns	1.8	ns		37.6	ns	38.5	26.2	
2001, site A										
120	21.7	21.0	21.5	21.4	ns	314.2	294.8	293.3	300.8	ns
180	21.8	23.0	22.4	22.4	ns	319.3	363.9	348.7	343.9	ns
Average	21.8	22.0	22.0	21.9	ns	316.7	329.4	321.0	322.4	ns
LSD	ns	1.8	ns	0.9		ns	ns	ns	28.3	
2001, site B										
120	21.5	18.5	23.8	21.3	ns	206.0	205.2	157.5	189.5	ns
180	22.5	21.4	25.4	23.1	ns	222.6	275.6	216.3	238.1	ns
Average	22.0	19.9	24.6	22.2	2.9	214.3	240.4	186.9	213.8	ns
LSD	ns	2.8	ns	ns		ns	ns	ns	36.6	
LSD †	ns	ns	ns	ns		25.3	61.2	54.1	26.8	

erations based on only soil water use diminish the difference between the two sites (except for the rain-shelter treatment).

The average soil water use in 2001, on the whole-field scale, was similar to the soil water use in 2000. In contrast, the difference between the two sites was higher in 2001 (41 mm) than in 2000 (16 mm) (Table 6). The highest soil water consumption was on the rain-shelter treatment at the B sites, in both experimental years, at the A site in 2000, and for the control in 2001. The lowest soil water consumption was always found for the irrigation treatment. In 2001, the use of soil water was more efficient at site B than at site A.

3.9 Soil mineral N

The soil mineral N (N_{min}) data were only available for 2001. The N_{min} differences at different sampling times could primarily be attributed to the site (and in many cases also to WT), whereas NT did not produce significant effects on N_{min} (Table 7). Before the first fertilizer N application in April and the beginning of the water supply treatment, no differences in N_{min} between the plots of each site were found. However, a higher soil N_{min} was found at site B than at site A (Figures 6, 7). The increase in N_{min} in the topsoil (0–30 cm) until mid of June was followed by a decrease until the end of June. Subsequently, N_{min} remained at a relatively low level or further declined at site A. At site B, a new increase in N_{min} until the end of July was observed. The absolute N_{min} content and the amplitude of change between the sampling dates, were always considerably higher at site B than A.

Differences between the corresponding plots of the two sites appeared to be somewhat more pronounced on the high-N than on the low-N treatments. Differences between the two sites decreased as the external water supply increased from the rain-shelter to the control and to the irrigation treatments. For the rain-sheltered treatments and high-N application in the middle of June, a maximum difference in N_{min} between the two sites of more than 80 kg N ha^{-1} was found. The difference was > 90 kg N ha^{-1} at the end of July. In the subsoil (31–60 cm) of the control and irrigation treatments, the differences between the two sites were generally less important than in the topsoil, except for the rain-shelter treatment, where the differences were still considerable. An increase in N_{min} after the end of July at site B was also observed in the subsoil.

Table 6: Water use efficiency (grain yield in kg divided by the sum in m^3 of rainwater, precipitation water, and soil water use), soil water use (difference in soil water content before and after trial), and soil water use efficiency (grain yield in kg divided by soil water use in m^3) as affected by site (A and B sites characterised by higher and lower PASW, respectively), fertiliser treatments, and water supply treatments. Data are based on records from April to July († assuming an additional consumption of 35 mm during the spring-summer growing season from layers below 90 cm soil depth).

	Control			**Irrigation**			**Shelter**			**total**
	low N	high N	average	low N	high N	average	low N	high N	average	average
Water use efficiency / kg grain m^{-3}										
2000										1.34
site A	1.55	1.78	1.67	1.23	1.34	1.29	1.63	1.97	1.80	1.59
site A †	(1.44)	(1.66)	(1.55)	(1.16)	(1.27)	(1.22)	(1.49)	(1.8)	(1.65)	(1.47)
site B	1.20	1.26	1.23	1.14	1.27	1.21	0.84	0.83	0.83	1.09
2001										2.54
site A	2.82	2.96	2.89	2.02	2.11	2.07	3.40	3.67	3.54	2.83
site A †	(2.59)	(2.70)	(2.65)	(1.90)	(1.98)	(1.94)	(3.06)	(3.30)	(3.18)	(2.59)
site B	2.42	2.45	2.43	1.89	2.11	2.00	2.14	2.53	2.33	2.26
Soil water use / mm										
2000										75
site A	–	–	82	–	–	76	–	–	91	83
site B	–	–	65	–	–	63	–	–	72	67
2001										74
site A	101	96	99	89	89	89	98	96	97	95
site B	54	54	54	47	49	48	58	60	59	54
Soil water use efficiency / kg grain m^{-3}										
2000										8.44
site A	8.68	9.98	9.33	9.76	10.63	10.20	6.70	8.09	7.40	8.97
site A †	(7.42)	(8.53)	(7.97)	(8.80)	(9.58)	(9.19)	(5.32)	(6.42)	(5.87)	(7.68)
site B	8.12	8.55	8.34	10.68	11.89	11.29	4.11	4.07	4.09	7.90
2001										13.25
site A	10.49	11.43	10.96	11.97	12.42	12.20	10.70	11.70	11.20	11.45
site A †	(7.80)	(8.37)	(8.09)	(8.58)	(8.92)	(8.75)	(7.88)	(8.57)	(8.23)	(8.35)
site B	16.77	18.86	17.82	17.01	16.46	16.74	9.85	11.37	10.61	15.05

4 Discussion

The results show that the response of winter wheat to water shortage or abundance and N fertilization is site-specific, *i.e.*, dependent on plant available soil water capacity. At the sites of low plant available soil water capacity, reduced water supply between stem elongation and heading, induced by rain-sheltering, resulted in considerable grain yield reduction compared to the control treatment, while irrigation during the same growth period strongly increased yield, especially on the high N treatment. At the sites of high plant available soil water capacity, the effect produced by reduced water supply on grain yield showed moderate yield reduction to small yield increase. *Lawes* et al. (2009) showed that at sites with high available soil water capacity the effect on wheat yield was dependent on the amount and temporal distribution of rainfall within the season. During the two trial years, climatic factors and particularly the distribution of precipitation appeared to be superimposed on the yield variability resulting from soil variability. The important yield increase on all treatments in 2001 compared to 2000 can readily be explained by the unfavourable distribution of precipitation in 2000, despite a higher total amount of rainfall from April to July in 2000 than in 2001. Irrigation was beneficial on the lighter textured soils, although it occurred during a less critical water demand period. Adequately high soil moisture in early growth stages stimulates vegetative growth (*Bruns* and *Croy*, 1983), which is important

Table 7: Water use efficiency (grain yield in kg divided by the sum in m^3 of rainwater, precipitation water and soil water use), soil water use (difference in soil water content before and after trial), and soil water use efficiency (grain yield in kg divided by soil water use in m^3) as affected by site (A and B characterised by higher and lower PASW, respectively), fertiliser treatments, and water supply treatments. Data are based on records from April to July († assuming an additional consumption of 35 mm during the spring-summer growing season from layers below 90 cm soil depth).

	Control			**Irrigation**			**Shelter**			**total**
	low N	high N	average	low N	high N	average	low N	high N	average	average
Water use efficiency / kg grain m^{-3}										
2000										1.34
site A	1.55	1.78	1.67	1.23	1.34	1.29	1.63	1.97	1.80	1.59
site A †	(1.44)	(1.66)	(1.55)	(1.16)	(1.27)	(1.22)	(1.49)	(1.8)	(1.65)	(1.47)
site B	1.20	1.26	1.23	1.14	1.27	1.21	0.84	0.83	0.83	1.09
2001										2.54
site A	2.82	2.96	2.89	2.02	2.11	2.07	3.40	3.67	3.54	2.83
site A †	(2.59)	(2.70)	(2.65)	(1.90)	(1.98)	(1.94)	(3.06)	(3.30)	(3.18)	(2.59)
site B	2.42	2.45	2.43	1.89	2.11	2.00	2.14	2.53	2.33	2.26
Soil water use / mm										
2000										75
site A	–	–	82	–	–	76	–	–	91	83
site B	–	–	65	–	–	63	–	–	72	67
2001										74
site A	101	96	99	89	89	89	98	96	97	95
site B	54	54	54	47	49	48	58	60	59	54
Soil water use efficiency / kg grain m^{-3}										
2000										8.44
site A	8.68	9.98	9.33	9.76	10.63	10.20	6.70	8.09	7.40	8.97
site A †	(7.42)	(8.53)	(7.97)	(8.80)	(9.58)	(9.19)	(5.32)	(6.42)	(5.87)	(7.68)
site B	8.12	8.55	8.34	10.68	11.89	11.29	4.11	4.07	4.09	7.90
2001										13.25
site A	10.49	11.43	10.96	11.97	12.42	12.20	10.70	11.70	11.20	11.45
site A †	(7.80)	(8.37)	(8.09)	(8.58)	(8.92)	(8.75)	(7.88)	(8.57)	(8.23)	(8.35)
site B	16.77	18.86	17.82	17.01	16.46	16.74	9.85	11.37	10.61	15.05

to achieve a high yield potential. A similar effect was reported by *Eck* (1988).

The response to the application of additional 60 kg N ha^{-1} on grain yield appeared also to be dependent on site and water supply, however, for different reasons for each site. At the site of higher plant available soil water capacity in 2001, a high yield was already obtained with 120 kg N ha^{-1} and tended to level off at 180 kg N ha^{-1}. At this site, in both years a higher, but non-significant yield increase was obtained by the increased N-rate when the water supply was reduced during stem elongation and heading (rain-shelter treatment), which may be caused by improved rooting and plant establishment due to better soil aeration.

At the site of low plant available soil water, the response of grain yield to the increased application of 60 kg N ha^{-1} underscores the importance of sufficient external water supply for the efficient N-use at these sites. Yield increases comparable to the sites of high plant available soil water were obtained in the irrigated treatment. Higher N-application rates did not increase the grain yield of the control treatment and increased slightly, but non-significantly, the yield in the rain-shelter treatment in 2001.

Even though the higher N-application rate resulted most frequently in substantially higher aboveground N-uptake values, the differences were statistically not significant. The aboveground N-uptake did not differ among the three treatments on the sites characterised by the higher available water capacity.

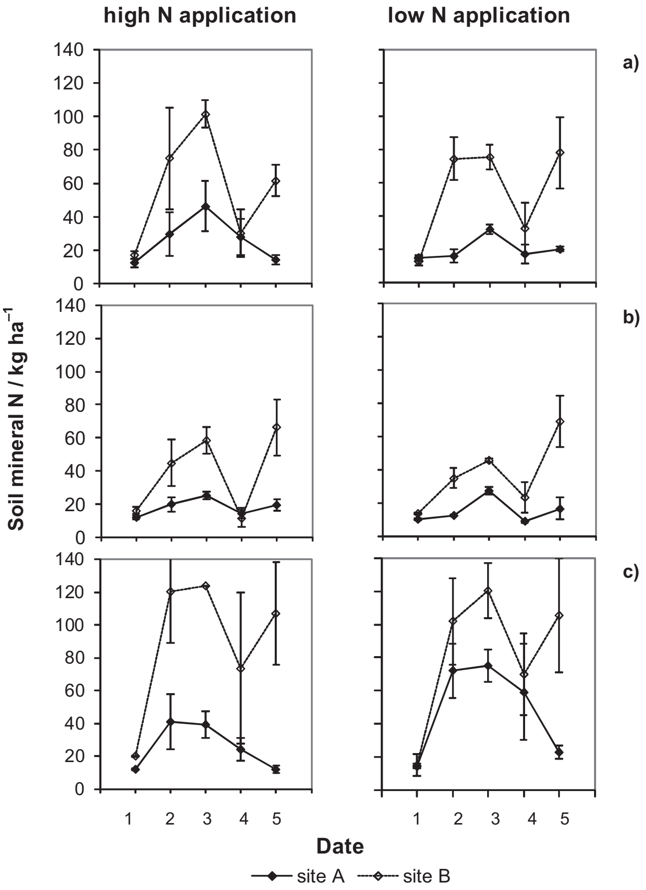

Figure 6: Soil mineral N content (kg ha^{-1}) from soil depths of 0 to 30 cm, at site A (higher PASW) and B (lower PASW). Measurements from 5 sampling dates (2 April, 18 May, 12 June, 26 June, and 25 July) during the 2001 growing season in: a) control, rain-fed; b) irrigation; and c) rain-sheltering treatments. N fertilizer was applied on 4 April, 26 April, 5 May, and 24 May as high-N (180 kg N ha^{-1}) and low-N (120 kg N ha^{-1}) applications.

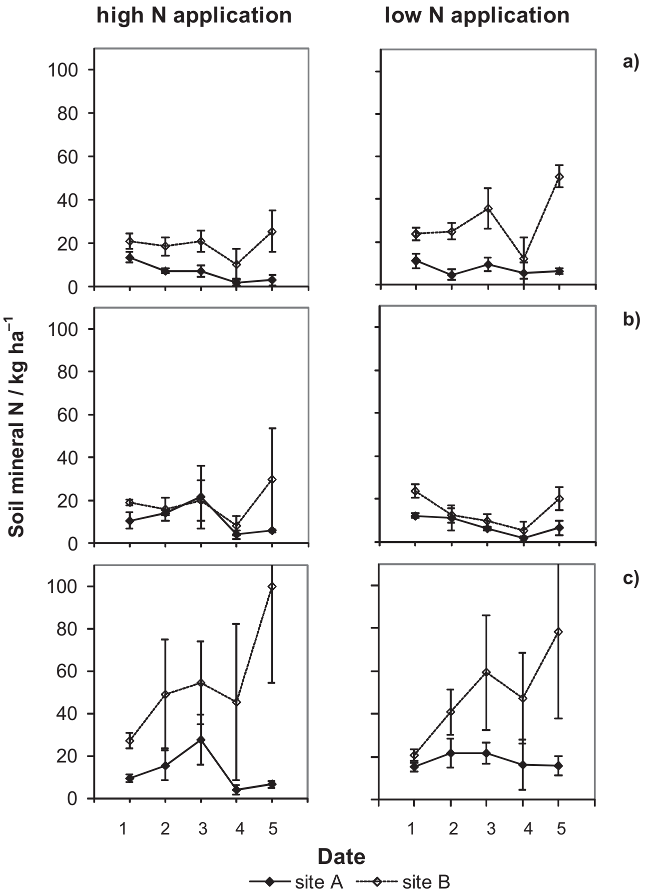

Figure 7: Soil mineral N content (kg ha^{-1}) from soil depths of 31 to 60 cm at site A (higher PASW) and B (lower PASW). Measurements from 5 sampling dates (2 April, 18 May, 12 June, 26 June, and 25 July) during the 2001 growing season in: a) control, rain-fed; b) irrigation; and c) rain-sheltering treatments. N fertilizer was applied on 4 April, 26 April, 5 May, and 24 May as high-N (180 kg N ha^{-1}) and low-N (120 kg N ha^{-1}) applications.

In contrast, on the site characterised by the lower available water capacity a markedly decreased aboveground N-uptake was found in 2000 on the rain-shelter treatment compared to the control, and particularly, compared to the irrigated treatment. Although the rain-shelter treatment in 2001 showed decreased aboveground N-uptake values compared to the irrigated treatment, on the site with reduced available water the difference was not significant.

In general, soil mineral N-contents following N-fertilizer application were higher on the sites with lower soil available water capacity compared to the site with a higher soil available water capacity. Interestingly, this seemed not to be influenced by the fertilizer application level. Markedly higher soil mineral N-contents were observed, also towards the end of the vegetation period, on the rain-shelter treatment at the site with the lower availability of soil water. In contrast soil mineral N-contents were clearly decreased on the control and even more on the irrigation treatment at site B.

Whereas the higher N-rate generally increased the grain N content in 2000 on both sites, such increases were only observed on the irrigated treatment on both sites in 2001. But, in both trial years, a relatively low grain N-content was observed on the irrigated plots at sites with low plant-available soil water. This suggests that a higher N fertilizer rate may be planned for these sites with ample water supply. However, when the water supply is reduced, decreased N application should be considered to avoid high residual nitrate after harvest which is prone to leaching losses. The rain-shelter treatment in this study resulted in considerably higher soil mineral N-content values compared to the other treatments which are at risk of leaching. Long-term investigations on heterogeneous field sites in this region (*Ebertseder* et al., 2003, 2005) advocated decreased N-supplies to sites characterized by lower plant available water capacity.

According to *Lawes* et al. (2009), regardless of season, soils with low plant available water capacity only have a limited capacity to cope with yield-limiting moisture stress. Therefore, these soils should be fertilised more conservatively than soils with much higher plant available water capacity.

Lord et al. (1997) inferred from their findings that increased yields were related to increased soil water use. The present work has shown that this is only true if we compare different sites. On the other hand, within each site, in particular at the sites of low plant available soil water capacity, the above conclusion cannot always be supported. The present study shows that evapotranspiration based on a total water use balance (precipitation + irrigation – water, withheld by rain-sheltering + change in soil water content) may not be a good indicator of production if no further details are given for the site and timing of water supply. For example, in 2000 the total water use from April to July ranged from around 360 mm on the rain-shelter treatment to 600 mm on the irrigation treatment, while the total water use for the same period in 2001 ranged from around 290 mm (rain-shelter) to around 500 mm (irrigation treatment). However, grain yield in 2001 was clearly higher on all treatments than in 2000. Also, whereas within each year a higher total water use at the sites of low plant available soil water capacity was related to an increased yield, this was not true for the sites of high plant available soil water capacity, where in quite a few cases yield decreased with increasing water supply. The observation of increased water use efficiency when yield increase also occurred, due to higher N application, is consistent with findings by *Eck* (1988). Similarly to *Lawes* et al. (2009), it can be highlighted that yield variability within the field was due to interactions of seasonal rainfall, plant available soil water capacities, and N fertiliser applications.

In both years, a greater water depletion down to a soil depth of 90 cm occurred at the site characterised by the higher available soil water capacity. The rise of plant available soil water depletion until July suggests that layers below 90 cm soil depth may also have contributed to water consumption by the plants. However, at the site with lower available soil water capacity only a small contribution to the water consumption by the crop, from these layers, may be assumed. It is possible that the coarse soil structure may have restricted the density and depth of rooting into the subsoil, thereby effectively reducing the water available to the crop.

A larger aboveground biomass stimulated by increased N availability results in greater transpiration demands (*Ritchie* and *Johnson*, 1990). If sufficient water supply or reserves are not available, greater water stress occurs during later critical crop development stages reducing the yield. Under extreme circumstances (*i.e.*, rain-shelter treatment in 2000), it may be desirable to limit the rate of exhaustion of water by limiting the vegetative growth, thereby saving a greater proportion of the available water for the reproductive stage. In this regard, one could theoretically increase the efficiency of water use and N fertilization in production of grain by withholding some of the N during the first part of the season and applying it later. This practise should reduce the vegetative growth, thereby saving more of the available water for grain production. This possibility may encounter the difficulty of making a delayed application of N fertilizer to the soil so as to be effective under dry conditions. *Black* (1966) suggested for such cases to spray N on plant in form of urea as a means of application which might prove satisfactory for the small quantities of N that would be effective.

It is arguable whether in the normal range of weather conditions plant water stress as severe as in this study or water supply as abundant occurs. Rainfall records in the area show that during May an amount of average monthly rainfall as important as on the irrigation treatment is less likely. In contrast an amount of average monthly rainfall as little as induced by rain-sheltering, although not reflecting the average precipitation in this region, has been documented in several locations in this region in recent years. It is to be expected that the likelihood for the latter scenario will occur with much higher frequencies as a consequence of predicted climate changes (*Maze*, 2012).

Various N and water supply has been examined in the present study, although other approaches to adjust management practices to heterogeneous sites characterized by varying plant available soil water capacities might also be considered. Among these approaches, adjusting the planting density or switching to wheat varieties being more drought tolerant on areas with lower water storage capacity can be used.

Due to the complexity of soil-plant relations, modified by climatic and topographic factors, precision management systems can be envisioned. These systems use simple input and output relations, such as models that emphasise yield maps and weather records corrected by on-the-go information. Crop simulation models that take into account weather variability can help make sense of such data by relating historic yield maps to historic weather records. The latter are split into temporal units creating patterns from seeding to harvest. This information can be retrieved at any time and be compared with actual weather data. Long-time statistical forecasts should then be integrated. The resulting data are finally corrected by on-the-go sensors. Such a decision tool will become iteratively more powerful with time. As *Runge* and *Hons* (1999) concluded from other works: much of the past historical yield variation would reoccur if we experienced similar weather patterns even if present-day crop varieties are used.

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