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

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LIST OF ABBREVIATIONS AND SYMBOLS

BBCH	Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und Chemische Industrie
CV	coefficient of variance
DM	dry matter
DWD	Deutscher Wetterdienst
ε	dielectric constant
F	variance ratio
GIS	geographic information system
gK	grain potassium concentration
gN	grain nitrogen concentration
gP	grain phosphorus concentration
HI	harvest index
HPLC	high performance liquid chromatography
ICP	inductively coupled argon plasma emission spectrometry
K	potassium
LSD	least significant difference
miss.	missing value
MMD	maximum monthly depletion
N	nitrogen
N_{min}	soil mineral nitrogen
NT	nitrogen treatment
P	phosphorus
PASW	plant available soil water
PVC	polyvinylchloride

R	coefficient of correlation
R^2	coefficient of determination
ρ_b	bulk density
RMSE	root mean square error
SF	scaled frequency
site A	site of high plant available soil water
site B	site of low plant available soil water
θ_v	volumetric soil water content
θ_{vFC}	volumetric soil water content at field capacity
θ_{vWP}	volumetric soil water content at wilting point
var	variable
WT	water treatment
WUE	water use efficiency

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1 GENERAL INTRODUCTION

The development of appropriate strategies for defining management units for specific operations is a significant challenge for precision farming. Information technologies offer an unparalleled ability to characterize the nature and extent of variation occurring in agricultural fields and to develop optimized management strategies for these conditions. At the field and subfield scale, information about the spatial heterogeneity of site characteristics makes it possible to manage the variation rather than attempting to overcome the variation with sufficiently high uniform rates of agricultural inputs.

Soils vary significantly as a result of regional geological origins and past and present cultural practices. At the highest level of resolution, soil physical, chemical and biological properties vary vertically, horizontally, with treatment, and with time. Some soil properties tend to vary more than others. Bulk density, for example is considered to be of low variation (coefficient of variation < 0.15), whereas soil hydraulic properties such as water retained at under various tensions, hydraulic conductivity (saturated and unsaturated) and water content are regarded as soil properties with high variation (CV > 0.5) (Warrick, 1998). The exact CV value will depend on the general variability of the field encountered and the size of the field for which the measurement is expressed.

Within-field variation in soil type may affect yield through variation in moisture supply to the crop (Gales, 1983). Water stress affects cereal growth in many aspects: It affects leaf extension rates (Gallagher et al., 1979); it increases stomatal and mesophyll resistances that lower the rate of photosynthesis (Lawlor, 1976); low water potentials during the late stages of floral initiation can decrease the number of grains per ear and ears per unit area (Day et al., 1978; Bingham, 1966); low water potentials can accelerate leaf senescence (Lawlor, 1976); and drought can restrict absorption of nutrients (Gales and Wilson, 1981; Day et al., 1978).

Whatever aspect of plant growth is considered the question arises of whether, in the normal range of soil and weather conditions, plant water stress resulting from soil water shortage is severe enough to decrease the yield significantly. The question can be answered, in part, from the results of irrigation experiments, and from theoretical consideration of crop water balance.

However, the performance of precision agriculture depends on the interaction between site conditions and stochastic factors. Stochastic factors such as weather often have a greater impact on yield variability than variations in soil productivity (Nielsen and Halvorson, 1991; Eck, 1988; Kirkham and Kanemasu, 1983; Dirks and Bolton, 1981; Singh, 1981; Schneider et al., 1969; Jensen and Sletten, 1965). On the other hand weather remains among the most important uncontrollable elements involved in crop growth, but the isolation of the impact of weather is made difficult by the confounding effects of soil.

The present study was conducted in the tertiary foothills of the Bavarian Alps where fields with heterogeneous soil texture are frequently found. Soil texture, however, is closely related to soil water content and plant available soil water, in turn, is closely linked to soil texture (Brady and Weil, 1999). The average (1961 – 1990) rainfall in the area of the present study during the spring-summer growing period of winter wheat (April – August) is 443 mm which usually covers the transpirational demand of grass during this period (409 mm), but the amount and the distribution of rainfall is highly variable between individual years (DWD, 1997).

Research on precision farming in Germany focuses on the variable application of N since P and K deficient soils are rare (Bach and Frede, 1998). The nitrogen economy of the soils is, however, strongly related to the availability of soil water (Brady and Weil, 1999; Gales and Wilson, 1981; Day et al., 1978).

There is little information on which to base fertilizer recommendations for wheat grown under variable soil and weather conditions. Thus, the principal objective of this study was to determine the interacting effects of water supply and N fertilization on winter wheat yield and yield components on soils of different soil texture within one field.

Considering the paramount role of soil water and water supply for plant growth, a further objective of the present study was to evaluate the usefulness of some existing methods for soil water monitoring. Only few commercially available sensors can assess soil water content in the field and practitioners are limited to sampling and laboratory analysis for determination of in-field variability of the soil water content, which is costly and time-consuming.

2 FIELD CALIBRATION OF A CAPACITANCE SOIL WATER PROBE IN HETEROGENEOUS FIELDS

2.1 Introduction

The amount and status of water in soils impacts crop growth and the fate of agricultural chemicals applied to the soil. The development of better management practices for efficient crop production requires greater understanding of the interdependent factors affecting the dynamics of water in soil. This requires reliable techniques to perform accurate soil water measurements with minimal soil disturbance. Soil water content may be measured indirectly by determining the dielectric properties of soil. This paper presents the results of field calibration of a high-frequency (in excess of 100 MHz) capacitance system, where the dielectric properties of a medium describe the response of that medium to an alternating electric field. Gaudu et al. (1993) reviewed reported relations between the dielectric constant ε and the volumetric soil water content (θ_v) obtained using capacitance methods in soils. Most were derived empirically and Gaudu et al. (1993) summarized these as strictly linear, linear over a limited range of θ_v and non-linear over a wide range of θ_v. Empirical calibrations are a practical means of representing the bulk dielectric properties of soil, which arise from complex and poorly characterized interactions between the dielectric properties of the soil components, that is, solid particles of different composition, shape and size; air, and free and bound water. Bell et al. (1987) conducted field calibrations using the depth probe in four different soils. They found that the relation between the capacitance probe readout and the water content is not linear and influenced by the type of soil. A linear approximation, however, is adequate for the restricted ranges of water content experienced in practice in many soils. Evett and Steiner (1995) using a capacitance system of similar design to that of Bell et al. (1987) also opted for linear calibrations. Tomer and Anderson (1995) using the same type of equipment, found that a second-order polynomial gave the best calibration in fine sand soils.

For a capacitance system (EnviroScan, Sentek Pty, Ltd., Kent Town, South Australia) from the same manufacturer and comparable to the one presented in this paper, but permanently installed, a nonlinear relation (θ_v (m^3 m^{-3}) = 0.490 $SF^{2.1674}$) between the soil volumetric water content and the scaled frequency (SF) was found (Paltineanu and Starr, 1997). The SF

represents the ratio of individual sensor's frequency response in soil (F_s) compared with sensor responses in air (F_a) and in nonsaline water (F_w) at room temperature (≈ 22° C):

$$SF = (F_a - F_s) / (F_a - F_w). \qquad \text{[Eq 1]}$$

Morgan et al. (1999) found that the manufacturer's calibration for this system underestimates many fine sand soils of Florida and provided a different calibration for this soil type ($\theta_v = 0.4514 \text{ x } SF^{2.1211}$). The manufacturer's calibration of the portable capacitance system as presented in this paper is:

$$SF = 0.3314 \text{ x } \theta_v^{0.2746} \quad \text{or} \quad \theta_v \text{ (cm}^3 \text{ cm}^{-3}) = 0.5581 \text{ x } SF^{3.6417} \qquad \text{[Eq 2]}$$

Our preliminary studies indicated that the moisture changes were measured reliably while the absolute θ_v values were unrealistic and did not agree with data from gravimetric soil sampling.

Thus, calibration for individual soils is necessary to obtain measurements of absolute water content using the capacitance system. Laboratory calibrations offer the advantage of a controlled bulk density but soil samples do not take the soil structure into account and are time consuming. The customized field calibration as proposed by the manufacturer is also tedious. Thus, the objective of this study is to investigate the suitability of a rapid and cheap soil sampling method for the calibration of capacitance probes.

2.2 Materials and methods

This research is part of a broader study of the response of winter wheat growth and yield to different N fertilizer levels and water regimes on sites of different plant available soil water (PASW).

To identify two sites of different PASW, a heterogeneous 5-ha field in South Germany was intensively texture-mapped by auger sampling down to 90 cm soil depth. Site A, a silt-loamy Cambisol on colluvial material, had a PASW of approximately 170 mm until 90 cm soil depth. Site B, a loam-sandy Cambisol had a PASW of approximately 100 mm until 90 cm soil depth. A water retention function was determined by placing soil core samples obtained from one soil profile made at each site on a ceramic plate in a pressure chamber and by consecutively applying gas pressures of 60 hPa, 300 hPa, 1000 hPa, 5000 hPa, and 15000 hPa and reweighing the samples after each pressure step. The equilibrium water content at 60 hPa for the coarse-textured soils and 300 hPa for the loamy soils was considered as field capacity (θ_{vFC}), and at 15000 hPa as wilting point (θ_{vWP}) (Cassel and Nielsen, 1986). Four horizons were sampled on average. Plant available soil water (PASW) was calculated as the difference of soil water content at field capacity and wilting point. PASW of the rooting zone was computed by adding the PASW of the different soil horizons.

At each site, two N fertilizer levels (120 kg N /ha and 180 kg N / ha) and three water supply treatments (irrigation, rain-sheltering and control) were assigned to plots in a completely randomized design. The same design was applied at each site. Thus, the total number of plots, with three replications, was 36.

All experiments reported here used the Diviner hand-held capacitance probe (Sentek Pty, Ltd., Kent Town, South Australia). Each unit comprises a data display connected by cable to a portable probe rod with one sensor attached. Because each sensor responds slightly differently to air and water, the sensors are normalized [Eq 1]. The sensor is normalized by placing the probe into a sealed tube and subsequently holding the probe in the air and in a 10-litre water bucket and by entering the respective raw counts.

The portable probe measures soil moisture content at regular intervals of 10 cm down through the soil profile. Readings are taken through the wall of a PVC access tube. The data stored in the display can be retrieved into a personal computer by a software application supplied by the manufacturer. The retrieved data can be displayed as charts using the manufacturer's software. The data can also be restored into a spreadsheet as scaled frequency or as volumetric water content after automatic transformation using the default or a customized calibration equation. The default equation supplied by the manufacturer is based on combined data gathered from a variety of different soils.

The Diviner access tubes were installed in each of the 36 plots. The installation of the access tubes took place while the soil surface was still frozen in the early morning hours of March to minimize soil compression by the tractor. The PVC pipes with an attached inward-tapered metal cutting edge were driven into the soil using a tractor mounted hydraulic hammering head. The soil was removed from within the tube by a screw auger supplied by the manufacturer. After installation, tubes were cleaned inside with a nylon brush and the subsurface end of the tube sealed with an expandable bung. The careful installation of the access tubes provided a snug fit to the soil.

Soil water content was measured weekly from end of March to the end of July 2000. On May 18, June 12, June 26 and July 5, the soil was parallely core-sampled with the Diviner measurements. Samples were taken with a 4-cm inner diameter auger in two depths per hole, from 0 to 30 cm and from 30 to 60 cm. Two samples were taken per depth at opposite sites, 50 cm from the access tube. The first 15 cm and the last 5 cm of each auger sample were disposed of, thus obtaining soil samples from 15 to 25 and 45 to 55 cm soil depth, since the center of measurement has a 5 cm axially symmetric zone of accurate influence ((Paltineanu and Starr, 1997). The two samples per depth and plot were then bulked, put into a plastic bag and immediately placed into an ice box.

Soil samples were weighed, dried in an oven at 105° C for 24 hours and reweighed. Bulk density was derived from data obtained from three soil profiles inside the trial field and two soil profiles in a neighboring field. The bulk density at site A was approximately 1.51 g cm^{-3} at 20 cm soil depth and 1.55 g cm^{-3} at 50 cm soil depth; at site B 1.64 g cm^{-3} and 1.68 g cm^{-3}, respectively.

The relationship between scaled frequency (*SF*) of the Diviner readings at 20 cm and 50 cm soil depth and the volumetric soil water content of the gravimetrically measured samples (θ_v) of the equivalent soil depth was based on the model used for factory calibration:

$$\theta_v = \mathrm{a}\, SF^{\,\mathrm{b}}$$

The exponential regression was fitted to the model using the SAS NLIN procedure for nonlinear regression (SAS, 1989). Even though SF is actually the dependent variable in this calibration, it was treated as the independent variable because the application of the equation is to derive θ_v from *SF* values from sensor frequencies measured in the field. The exponential function was chosen rather than another mathematical relation because this function was previously used by others (Paltineanu and Starr, 1997) working with these capacitance sensors. Besides, second or third order polynomial functions were also tested but the exponential function performed generally better than other models.

Linear regression equations were developed relating soil moisture content obtained by the thermogravimetric method to instrument readings transformed into θ_v by different calibration equations. The coefficients of these equations were statistically compared to those of a one-to-one (1:1) line (slope = 1, intercept = 0) using tests of hypothesis (SAS, 1989).

Calibration equations were also developed on a reduced number of observations, i.e. the data of one water regime treatment, one single sampling day or after dividing arbitrarily each site into three groups with an equal number of plots (group A1, A2, A3 for site A; B1, B2 and B3 for site B) for each site. A further data reduction was obtained by using only the data of one single sampling day and one group for the development of a calibration equation.

Usually, the customized calibrations based on a reduced number of observations were tested on the entire data set of the field or site. In a second approach, the validity of these calibration equations were also tested by applying these calibrations to all data but the data used for developing the calibration.

2.3 Results and Discussion

Volumetric water content of the 140 samples collected for the calibration at site A ranged from 0.04 cm^3 cm^{-3} to 0.50 cm^3 cm^{-3} and from 0.04 cm^3 cm^{-3} to 0.38 cm^3 cm^{-3} for the 142 samples collected at site B (table 1). Due to the different water regime treatments the moisture range may be regarded as the range normally experienced in these soils.

Table 1 Mean, maximum and minimum value, and standard deviation of soil water content obtained by core sampling at a silt-loamy site (site A) and at a loam-sandy site (site B) of one field using various data sets (treatment = water supply treatment; date = sampling date; group = data subset within site or sampling date).

treatment	date	group	N	mean	max	min	stddev
				-------------------------------	(cm^3 cm^{-3})	-------------------------------	
			site A				
mean site A			140	0.28	0.50	0.04	0.13
control			44	0.28	0.47	0.04	0.14
irrigated			48	0.32	0.50	0.04	0.13
rain-sheltered			48	0.25	0.46	0.05	0.13
		A1	48	0.29	0.48	0.05	0.13
		A2	44	0.27	0.50	0.05	0.14
		A3	48	0.29	0.48	0.04	0.13
	June 12		36	0.35	0.48	0.16	0.09
	May 18		34	0.35	0.50	0.05	0.12
	June 26		36	0.24	0.47	0.05	0.14
	July 05		34	0.19	0.41	0.04	0.12
	May 18	A1	12	0.36	0.47	0.12	0.11
	May 18	A2	10	0.32	0.50	0.05	0.14
	May 18	A3	12	0.34	0.48	0.10	0.12
	July 05	A1	12	0.19	0.35	0.05	0.11
	July 05	A2	10	0.19	0.36	0.05	0.12
	July 05	A3	12	0.21	0.41	0.04	0.12
			site B				
mean site B			142	0.17	0.38	0.04	0.07
control			48	0.16	0.30	0.05	0.07
irrigated			47	0.19	0.38	0.05	0.08
rain-sheltered			47	0.15	0.27	0.04	0.05
		B1	48	0.19	0.31	0.05	0.07
		B2	47	0.19	0.38	0.05	0.08
		B3	47	0.13	0.21	0.04	0.05
	June 12		36	0.20	0.38	0.06	0.07
	May 18		36	0.19	0.31	0.05	0.06
	June 26		34	0.16	0.30	0.05	0.07
	July 05		36	0.13	0.30	0.04	0.06
	May 18	B1	12	0.22	0.30	0.12	0.05
	May 18	B2	12	0.20	0.31	0.09	0.05
	May 18	B3	12	0.15	0.21	0.05	0.05
	July 05	B1	12	0.14	0.28	0.05	0.07
	July 05	B2	12	0.15	0.30	0.05	0.08
	July 05	B3	12	0.09	0.13	0.04	0.03

Table 2 shows the calibration equations as developed from the entire data set or from subsets of this study and the calibrations provided by the manufacturer or proposed by different authors.

At the silt-loamy site A, the soil water contents (θ_v) estimated by the use of the default calibration were generally less than the soil moisture contents based on the thermogravimetric method (figure1). This is not consistent with the findings of Hanson and Peters (2000) who showed that readings of a comparable system (EnviroScan) generally were much greater than neutron moisture meter readings on a silt-loamy site when based on the manufacturer's calibration. For the coarse-textured site (site B), the Diviner readings underestimated soil water content until a scaled frequency of around 0.65 (which corresponds to $\theta_v = 0.13$ cm^3 cm^{-3}). This is in agreement with the findings of Morgan et al. (1999) who demonstrated that on some sandy soils of Florida soil water content is underestimated by the EnviroScan default calibration, especially in the low soil water content range. At a scaled frequency of around 0.8 (0.25 cm^3 cm^{-3}) or greater, however, the soil water content of the coarse-textured site of this study was overestimated by the default equation.

The calibration equation of this study developed from the combined data of both sites (field equation) provided a curve that compromised between the data sets of the two sites (figure 1). As a result, the gravimetric soil water content of site A is constantly underestimated while the θ_v of site B is constantly overestimated. Thus, a soil water content estimated by this field calibration does not provide accurate values either, but its bias is more consistent.

Differences between estimated values from the default or the field equation and the estimations based on site-specific calibrations are substantial. At the dry range of site A and the wet range of site B, these differences exceeded 0.10 cm^3 cm^{-3}.

When the estimated θ_v is linearly regressed on the gravimetrically obtained θ_v (figure 2 and table 3), both field equation and the combination of the site-specific equations resulted in curves that did not significantly differ from the 1:1 line. The combined equation provided however a much smaller scatter and thus a smaller root mean square error (RMSE). The regression curve based on estimates using the default equation deviates significantly from the 1:1 line. This is mainly due to its poor performance at site B. At site A, the slope of the regression curve is not significantly different to one, but it is shifted with an intercept significantly different from 0.

At the field level, the equations provided by Paltineanu and Starr (1997) and by Morgan et al. (1999) for the EnviroScan performed both better than the default equations and performed

Table 2 Calibration equations (θ_v = a *SF* ^{b}) supplied by the manufacturer (default) and by other studies compared to the calibrations of this study developed from various data sets obtained in one field (date = sampling date; group = data subset within site or sampling date).

	field				site A				site B			
	a	b	N	RMSE	a	b	N	RMSE	a	b	N	RMSE
default	0.4940	3.0175										
field	0.4619	2.3419	282	0.06								
site A					0.5183	2.1367	140	0.04				
site B									0.3311	1.9368	142	0.03
Paltineanu & Starr (1997)	0.4900	2.1674										
Morgan et al. (1999)	0.4514	2.1211										
18th May					0.5330	2.0277	34	0.03	0.3267	1.8177	36	0.02
12th June					0.5212	1.9454	36	0.03	0.3577	2.0494	36	0.03
26th June					0.4992	2.1704	36	0.04	0.3224	1.8639	34	0.02
5th July					0.4475	1.9811	34	0.03	0.2972	1.8994	36	0.02
group A1					0.5114	1.9857	48	0.04				
group A2					0.5245	2.2526	44	0.04				
group A3					0.5200	2.1897	48	0.03				
group B1									0.3312	1.7913	48	0.03
group B2									0.3215	1.7405	47	0.03
group B3									0.3254	2.0964	47	0.02
May 18 group A1					0.5238	1.8421	12	0.02				
May 18 group A2					0.5362	2.0600	10	0.04				
May 18 group A3					0.5370	2.1535	12	0.03				
May 18 group B1									0.3219	1.4712	12	0.02
May 18 group B2									0.3187	1.7289	12	0.02
May 18 group B3									0.3301	2.0832	12	0.02
July 5 group A1					0.4192	1.7750	12	0.02				
July 5 group A2					0.4524	2.0454	10	0.03				
July 5 group A3					0.4678	2.1130	12	0.03				
July 5 group B1									0.2975	1.8792	12	0.02
July 5 group B2									0.2926	1.7254	12	0.08
July 5 group B3									0.2491	1.6979	12	0.01
control plots					0.5158	2.2588	44	0.04	0.3232	1.8537	48	0.02
irrigated plots					0.5264	2.0214	48	0.04	0.3476	1.8934	47	0.03
sheltered plots					0.5039	2.0931	48	0.03	0.2907	1.7734	47	0.02

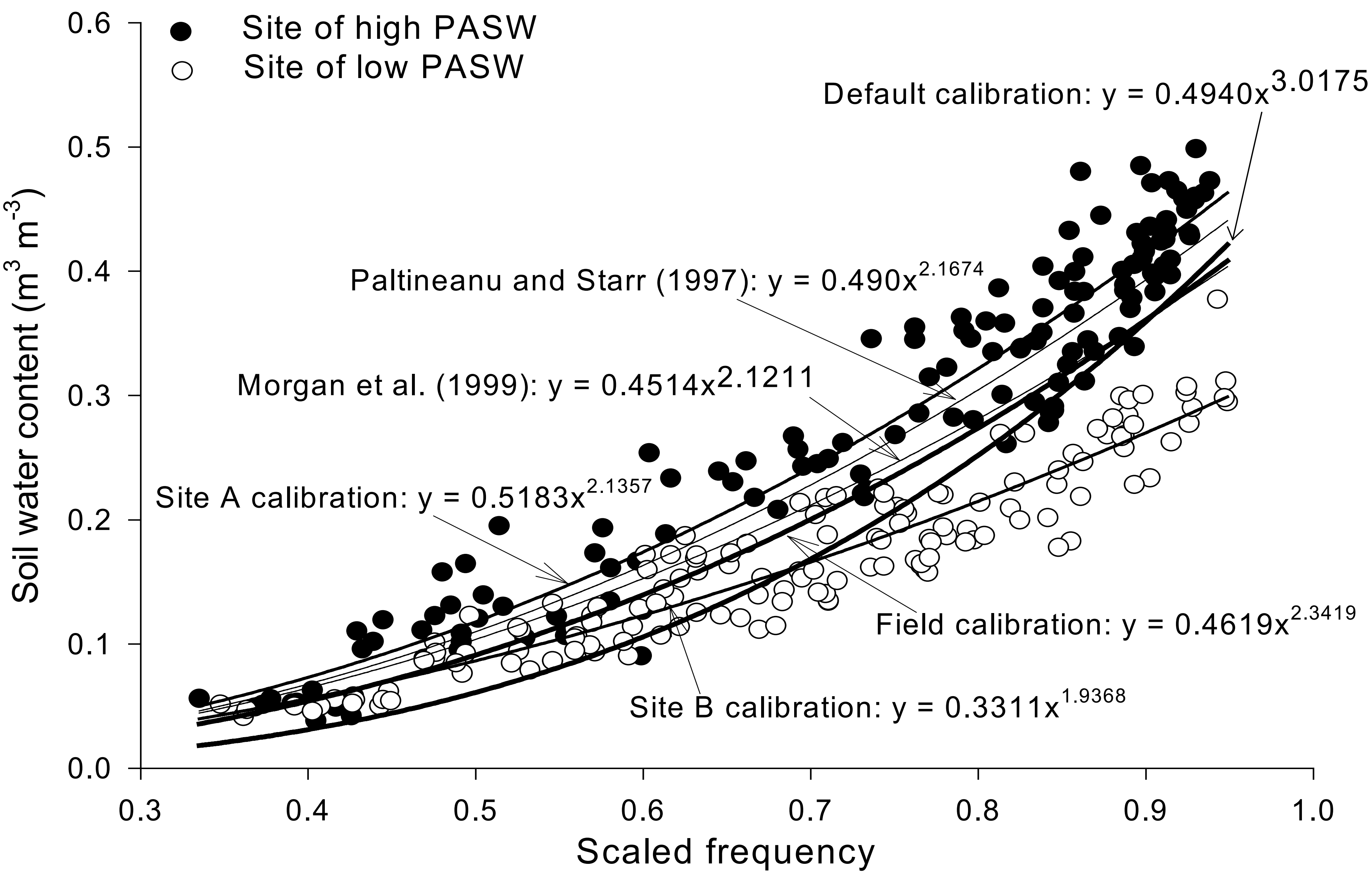

Figure 1 Whole field and site-specific calibrations of Diviner capacitance probe compared to the calibrations supplied by the manufacturer and compared to the customized calibrations proposed by Paltineanu and Starr (1997), and by Morgan et al. (1999). PASW = plant available soil water

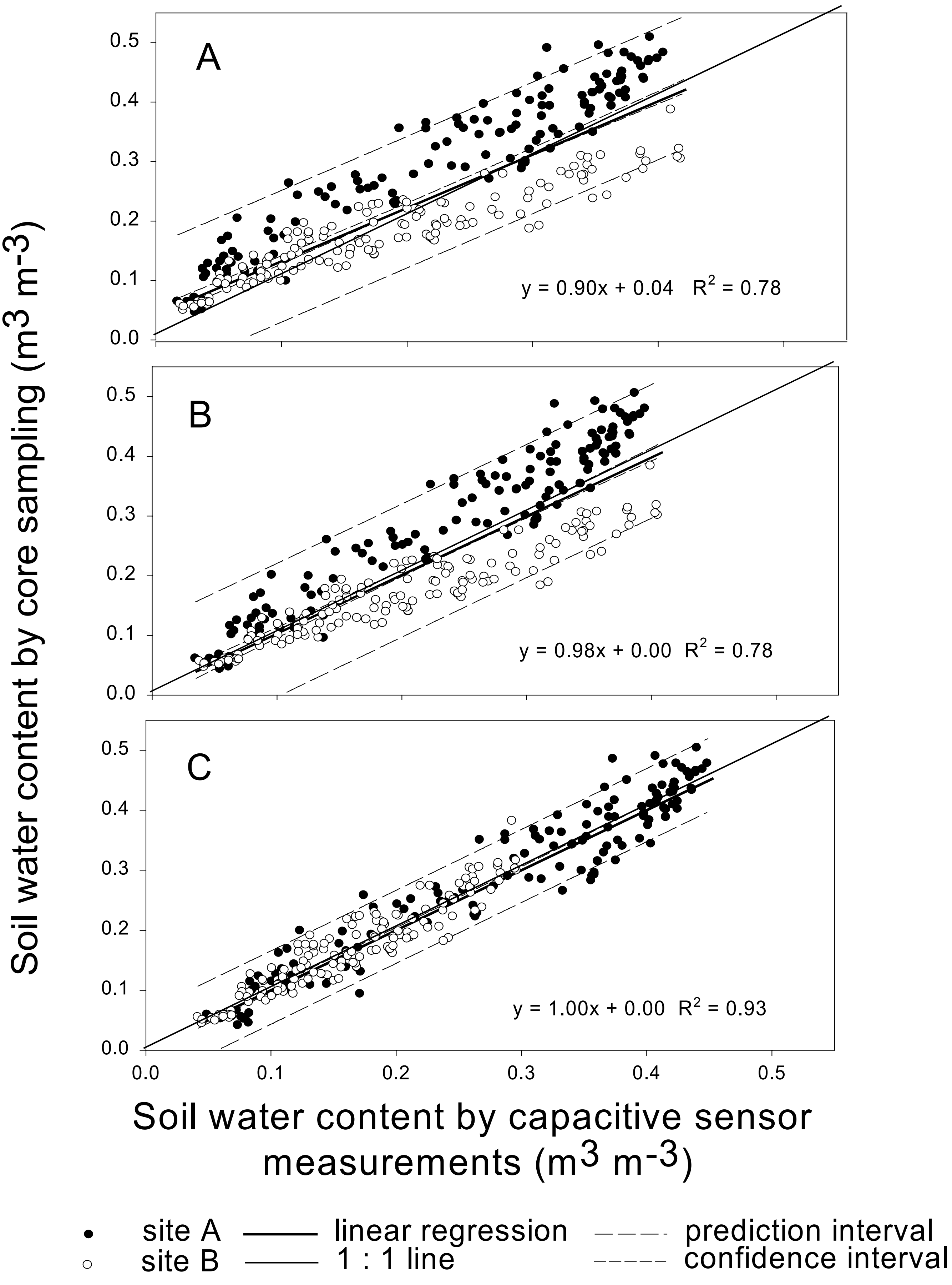

Figure 2 Soil water content estimated by Diviner readings using the default calibration (A), a whole field calibration (B), and site-specific calibrations (C) plotted against soil water content obtained by core sampling.

Table 3 Slope, intercept and root mean square error (RMSE) of the linear regression of soil water content derived from Diviner readings on soil water content obtained by core sampling (date = sampling date; group = data subset within site or sampling date).

	field				site A				site B			
	slope	intercept	N	RMSE	slope	intercept	N	RMSE	slope	intercept	N	RMSE
default	0.90	0.04	282	0.06	1.01**	0.06	140	0.03	0.62	0.05	142	0.03
field	0.98**	0.00*	282	0.06	1.11	0.02	140	0.04	0.68	0.03	142	0.03
site A	0.89	-0.01*	282	0.06	1.00**	0.00*	140	0.04	0.62	0.01*	142	0.03
site B	1.43	-0.03	282	0.06	1.61	-0.02	140	0.04	1.00**	0.00*	142	0.03
site A + B	1.00**	0.00*	282	0.03								
Paltineanu & Starr (1997)	0.94	-0.01*	282	0.06	1.06	0.00*	140	0.04	0.65	0.02	142	0.03
Morgan (1999)	1.03**	-0.01*	282	0.06	1.15	0.00*	140	0.04	0.71	0.01*	142	0.03
May 18					0.99**	-0.01*	140	0.04	1.03**	-0.01*	142	0.03
June 12					1.02**	-0.02	140	0.04	0.91	0.01*	142	0.03
June 26					1.04**	0.00*	140	0.04	1.03**	0.00*	142	0.03
July 5					1.18	-0.02	140	0.04	1.11	0.00*	142	0.03
group A1					1.04**	-0.02	140	0.04				
group A2					0.98**	0.01*	140	0.04				
group A3					0.99**	0.00*	140	0.04				
group B1									1.02**	-0.01*	142	0.03
group B2									1.06**	-0.02*	142	0.03
group B3									0.99**	0.01*	142	0.03
May 18 group A1					1.03**	-0.03	140	0.04				
May 18 group A2					0.98**	-0.01*	140	0.04				
May 18 group A3					0.97**	0.00*	140	0.04				
May 18 group B1									1.13	-0.04	142	0.03
May 18 group B2									1.07	-0.02	142	0.03
May 18 group B3									0.98**	0.01*	142	0.03
July 5 group A1					1.30	-0.04	140	0.04				
July 5 group A2					1.16	-0.01*	140	0.04				
July 5 group A3					1.12	0.00*	140	0.04				
July 5 group B1									1.12	0.00*	142	0.03
July 5 group B2									1.17	-0.02	142	0.03
July 5 group B3									1.38	-0.02	142	0.03
control plots					1.00**	0.00*	140	0.04	1.03**	-0.01*	142	0.03
irrigated plots					1.00**	-0.01*	140	0.04	1.16	-0.01*	142	0.03
sheltered plots					1.04**	-0.01*	140	0.04	0.95**	-0.00*	142	0.03

* <u>not</u> significantly different from 0 at P=0.05 ** <u>not</u> significantly different from 1 at P=0.05

more or less equally well as the field calibration of this study. At site A, the equation from Paltineanu and Starr (1997) appeared to be even more appropriate than the field equation of the present study. All three calibrations were, however, unacceptable for the sandy soil, even the calibration for sandy Florida soils of Morgan et al. (1999).

The site-specific calibrations of this study that were developed on a reduced number of observations, i.e. a subset of around 35 observations, also performed satisfactorily (table 3). It did not matter whether data stemmed from only one water regime treatment, one single day or from a reduced number of plots per site. However, the data of July 5 of both sites, the data of June 12 of site B and the data of the irrigated plots of the site B produced slopes of the linear regression equations between Diviner reading and gravimetrically obtained soil water content that were statistically different from that of the 1:1 line.

A further reduction in the number of observations for the development of the calibration had varying results. The regression of estimated on gravimetrically obtained soil water content of the entire set of data from May 18 of site B, for example, provided a calibration that did not significantly differ from the 1:1 line. Two of the three calibrations developed on one of the subsets of the data of this day and site (May 18 group B1, B2 or B3) each containing 10-12 observations, resulted in regression curves that deviated substantially from the 1:1 line. A possible explanation is the growing influence exerted by outliers as the number of observations decreases.

When the validity of an equation was tested on all data but the data used for developing the equation, the quality of the customized calibrations was, except for group B2, comparable to the performance of the calibrations that included the data used for developing the calibrations (table 4). This is an interesting finding since not all data subsets used for the development of these calibration equations covered the entire range of soil water that can be potentially experienced at either site. This, and the excellent performance of the data from the control plots for the calibration suggest that the usefulness of the presented method is not necessarily limited to conditions as provided by the field trial of the present paper where covering and irrigation created an artificially large range of soil water content data.

All calibration curves show a more or less strong scattering of points. Because the sphere of influence of the capacitance probe is small, small-scale heterogeneity of soil texture and of soil moisture is certainly a cardinal source of error. Thus, while profiles only 0.5 m apart may be quite similar in form, in detail there may be many differences. Bulk density (ρ_b) is an additional source of uncertainty as a factor affecting the dielectric constant ε (Gardner et al., 1998; Perdok et al., 1996), but above all because it governs the relation between mass wetness

Table 4 Slope, intercept and root mean square error (RMSE) of the linear regression of soil water content (θ_v) derived from Diviner readings on soil water content (θ_v) obtained from core sampling excluding the data used for developing the calibrations (date = sampling date; group = data subset within site or sampling date).

	site A				site B			
	slope	intercept	N	RMSE	slope	intercept	N	RMSE
18th May	0.96**	-0.01*	106	0.04	1.03**	-0.01*	106	0.03
12th June	1.01**	-0.02	104	0.04	0.88**	0.01	106	0.02
26th June	1.05**	0.00*	106	0.04	1.05**	-0.01*	108	0.03
5th July	1.20	-0.02	106	0.03	1.12	0.01	106	0.03
group A1	1.04**	-0.02	100	0.04				
group A2	0.97**	0.01*	104	0.03				
group A3	0.99**	0.01*	100	0.04				
group B1					1.00**	-0.01*	102	0.02
group B2					1.08	-0.02	103	0.02
group B3					0.96**	0.0233	103	0.03
18th May group A1	1.03**	-0.03	130	0.04				
18th May group A2	0.97**	0.00*	132	0.04				
18th May group A3	0.96**	0.00*	130	0.04				
18th May group B1					1.11	-0.05	132	0.03
18th May group B2					1.07	-0.02	132	0.02
18th May group B3					0.98**	0.01	132	0.03
5th July group A1	1.32	-0.04	130	0.04				
5th July group A2	1.16	-0.01	132	0.04				
5th July group A3	1.12	0.00	130	0.04				
5th July group B1					1.12	0.00*	132	0.03
5th July group B2					1.18	-0.02	132	0.03
5th July group B3					1.37	-0.02	132	0.03
control plots	1.00**	0.01*	96	0.04	1.05**	-0.01*	94	0.03
irrigated plots	0.99**	-0.01*	92	0.04	1.09	-0.01*	95	0.02
sheltered plots	1.05**	-0.01*	92	0.04	0.97**	-0.00*	95	0.02

* not significantly different from 0 at P=0.05 ** not significantly different from 1 at P=0.05

(θ_m) and θ_v. In this study, ρ_b had been derived from a limited number of soil profiles inside the trial field and in neighboring fields, and it was assumed to be the same for a given plot and at a given soil depth if the soil texture was similar to the soil texture of the soil profile at this depth. This assumption is, however, not necessarily true for all sampling points, especially in heterogeneous fields. At the coarse-textured site at 60 cm soil depth, for example, the standard deviation of ρ_b was estimated to be 0.17 g cm^{-3}. At θ_v= 0.3 cm^3 cm^{-3}, for example, this standard deviation corresponds to ± 0.05 cm^3 cm^{-3} of volumetric water content or a potential range of 0.10 cm^3 cm^{-3}.

Since we had some difficulty installing PVC tubes in the sandy site, one might conjecture that the scaled frequency values from the sandy site were more variable due to possible soil disturbance and air gaps between the tube and soil that would introduce large errors. However, the RMSE was generally smaller at site B than at site A. This might be explained by a smaller sensitivity of the capacitance probe to changes in θ_v in dry soils and thus generally flatter calibration curves for coarse-textured soils.

2.4 Conclusion

The usefulness of the Diviner capacitance sensors is affected by an unsuitable calibration. In this study, the use of the calibration supplied by the manufacturer and the calibration proposed by Paltineanu and Starr (1997) gave satisfactory results for a fine-textured site in a heterogeneous field. At the coarse-textured site, these two calibrations, but also the calibration suggested by Morgan et al. (1999) for sandy Florida soils gave unacceptable results. The calibration developed for this study on the pooled data of both sites strongly underestimated the soil water content of the fine-textured site, and strongly overestimated the soil water content of the coarse-textured soil, although on the field level, it performed better than the manufacturer's calibration and the calibration proposed by Paltineanu and Starr (1997). Thus for field observations and measurements that require more accurate readings, a site-specific calibration is needed.

This study shows a speedy and cheap method to calibrate Diviner capacitance sensors. In spite of concerns about different zones of influence and the impact of small-scale changes in soil water content especially on heterogeneous soils, the results demonstrate that this calibration method provides reasonable calibration equations. The method requires knowledge of the bulk density, and, in this study, at least 35 observations per site were needed to develop an accurate calibration.

3 VARIABILITY OF SOIL WATER MATRIC SUCTION IN HETEROGENEOUS FIELDS AND ITS EFFECT ON WINTER WHEAT YIELD

3.1 Introduction

For many studies soil water content information is of primary interest. However, for studies involving water transport and storage in soils and soil-water-plant relationships, the energy status of the soil solution phase (soil water) is required. The tenacity with which water is held in soils is an expression of soil water matric suction. Field tensiometers measure this attraction or tension. The tensiometer is basically a water-filled tube closed at the bottom with a porous ceramic cup and at the top with an airtight seal. Once placed in the soil, water in the tensiometer moves through the porous cup into the adjacent soil unit until the water potential in the tensiometer is the same as the matric water potential in the soil. As the water is drawn out, a vacuum develops under the top seal, which can be measured by a vacuum gauge, a manometer or an electronic transducer.

Suction measurements by tensiometry are generally limited to matric suction values of below 1000 hPa. This is due to the fact that the vacuum gauge (or manometer or transducer) measures a partial vacuum relative to the external atmospheric pressure, as well as to the general failure of water columns in macroscopic systems to withstand tensions exceeding 1000 hPa. Furthermore, as the ceramic material is generally made of the most permeable and porous material possible, too high a suction may cause air entry into the cup, which would equalize the internal pressure to the atmospheric. Under such conditions, soil suction will continue to increase even though the tensiometer fails to show it.

Thus, in practice, the useful limit of most tensiometers is at about 800 hPa of maximal suction. Though the suction range of 0 – 800 hPa is but a small part of the total range of suction variation encountered in the field, it generally encompasses the greater part of the soil wetness range. In many agricultural soils the tensiometer range accounts for more than 50 % (and in coarse-textured soils 75 % or more) of the amount taken up by the plants (Hillel, 1982).

Tensiometers have long been used in guiding the scheduling of irrigation field and orchard crops, as well as potted plants. A general practice is to place tensiometers at one or more soil depths representing the root zone, and to irrigate when the tensiometers indicate some prescribed value.

Plants show different resistance to water shortage. For example, to maximize crop yield Hanson et al. (2000) recommend an allowable depletion of 400 – 500 hPa for small grain crop, for corn 500 – 600 hPa or for lettuce 300 hPa.

Preliminary studies to the present study showed that the relation between matric suction and yield is not straightforward. As an example some results of a field trial conducted in 1999 are presented in figure 3 to 5. Figure 3 shows the distribution of plant available soil water as estimated by the guidelines of the German Soil Science Society (Finnern et al. 1996) and figure 4 shows the results of a yield mapping conducted during harvest. Crop was maize but the results of the yield mapping confirmed yield patterns obtained for other crops on the same field in preceding years. A large part, although not all, of the yield variability can apparently be explained by the distribution of plant water availability. High plant available soil water suggests less stress due to water shortages, a potentially higher transpiration and thus more yield. This seems, however, to be not always the case as it can be seen in figure 5. The six sites equipped with tensiometers splitted into one group of sites with high and one group of sites with low matric suction, but no consistent relation between yield, plant available soil water and one of the groups could be detected. Thus, the objective of this study was to monitor matric suction of soil water under differing water and fertilizer regimes and to evaluate its impact on winter wheat yield.

3.2 Materials and methods

The present study was part of a broader two-year research trial investigating the interacting effect of soil water, external water supply, nitrogen fertilization and site on yield and plant characteristics of winter wheat. The trial consisted of a randomised two-factorial design, with two N-levels (120 kg N ha^{-1} and 180 kg N ha^{-1}; N treatment = NT) and three water supply treatments (irrigation, rain-shelter and control; water treatment = WT), with three replications. The experiment was conducted simultaneously on two sites of different plant available soil water within one field. Each experimental plot was further divided into two subplots, one subplot for pre-harvest biomass sampling and for the installation of one set of tensiometers and one to two capacitive probes for soil water monitoring, and one subplot for harvest. A set of tensiometers consisted of three depths (20 cm, 60 cm and 90 cm) with three replications. At

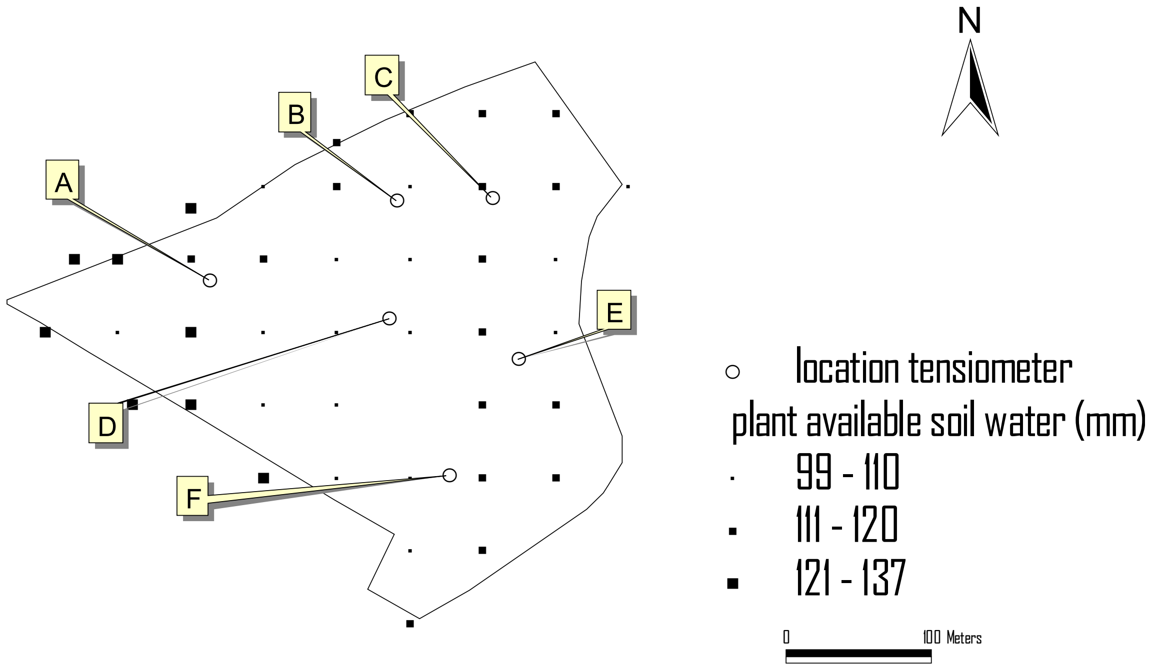

Figure 3 Plant available soil water (75 cm) at Schafhof.

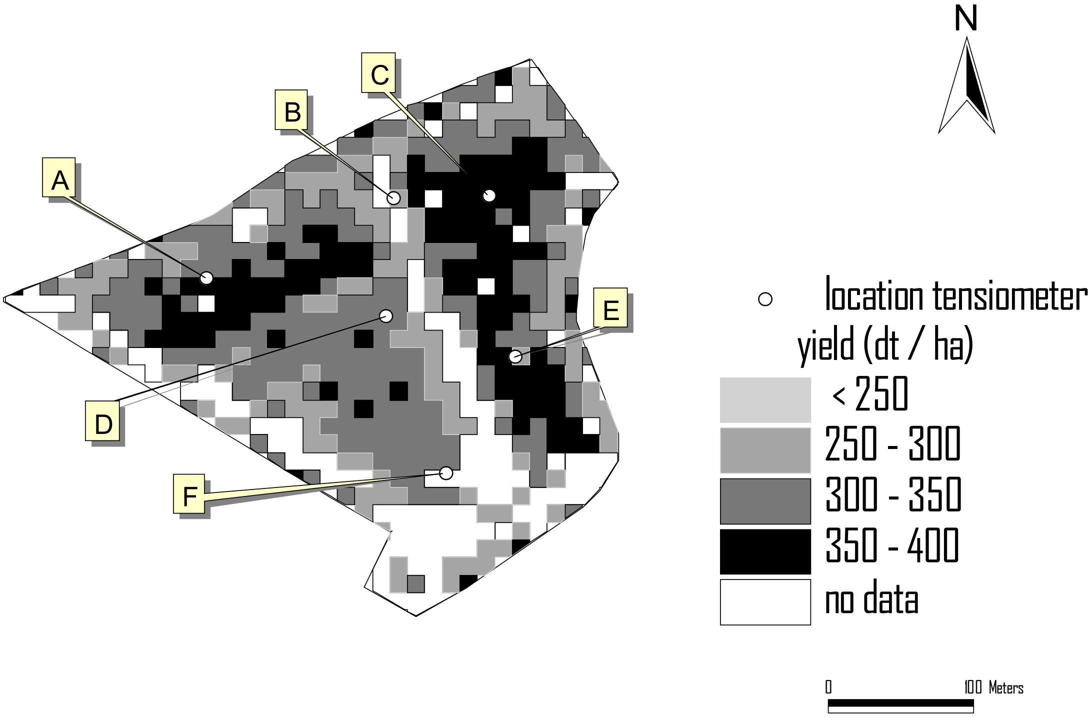

Figure 4 Yield map of silage maize at Schafhof, 1999.

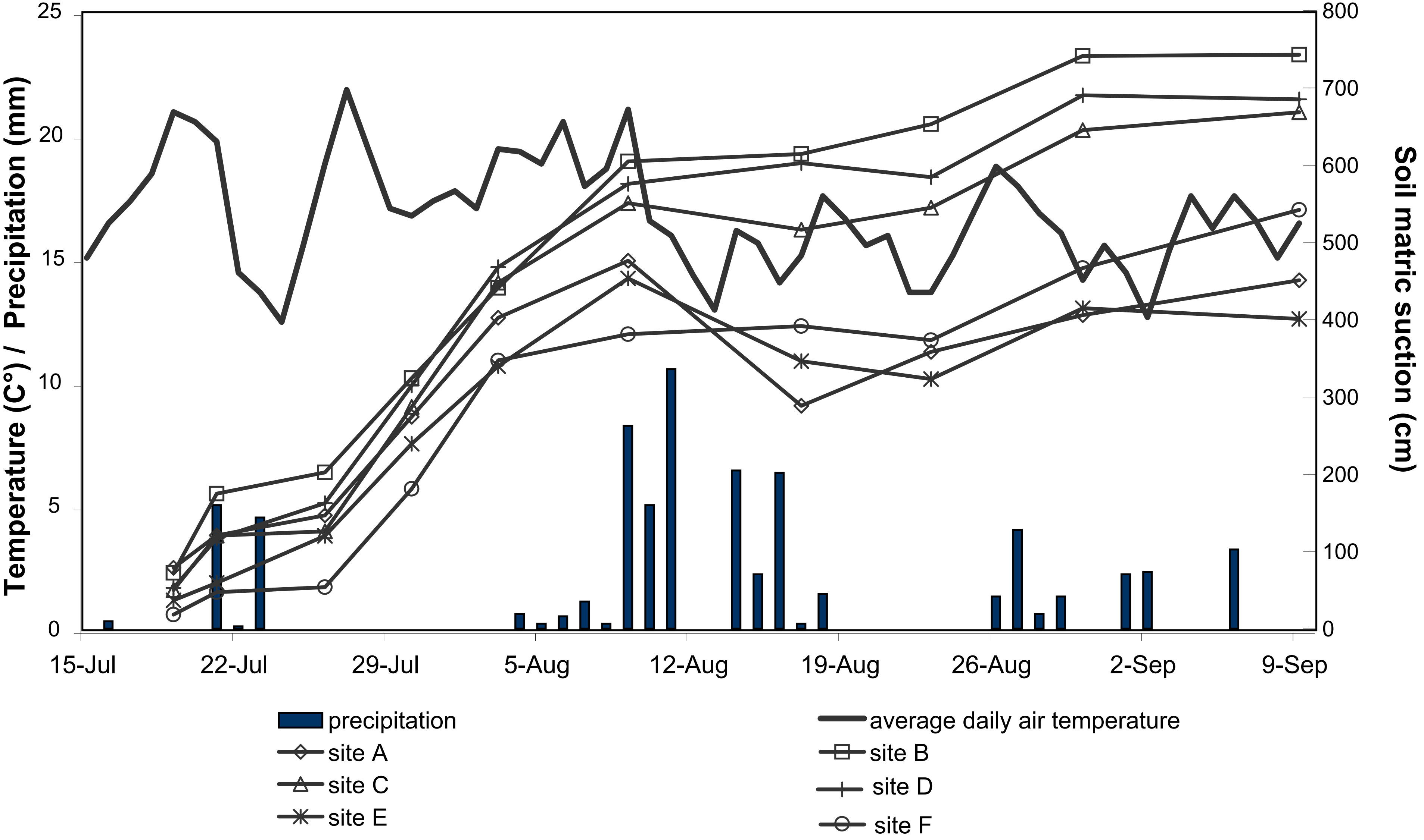

Figure 5 Average matric suction between 20 and 100 cm soil depth at Schafhof, 1999.

the site of high plant available soil water and at both sites in 2001, the number of tensiometers sets was 18. In 2000, at the site of low plant available soil water, tensiometer sets were also installed in 14 harvest subplots since the installation of the water supply equipment required in some cases a separation of corresponding subplots, thus resulting in 32 sets of tensiometers at this site. Tensiometers were read weekly between April 11 and July 25.

The custom-made tensiometers as used in this study consisted of a ceramic cup (SDEC, Reignac, France) fixed with epoxy cement to a 20 mm-diameter PVC pipe (GM Wassertechnik, Bad Abbach, Germany), with all parts filled with de-aired water and sealed with a silicon septum stopper (Riesbeck, Biebergemünd, Germany). The ceramic cup had a pore size of 2 µm, an air entry value of 1500 hPa and a hydraulic conductivity of 5.5×10^{-7} cm s^{-1}. Water suction was measured by piercing a syringe needle, itself connected to a portable pressure transducer with read-out digital display (von Ballmoos AG, Horgen, Switzerland), through the silicon stopper.

A correlation matrix of grain and straw yield and aboveground biomass against different variables characterizing the development of the matric suction was computed. Variables were: number of readings greater than a prescribed matric suction value (from 100 to 800 hPa in 100 hPa increments), the sum, the average, the median and the missing values of all readings of each plot during the aforementioned period. In a second approach, the same variables were used, however, but calculated for each month from April through July. Since many of the missing readings of tensiometers at 20 cm were missing due to a matric suction greater than 800 hPa and thus exceeding the capacity of the tensiometer, an alternative approach ('variation') was also computed by adding the number of missing values to all 'greater than' counts. A stepwise regression procedure was then used to arrive at a reasonable subset of possible variables relating matric suction to yield. Only variables with a correlation coefficient significantly different from 0 ($P = 0.05$) and that were significantly related to grain yield in both years were entered into the stepwise regression procedure. Also, when two variables were correlated (for example sum and average), only the variable with the higher correlation coefficient was used to avoid an inflation of variance (Myers, 1990).

A general linear model was used to compute variance ratios of the main and interaction effects of the treatments on matric suction and to compute the least significant difference between mean matric suction of the treatments. Since the recurrent measurement of matric suction during the growing period provided another source of variation, a variable time was also specified in the general linear model.

3.3 Results and discussion

Average daily temperature, precipitation, irrigation amount and the period of rain-sheltering from April through July 2001 are shown in figure 6. Temperature and precipitation in the growing period were near 30-year average except for May and July that were warmer and dryer than average.

The number of charts presented here (figure 7 to 9) to illustrate the development of the matric suction during the trial was reduced for reasons of clarity. Thus, only the charts based on the measurements of the matric suction of the water treatments within the high N treatment in 2001 are shown, since charts based on measurements of other treatments (low N) and of the trial in 2000 do not contribute substantial supplementary information.

One main feature that can be recognized from the graphs is the high standard deviation of the measured values. This may, in part, be explained by the spatial soil moisture variability. Beckett and Webster (1971) resumed from different works a variation of pF within 10 m^{-2} with a coefficient of variance up to 26 %. The high variability can also be attributed to the response time of tensiometers to changes in soil water pressure head and of the threshold and extent of air entry with individual differences between tensiometers (Cassel and Nielsen, 1986). On the other hand, a low standard deviation, especially concerning the tensiometers installed at 20 cm soil depth, does not necessarily imply a low soil moisture variability but rather a reduced number of observations due to failed readings. In spite of the high standard deviation, the charts reflect well the different water treatments. Irrigation resulted in low matric suction while rain-sheltering increased the matric suction compared to control. It is also noticeably that, at 60 cm and 90 cm soil depth, matric suction steadily increased at the site of high plant available soil water, whereas at the site of low plant available soil water, matric suction remained at a relatively low level at these soil depths suggesting a deep rooting activity at the former site.

Table 5 shows the interaction and main effects of site and treatments on matric suction. Least significant differences (LSDs) as shown in table 6 were only calculated when significant differences were found (P=0.05). At the site of high plant available soil water, matric suction at 20 cm and 60 cm soil depth were similar and in some cases even an increase in matric suction from 20 cm to 60 cm could be observed, which then declined down to 90 cm. At the site of low plant available soil water, matric suction decreased from 20 cm to 60 cm soil depth and stayed on a very low level (2000) or further declined (2001) to a very low level down to 90 cm.

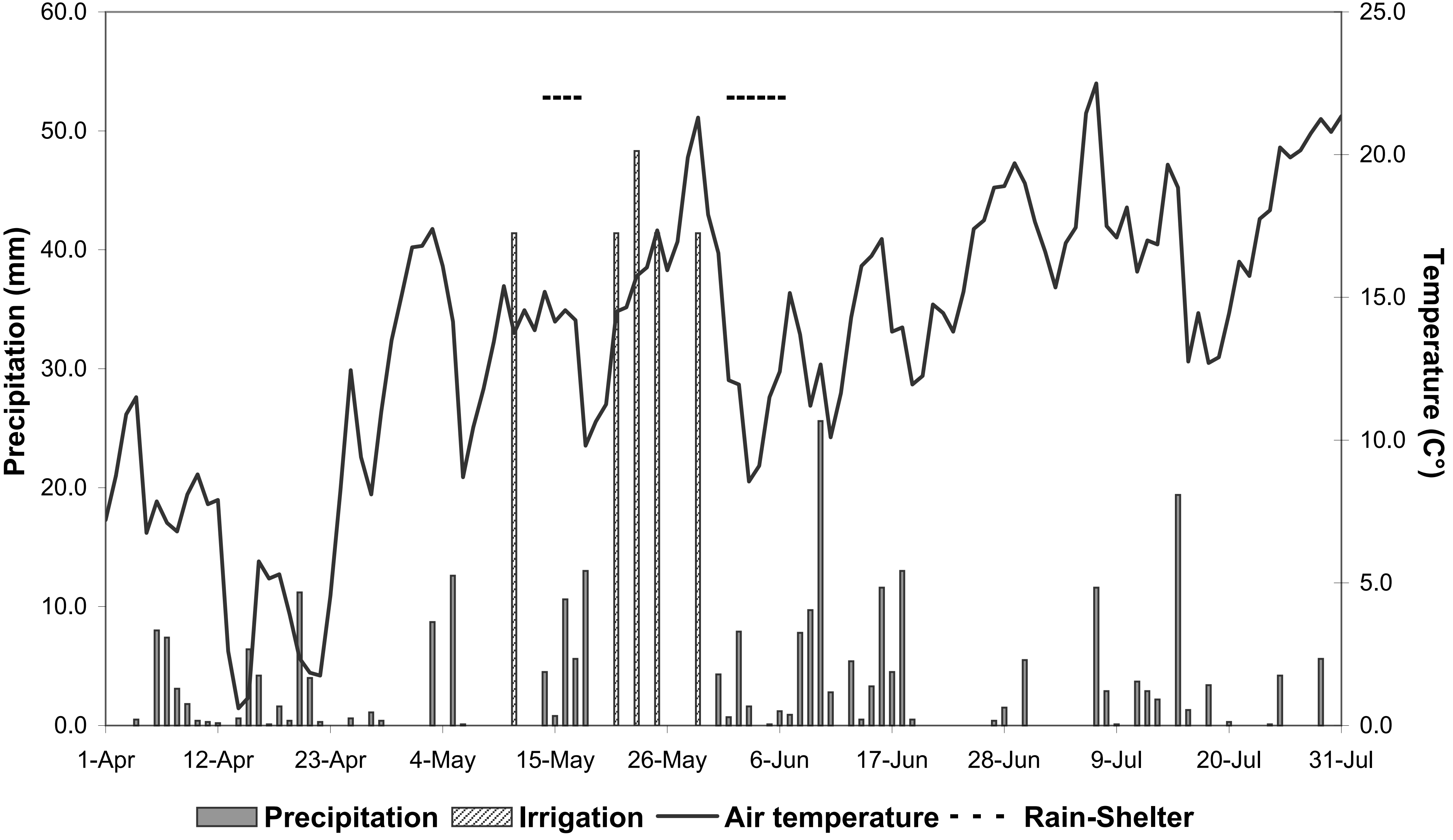

Figure 6 Mean daily air temperature, precipitation and irrigation events during field trial at Krohberg, 2001.

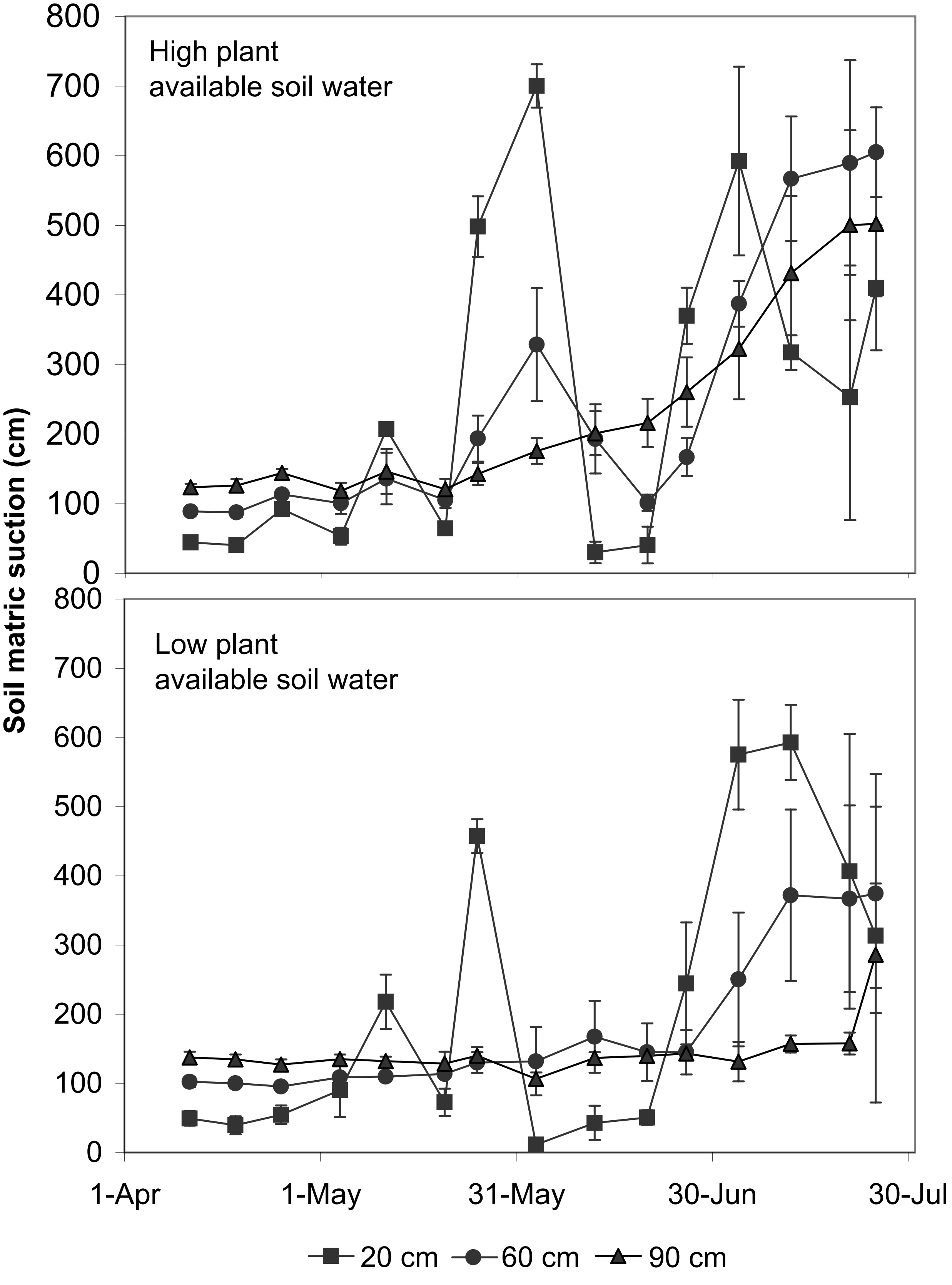

Figure 7 Soil matric suction on the control treatments, high N, at two sites at Krohberg in 2001. The error bars show the standard deviation.

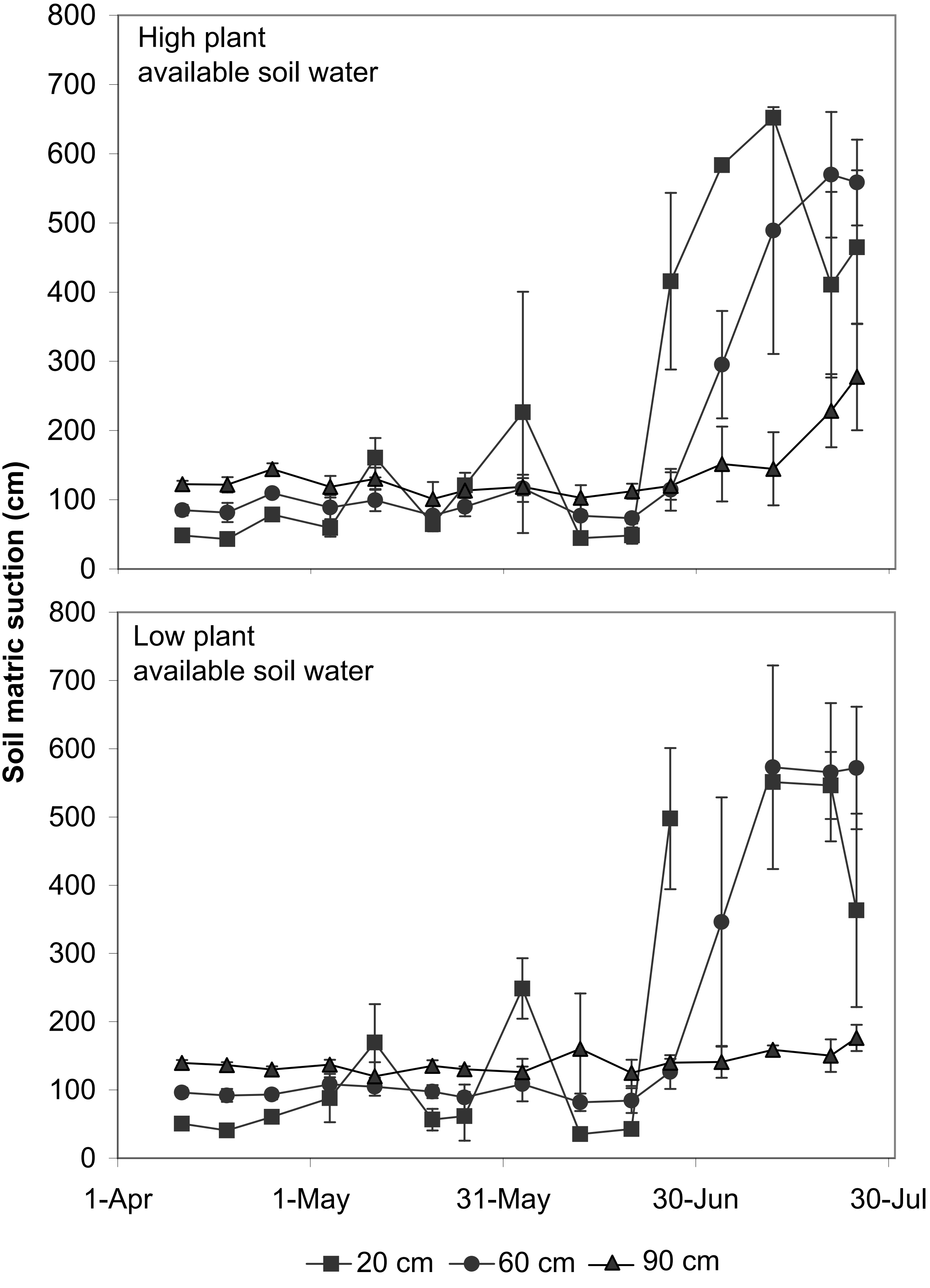

Figure 8 Soil matric suction on the irrigation treatments, high N, at two sites at Krohberg in 2001. The error bars show the standard deviation.

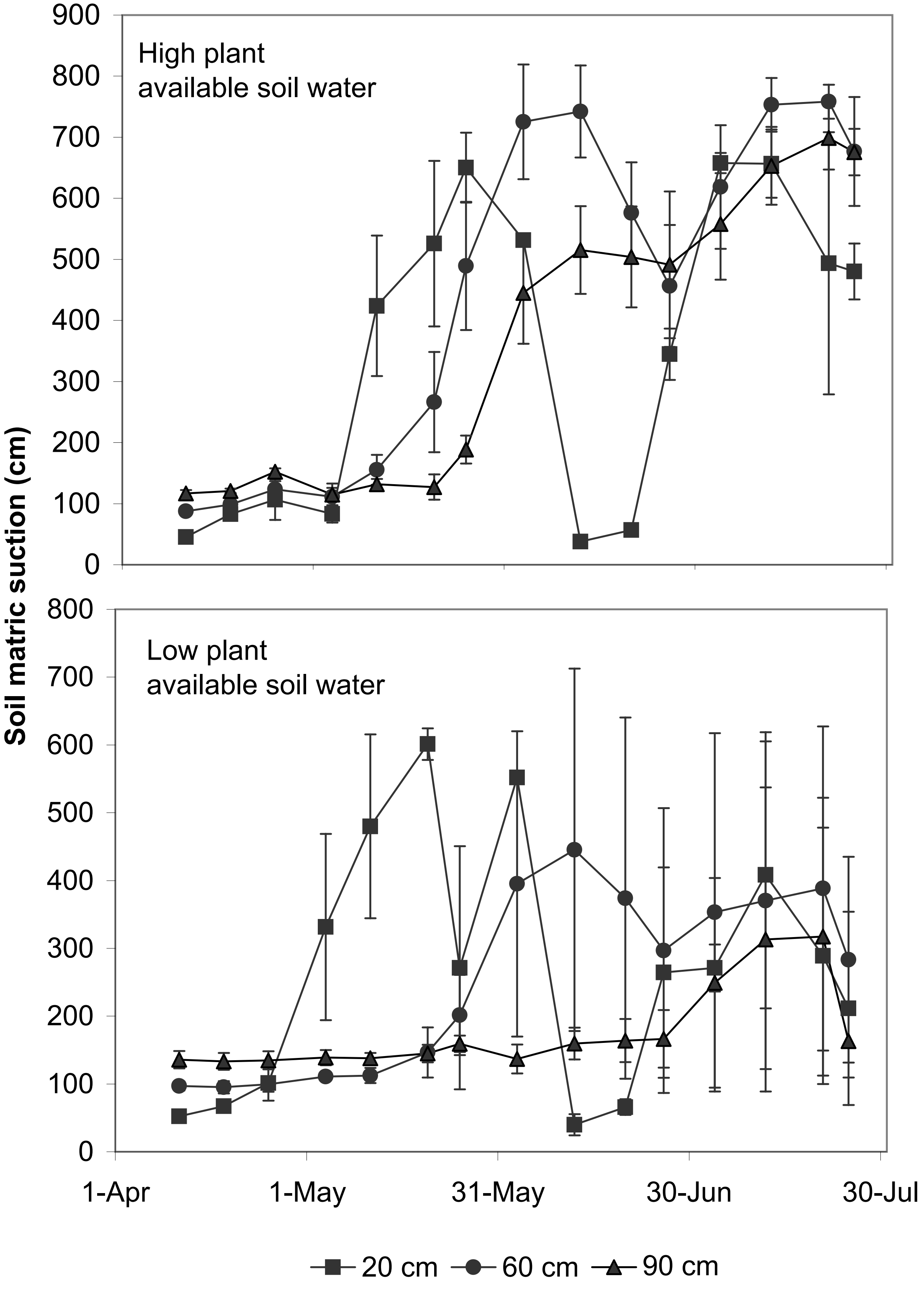

Figure 9 Soil matric suction on the rain-shelter treatments, high N, at two sites at Krohberg in 2001. The error bars show the standard deviation.

Table 5 Variance ratios (F) of the interaction and main effects of site, N fertilizer application (NT) and external water supply on matric suction of the soil water at three different soil depths.

		2000			**2001**		
Source	D.F.	20 cm	60 cm	90 cm	20 cm	60 cm	90 cm
					both sites		
site	1	85.6**	3214.2**	296.0**	17.4**	121.5**	207.0**
WT	2	450.0**	875.5**	92.0**	15.5**	92.1**	121.6**
site x WT	2	13.8**	706.7**	81.3**	1.7	34.9**	83.2**
NT	1	1.0	10.9**	8.0**	20.0**	17.2**	15.7**
site x NT	1	1.7	13.7**	9.1**	0.4	2.7	3.9
WT x NT	2	1.6	17.9**	6.6**	0.8	0.9	6.8**
site x WT x NT	2	0.9	20.1**	6.4**	0.5	0.04	1.6
					site A		
WT	2	398.8**	473.2**	40.0**	25.7**	182.7**	172.8**
NT	1	3.4	7.4**	4.0*	4.7*	4.8*	15.0**
WT x NT	2	3.6*	11.3**	2.9	2.2	0.6	5.5**
					site B		
WT	2	230.9**	33.5**	4.1*	1.0	5.7**	3.0
NT	1	0.07	0.4	0.4	13.2**	12.5**	2.9
WT x NT	2	0.07	0.4	6.0**	0.5	0.4	2.6

* $P < 0.05$ ** $P < 0.01$

Within each depth, site was the primary factor affecting matric suction of soil water. At all depths measured and in both years, the differences between the site of high plant available soil water and site of low plant available soil water was highly significant. Water tension was usually higher at the site of high plant available soil water than at a site of low plant available soil water, which can be ascribed to a higher biomass inducing a higher suction at the former site. The differences between the two sites were not significant on the irrigated treatments at all depths, but pronounced on the rain-shelter treatment.

The impact of the water supply treatment on matric suction was higher at the site of high plant available soil water than at the site of low plant available soil water. Lowest matric suction values are found on the irrigated treatment but highest matric suction values on the rain-shelter treatment. Generally, WT impacted the matric suction down to 90 cm at the site of high plant available soil water, whereas at the site of low plant available soil water the differences between the WT were small at 60 cm and erratic at 90 cm.

Differences in matric suction between the two N treatments were usually less important, and only trends can be observed. Within the rain-shelter treatment, matric suction was usually

Table 6 Average matric suction as affected by water supply and fertilization (LSD = least significant difference within site).

Fertilizer	20 cm					60 cm					90 cm				
(kg ha $^{-1}$)	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD
							site A, 2000								
120	253	120	372	248	26	278	61	312	217	38	98	45	163	102	29
180	237	110	397	248	22	297	34	378	236	23	101	46	229	125	17
average	245	115	385	248	21	288	48	345	227	19	100	46	196	114	27
LSD	ns	ns	24	ns		ns	12	41	10		ns	ns	ns	23	
							site B, 2000								
120	193	125	295	204	22	38	32	52	41	10	35	27	34	32	6
180	191	119	295	202	29	34	33	52	40	9	28	32	34	31	6
average	192	122	295	203	17	36	33	52	40	11	32	30	34	32	4
LSD	ns	ns	ns	ns		ns	ns	ns	ns		5	2	ns	ns	
LSD †	14	ns	17	11		12	6	17	6		15	6	23	9	
							site A, 2001								
120	168	104	196	156	33	163	91	333	196	31	95	40	182	106	26
180	155	125	255	178	36	169	129	352	217	29	126	40	281	149	28
average	162	115	226	167	19	166	110	343	206	25	111	40	232	127	23
LSD	ns	ns	45	22		ns	22	ns	19		ns	ns	40	17	
							site B, 2001								
120	131	115	129	125	ns	66	58	108	77	ns	51	33	40	41	ns
180	145	113	172	143	41	101	120	172	131	54	45	39	79	54	14
average	138	114	151	134	ns	84	89	140	104	36	48	36	60	48	ns
LSD	12	ns	37	13		31	ns	ns	30		ns	ns	32	ns	
LSD †	23	ns	32	15		22	ns	43	18		20	ns	26	11	

ns: nonsignificant at $P = 0.05$ † least significant difference between two sites

higher on the high N treatment than on the low N treatment at all depths and at both sites. At the site of high plant available soil water, at 60 cm and 90 cm, higher matric suction on the high than on the low N treatment was also often found within the control treatment. In all other cases, the differences between the two N treatments were erratic. Especially on the irrigation treatment, differences were small and often not significant.

Although the relation between site, WT and NT and grain yield is not subject of this chapter, the correlations between these parameters are presented in table 7 in order to facilitate the evaluation of the correlation between matric suction and grain yield and to understand the importance of each treatment during the trial. On the whole field level, water supply and site were the major factors affecting grain yield, straw yield and above-ground biomass. It can be shown, that in 2000, more than 70 %, and in 2001 more than 60 % of the yield variability of the trial fields can be explained by these two factors. At the sites of high plant available soil water, the yield increase by the application of additional 60 kg N ha^{-1} was more important on grain yield than the effect of water supply. In all other cases, i.e. straw yield and biomass at the sites of high plant available soil water, and grain yield, straw yield, biomass at the sites of low plant available soil water, the effect of WT was prevailing over or, at least, comparable to the effect of NT.

Correlations between soil matric suction and grain yield are shown in table 8a – 8c. Only correlations between grain yield and soil matric suction that occurred in both years are presented. The entire list of correlations with a correlation coefficient significantly different from zero can be found in the annex.

Correlations based on the observations of the entire spring-summer growing season (April to July, table 8a) are usually smaller than correlations based on single months during this period. In many cases, the correlation of the same variable is greater in 2001 than in 2000. The prevailing presence of the number of variables based on measurements of matric suction at 60 cm soil depth is striking. This can also be observed when only the year 2001 is considered (see annex), but in 2000, measurement made at 20 cm soil depth seem also to be often, although negatively, related to grain yield. On site level, when correlations were based on the observations of the entire spring-summer season, no correlation between soil matric suction and grain yield was found that was common to both years at the site of low plant available soil water. At the site of high plant available soil water, matric suction at 20 cm soil depth was correlated with yield. A continuously high matric suction during the aforementioned growing season may be caused by shallow rooting indicating less vigorous plants which may explain

Table 7 Correlations between treatments (WT = water supply treatment, NT = N fertilizer treatment) and yield.

2000

both sites (N=50)

grain			straw			biomass		
var	**R**	**P**	**var**	**R**	**P**	**var**	**R**	**P**
WT	0.66	< 0.0001	WT	0.71	< 0.0001	WT	0.70	< 0.0001
site	0.58	< 0.0001	site	0.53	< 0.0001	site	0.56	< 0.0001
NT	0.14	0.33	NT	0.14	0.34	NT	0.14	0.33

high plant available soil water (N=18)

grain			straw			biomass		
var	**R**	**P**	**var**	**R**	**P**	**var**	**R**	**P**
NT	0.49	0.04	WT	0.62	0.006	WT	0.57	0.01
WT	0.41	0.09	NT	0.26	0.30	NT	0.38	0.12

low plant available soil water (N=32)

grain			straw			biomass		
var	**R**	**P**	**var**	**R**	**P**	**var**	**R**	**P**
WT	0.93	< 0.0001	WT	0.90	< 0.0001	WT	0.93	< 0.0001
NT	0.08	0.65	NT	0.13	0.49	NT	0.11	0.56

2001

both sites (N=36)

grain			straw			biomass		
var	**R**	**P**	**var**	**R**	**P**	**var**	**R**	**P**
site	0.69	< 0.0001	site	0.83	< 0.0001	site	0.79	< 0.0001
WT	0.33	0.05	WT	0.36	0.03	WT	0.35	0.03
NT	0.15	0.37	NT	0.18	0.29	NT	0.17	0.31

site of high plant available soil water (N=18)

grain			straw			biomass		
var	**R**	**P**	**var**	**R**	**P**	**var**	**R**	**P**
NT	0.39	0.11	NT	0.50	0.03	NT	0.52	0.03
WT	0.02	0.95	WT	0.45	0.61	WT	0.34	0.17

site of low plant available soil water (N=18)

grain			straw			biomass		
var	**R**	**P**	**var**	**R**	**P**	**var**	**R**	**P**
WT	0.69	0.002	WT	0.78	0.0001	WT	0.75	0.0004
NT	0.19	0.46	NT	0.24	0.35	NT	0.23	0.39

Table 8a Correlations (R) between variables derived from matric suction measurements and grain yield that occur in both trial years. Correlations are based on all measurements during spring-summer growing season (April to July) (> value = number of matric suction readings above a given value in hPa; average = average matric suction; sum = cumulative value of measured matric suction; variation = considering failed tensiometer readings as matric suction > 800 hPa).

GROWING SEASON						
both sites						
			2000		**2001**	
variable	**depth**	**month**	**R**	**P**	**R**	**P**
> 400	60		0.38	0.007	0.44	0.008
> 200	60		0.37	0.009	0.47	0.004
> 300	60		0.37	0.009	0.47	0.004
> 500	60		0.33	0.02	0.33	0.05
average	60		0.31	0.03	0.39	0.02
sum	60		0.31	0.03	0.38	0.02
miss.	20		0.29	0.04	0.29	0.08
site of high plant available soil water						
> 100	20		-0.63	0.005	-0.52	0.03
site of low plant available soil water						
no						
--- variation ---						
both sites						
> 400	60		0.38	0.007	0.44	0.008
> 200	60		0.37	0.009	0.47	0.004
> 300	60		0.37	0.009	0.47	0.004
> 500	60		0.33	0.02	0.33	0.05
average	60		0.31	0.03	0.39	0.02
sum	60		0.31	0.03	0.38	0.02
> 400	20		-0.28	0.05	0.34	0.04
site of high / low plant available soil water						
no						

Table 8b Correlations (R) between variables derived from matric suction measurements and grain yield that occur in both trial years. Correlations are based on measurements of one month.

MONTHLY

both sites

			2000		2001	
variable	**depth**	**month**	**R**	**P**	**R**	**P**
> 400	60	July	0.38	0.007	0.53	0.001
> 500	60	July	0.35	0.01	0.39	0.02
> 200	60	July	0.35	0.01	0.63	<.0001
> 300	60	July	0.35	0.01	0.64	<.0001
median	60	July	0.32	0.02	0.65	<.0001
miss.	20	July	0.31	0.03	0.57	0.0003
average	60	July	0.29	0.04	0.61	<.0001
sum	60	July	0.29	0.04	0.64	<.0001
> 200	20	June	-0.43	0.002	0.59	0.0001
sum	20	June	-0.53	<.0001	0.39	0.02
> 300	20	June	-0.62	<.0001	0.51	0.001
site of high plant available soil water						
> 100	90	May	-0.51	0.03	-0.56	0.01
site of low plant available soil water						
> 100	20	June	-0.46	0.008	0.65	0.004
median	60	July	-0.50	0.004	0.57	0.01
> 200	20	June	-0.51	0.003	0.58	0.01
sum	60	July	-0.54	0.002	0.53	0.02
average	60	July	-0.55	0.001	0.50	0.04
> 100	20	May	-0.73	<.0001	-0.57	0.01
> 200	20	May	-0.73	<.0001	-0.59	0.01
average	20	May	-0.85	<.0001	-0.49	0.04

Table 8c Correlations (R) between variables derived from matric suction measurements and grain yield that occur in both trial years. Variation = considering failed tensiometer readings as matric suction > 800 hPa. Correlations are based on measurements of one month.

			MONTHLY			
			--- variation ---			
			both sites			
			2000		2001	
variable	**depth**		**R**	**P**	**R**	**P**
> 300	20	July	0.54	<.0001	0.53	0.001
> 400	20	July	0.49	0.000	0.57	0.0003
> 200	20	July	0.44	0.001	0.47	0.004
> 500	20	July	0.42	0.002	0.55	0.001
> 400	60	July	0.38	0.01	0.53	0.001
> 500	60	July	0.35	0.01	0.39	0.02
> 200	60	July	0.35	0.01	0.63	<.0001
> 300	60	July	0.35	0.01	0.64	<.0001
median	60	July	0.32	0.02	0.65	<.0001
> 700	20	July	0.31	0.03	0.57	<.0001
miss.	20	July	0.31	0.03	0.57	<.0001
average	60	July	0.29	0.04	0.61	<.0001
sum	60	July	0.29	0.04	0.64	<.0001
sum	20	June	-0.53	<.0001	0.39	0.02
			site of high plant available soil water			
> 100	90	May	-0.51	0.03	-0.56	0.01
			site of low plant available soil water			
> 400	20	July	0.40	0.02	0.48	0.04
> 300	20	July	0.38	0.03	0.54	0.02
> 600	20	June	-0.44	0.01	-0.64	0.004
median	60	July	-0.50	0.004	0.57	0.01
sum	60	July	-0.54	0.002	0.53	0.02
average	60	July	-0.55	0.001	0.50	0.04
> 200	20	May	-0.78	<.0001	-0.55	0.02
> 100	20	May	-0.83	<.0001	-0.52	0.03
average	20	May	-0.85	<.0001	-0.49	0.04

the negative relation between matric suction at 20 cm soil depth and grain yield at the site of high plant available soil water.

When correlations between grain yield and variables are computed from the matric suction measurements of each month (table 8b and 8c), the variables that, on the whole field scale, are most often correlated with grain yield are those calculated on the base of measurements from 60 cm in July. A relatively high correlation is also frequently found between grain yield and variables from measurements at 20 cm in June. It is interesting to notice that the latter correlations of matric suction and grain yield are most often negative in 2000 (i.e. except for the correlation between missing values and grain yield) and always positive in 2001. Low rainfall in June 2000 may have resulted in water stress during heading and blooming considered as a crucial water demand period for maximal yield (Kirkham and Kanemasu, 1983) while high matric suction during a period of high rainfall, i.e. June 2001, rather indicates suction induced by plant roots resulting in an increased productivity. This explanation is corroborated by the findings at the site of low plant available soil water where plants largely depend on topsoil water. At the site of low plant available soil water, it can furthermore be observed that matric suction values at 20 cm in May are negatively correlated with grain yield in both years, but stronger in 2000 than in 2001. In May 2000, precipitation was above average causing a strong plant growth (and as a consequence higher soil matric suction) with higher transpirational during heading and blooming which was not met in June 2000 and thus, yield substantially decreased. In May 2001, precipitation was below average, which caused a more moderate plant growth in the beginning with less transpirational demand which could, however, be easier supported due to an above average rainfall in June 2001. At the site of high plant available soil water only one common (in 2000 and 2001) correlation can be observed, i.e. the variable based on measurements in 90 cm in May. Since the correlation is negative in both years, the finding suggests that an early onset of water stress, by plant uptake or by percolation at 90 cm, may reduce the yield potential of a plant since the relative importance of lower layers increases in late season – at sites allowing rooting to this depth –due to the successive depletion of upper soil layers. Another possible explanation is that early depletion of subsoil water at 90 cm indicates strong plant growth with 'insatiable' transpirational demand that - analogous to the explanation given for the correlations at the site of low plant available soil water – increases transpirational demand in a latter crucial water demand period.

Further aspects appear when comparing the results of 2000 and 2001 (see annex). In 2000, on the whole field scale, most correlations between matric suction and grain yield were found among measurements made in June and May at 20 cm. The correlations were most often negative. In 2001 most correlations were positive and found among variables based on measurements made at 60 cm in July. Also, in 2001, the matric suction of soil water at 90 cm was also more frequently related to grain yield than the matric suction at 20 cm. A the sites of high plant available soil water, in both years, variables obtained from matric suction measurements at 20 cm soil depth but also at 90 cm were more often related with grain yield, many times negatively, than the matric suction at 60 cm. In 2000, correlations between variables from matric suction and grain yield were often found among variables from measurements made in June and May, whereas in 2001, correlations were more frequently observed with measurements made in July. At sites of low plant available soil water, almost no correlations between matric suction at 90 cm soil depth and grain yield was found, because apparently no considerable rooting occurred at this depth at this site. In 2000, at this site, almost all correlations were negative and based on measurements made in May or June, but in 2001 correlations were more frequently observed in June and July, mostly negative but always positive when based on measurements made at 60 cm. The relatively high number of correlations in June 2000, and the relatively high number of correlations in July 2001, can possibly explained by differences in the distribution of precipitation in the two years. In 2000, precipitation was high in July but deficient in June, thus reducing yield due to water deficiency during heading and blooming considered as the critical water demand periods for maximum yield. In 2001, precipitation was below and temperature above average in July but average in June which are favourable conditions for grain filling (Kirkham and Kanemasu, 1983).

It becomes clear when examining the data of the present study that correlations between soil matric suction and yield is often the result of several confounded causes. High matric suction may indicate high plant root activity but also coarse soil structure with easily depleted water reserve. These two causes have, however, different effects that again are modified by the timing and severity they occur. In some cases conflicting relations between matric suction and yield can be simply ascribed to the erratic results of stochastic probability of a correlation matrix containing a multitude of variables (Sokal and Rohlf, 1995).

The outcome of the addition of missing values at 20 cm to the number of observations larger than any given threshold value at 20 cm ('variation') depended on the signs of the correlation coefficient of the variables based on the measurement made at 20 cm and of the variable based on the missing values at 20 cm. In most cases, the number of missing values was positively related with grain yield whereas the variables based on the measurements at 20 cm was sometimes negatively and sometimes positively related with grain yield, often depending on the month. Thus the order and number of correlations as presented in table 8 a and b did not considerably change as correlations are based on the observations of the entire season. As for the correlations computed for each month, the number of significant correlations was increased by the variables based on measurements made at 20 cm in July at the whole field level, while at the sites of low plant available soil water, variables based on measurements made in May at 20 cm entered the list of common significant correlations while some of the variables based on measurements made in June at 20 cm disappeared.

A stepwise regression procedure entering all variables with significant correlation coefficient that occur in both years, left between one and five variables in the model (table 9a and 9b).

Table 9a Regression models resulting from stepwise procedure applied to matric suction variables common to both experimental years (spring-summer growing season). Variation = considering failed tensiometer readings as matric suction > 800 hPa.

		2000					2001		
parameter	**depth**	**month**	**parameter estimate**	**model R^2**	**parameter**	**depth**	**month**	**parameter estimate**	**model R^2**
				GROWING SEASON					
				both sites					
Intercept			6.44		Intercept			9.02	
> 400	60		1.36		> 200	60		1.05	
average	60		-0.021		> 400	60		0.60	
					average	60		-0.034	
				0.22					0.35
				site of high plant available soil water					
Intercept			9.20		Intercept			12.08	
> 100	20		-0.31		> 100			-0.23	
				0.40					0.27
				--- variation ---					
				both sites					
				idem					
				site of high / low plant available soil water					
				no					

The models explained between 22 to 35 % of the grain yield variability in the trials when considering the entire growing season at whole field scale and between 27 to 40 % at the site of high plant available soil water whereas at the site of low plant available soil water, no

Table 9b Regression models resulting from stepwise procedure applied to matric suction variables common to both experimental years (calculated from monthly data). Variation = considering failed tensiometer readings as matric suction > 800 hPa.

		2000					2001		
parameter	**depth**	**month**	**parameter estimate**	**model R^2**	**parameter**	**depth**	**month**	**parameter estimate**	**model R^2**
MONTHLY									
both sites									
Intercept			7.31		Intercept			6.13	
> 300	20	June	-2.22		> 200	20	June	0.73	
> 400	60	July	0.90		median	60	July	0.005	
					miss.	20	July	0.67	
				0.60					0.63
site of high plant available soil water									
Intercept			7.67		Intercept			11.00	
> 100	90	May	-0.89		> 100	90	May	-1.01	
				0.26					0.32
site of low plant available soil water									
Intercept			8.22		Intercept			8.14	
average	20	May	-0.01		> 100	20	June	0.47	
					> 100	20	May	-1.02	
					median	60	July		
				0.72					0.63
--- variation ---									
both sites									
Intercept			6.42		Intercept			6.13	
> 200	20	July	0.96		> 800	20	July	0.87	
> 200	60	July	0.56		median	60	July	0.006	
> 300	20	July	1.00						
> 700	20	July	-0.93						
sum	20	June	-0.003						
				0.65					0.60
site of high plant available soil water									
Intercept			7.67		Intercept			11.00	
> 100	90	May	-0.89		> 100	90	May	-1.01	
				0.26					0.32
site of low plant available soil water									
Intercept			9.66		Intercept			9.50	
> 100	20	May	-1.31		> 100	20	May	-0.66	
> 300	20	July	0.80		> 600	20	June	-1.69	
					median	60	July	0.006	
				0.76					0.70

significant model was found. When variables were computed for each month, the model explained around 60 % of the whole field grain yield variability and between 63 to 72 % of the variability at the site of low plant available soil water, but much less at the sites of high plant available soil water (26 to 32 %). When variables from the modified approach (variation) were used, the percentage of grain yield variability explained by the model was slightly improved at the sites of low plant available soil water.

The order of correlations found between variables based on matric suction of soil water and straw yield or aboveground biomass were similar, although rarely identical, to those found for grain yield. Yet, in 2001 at each site, a trend can be observed that correlations between biomass or straw yield and variables based on the monthly computation of matric suction occur earlier than between these variables and grain yield.

3.4 Conclusion

Between all treatments of this trial, site is the major factor affecting soil water matric suction. On the site of low plant available soil water, soil water matric suction close to zero at 90 cm soil depth indicate the absence of root activity at this depth. Variables based on average monthly soil water matric suction generally perform better in identifying yield variability than variables based on the average matric suction of the entire spring-summer growing period. Among all variables tested for both experimental years, variables based on measurements of soil matric suction made at 60 cm in June and July on the whole field level, at 90 cm in May at the loamy site, and at 20 and 60 cm in May and July at the sandy site, are best indicators to explain grain and straw yield and biomass variability within the trial fields. Matric suction is a confounded effect of soil properties, root activity and climate. Quality and character of correlations between soil water matric suction and yield vary considerably between years which can in part be attributed to yearly rainfall patterns.

4 SITE-SPECIFIC EFFECTS OF WATER SUPPLY AND NITROGEN FERTILIZATION ON WINTER WHEAT

4.1 Introduction

Variability of plant available soil water as a consequence of variability of soil texture is the norm rather than the exception in most fields. Precipitation variability is often no less important than soil variability, and its effect on the yield of winter wheat may often be even more considerable than spatial variability. The impact of plant available soil water and precipitation on yield of winter wheat differs, however, depending on the area under consideration. Weir and Barraclough (1986) reported for the UK no significant difference in grain yield between irrigated and drought stressed winter wheat on loamy soil and resumed from other authors that winter wheat grown on all major wheat-growing soils except the lightest can sustain prolonged droughts with little loss in grain yields.

In many areas of the world, however, available soil water and precipitation or irrigation amount and distribution are among the primary factors determining winter wheat yields (Stephens and Lyons, 1998; Nielsen and Halvorson, 1991; Eck, 1988; Kirkham and Kanemasu, 1983; Singh, 1981; Schneider et al., 1969; Jensen and Sletten, 1965). Brunner (1998) found for a small area in vicinity of the area of the present study, an average variation in sand content of 40 % and reported an important interacting effect of weather and soil on yield. Auerswald et al. (1997) showed for the same area that winter wheat varied by a factor of two within a distance of 50 m, and that most of the yield variance could be explained by site, land-use and weather factors.

The optimum fertilizer N level is related to the amount, timing and kind of water supply (Eck, 1988; Schneider et al., 1969; Jensen and Sletten, 1965). Read and Warder (1974) reported for spring wheat, and Singh et al. (1975) for winter wheat, that the rainfall during the growing season had a greater influence than stored soil water on the yield of wheat grown on unfertilized plots, but the amount of stored soil water had a greater influence on the effect of fertilizer on yield variation than did the growing season rainfall. Nielsen and Halvorson (1991) observed that grain yields increased with N application up to a certain level but declined at higher N-rates and suggested as cause an insufficient available water supply to support the greater transpirational demand from the greater leaf-area index. Black (1982) showed that, on loamy soil in Montana, the efficiency of spring wheat to use available water supplies (stored soil water and growing season precipitation) in producing grain was influenced markedly by fertilization. Without N-P fertilization, no significant relationship could be established across years between growing season precipitation and grain yields. With adequate N and P fertilization, grain yields were positively correlated with growing season precipitation. More N was needed for maximum yield response as growing season rainfall increased. Schneider et al. (1969) demonstrated that the most critical period for adequate soil water for winter wheat was from booting through grain filling stages. They found that timing of irrigation was as important as total the quantity of water applied.

The present study was part of a broader research program on precision farming. The objective of the present study was to evaluate the impact of varying soil water and precipitation (or irrigation) conditions on yield and various plant characteristics of winter wheat. Knowledge of these variables and of the effect that they have on variations in the response to fertilizer is necessary when planning a fertilizer program.

4.2 Materials and Methods

The trial described here was conducted in the tertiary foothills of the Bavarian Alps where fields with heterogeneous soil texture are frequent. In 1999, prior to the study, two adjacent fields were carefully texture-mapped according to the guidelines of the German Soil Society (Finnern et al., 1996) until a depth of 90 cm (considered as rooting zone). A loamy Cambisol (site A in 2000) and a loam-sandy Cambisol (site B in 2000) were selected for the trial of the year 2000, a silt-loamy Cambisol (site A in 2001) and a loam-sandy Cambisol (site B in 2001) were selected for the year 2001 trial. Groundwater level was more than 2 m deep.

At each site, a completely randomised two-factorial experiment was set up with two different N fertilizer treatments (NT) and three different water supply treatments (WT).

Water treatment variables were: stress by rain-sheltering; irrigation by T-Tape trickle irrigation (T-Systems Europe, Ltd., Toulouse, France); and control (rain-fed only). The mobile rain-shelter consisted of timber frames covered with 0.5 mm transparent polyethylene sheet supported by 2 and 2.3 m verticals set 0.5 m into the ground to give a 0.3 m pitch. Drainage from the roof was discharged well away from the site. Driving rain was kept out by side curtains that were lowered if necessary. Temperature under the shelter were somewhat higher than outside, particularly at night and at days of clear sky. Plots were covered before and rain-shelters removed after rains and thus, plots stayed never covered longer than four consecutive days to avoid masking side effects. Irrigation and rain-shelter was applied depending upon weather conditions between two-node stage to flag leaf stage in 2000, and in 2001 between three-node stage and the first visible appearance of the awns.

Fertilizer treatments were N at total rates of 180 N kg ha^{-1} and 120 N kg ha^{-1} broadcast in form of calcium ammonium nitrate at four different times at amounts of 60/40/40/40 kg ha^{-1}, and 30/30/30/30 kg ha^{-1}, respectively. Application time was at the beginning of the spring growing season, at the beginning of stem elongation, at the two-node stage and at the beginning of heading.

Weekly once, soil water was measured in soil depths ranging from 10 to 100 cm in 10 cm increments using a portable Diviner capacitance probe (Sentek Pty Ltd., South Australia). The 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 percent volumetric water content using a customized calibration. The customized calibration was obtained by simultaneous soil core sampling and by relating gravimetrically obtained soil water content to the electromagnetic field frequency of the capacitance probes. For the determination of gravimetric soil water content, soil samples were weighed, dried in an oven at 105° C for 24 hours and reweighed. Bulk density was derived from data obtained from soil profiles inside the trial and neighbouring fields. In 2000, the access tubes were installed disregarding low N and high N treatments thus monitoring only the effect of WT on soil water. In 2001, all plots were equipped with access tubes and, in addition, at each site, one irrigated, one control and one rain-sheltered plot within each NT were equipped with EnviroScan capacitive multisensor probes (Sentek Pty Ltd., South Australia) with sensors in 20 cm increments to a depth of 100 cm. These sensors remained permanently in situ during the trial and were hourly logged.

A water retention function was determined by placing soil core samples obtained from one soil profile made at each site on a ceramic plate in a pressure chamber and by consecutively applying gas pressures of 60 hPa, 300 hPa, 1000 hPa, 5000 hPa, and 15000 hPa and reweighing the samples after each pressure step. The equilibrium water content at 60 hPa for the coarse-textured soils and 300 hPa for the loamy soils was considered as field capacity θ_{vFC}, and at 15000 hPa as wilting point θ_{vWP} (Cassel and Nielsen, 1986). The selection of the upper limits for the calculation of plant available soil water is not straightforward. The two different approximations of field capacity chosen in this work produced, however, results that were in good agreement with the soil water content at the end of winter.

Four horizons were sampled on average. Plant available soil water (PASW) was calculated as the difference of soil water content at field capacity and wilting point. PASW of the rooting zone was computed by adding the PASW of the different soil horizons. With θ_v being the volumetric water content determined from capacitive sensor reading, the depletion of PASW was calculated from

$$(\theta_v - \theta_{vWP} / \theta_{vFC} - \theta_{vWP}) \text{ x } 100$$

The median value from 4 – 5 measurements per month per 10 cm increment was used to describe the monthly depletion status of PASW. Since the monthly depletion as monitored in the present trial suggested two major soil layers, i.e. an upper layer from 0 to 50 cm and a lower soil layer from 60 to 90 cm, an average monthly depletion for each layer which corresponded to the mean value of the aforementioned monthly depletion of PASW of the respective 10 cm increments of each layer was also calculated. The maximum monthly depletion (MMD) of a layer was then defined as the highest depletion value between the months April through July.

During the trial soil core samples were regularly taken from each plot to determine gravimetric soil water and also, in 2001, soil mineral N content (N_{min}) from 0 – 30 cm and from 31 – 60 cm soil depth. Soil samples were extracted with 0.1 N $CaCl_2$ and analysed for soil mineral nitrate by high performance liquid chromatography (HPLC), and for ammonium nitrogen by means of the indophenol blue method. Bulk density was derived from data obtained from three soil profiles inside the trial field and two soil profiles in a neighbouring field. The bulk density at site A in 2000 was approximately 1.51 g cm^{-3} (1.52 g cm^{-1} for site A in 2001) at 20 cm soil depth and 1.55 g cm^{-3} (1.55 g cm^{-3}) at 50 cm soil depth; at site B 1.64 g cm^{-3} (1.64 g cm^{-3}) and 1.68 g cm^{-3} (1.65 g cm^{-3}) in 2000 and 2001, respectively.

Each plot consisted of two subplots of 1.85 x 6 m: one subplot was used for the installation of soil water measurement devices and, in 2001, for soil sampling and for pre-harvest above-ground biomass sampling, while the second subplot was used for the final harvest. Winter wheat variety was 'Pegassos'. Row distance was 13.2 cm. In both years, preceding crop was maize and mustard as catch crop.

At the end of the trial, each plot (i.e the harvest subplot) was separately hand-harvested. The entire yield per plot was weighed and the number of heads per square meter was estimated from the number of heads in a subsample related by its weight to the respective plot yield. The yield was then threshed with a nursery thresher, and straw yield was determined as the difference between aerial dry matter and grain yield. Subsamples of grain and straw were oven-dried at 65°C to constant weight and then ground for total N analysis by the Dumas technique in a Macro-N-Analyser. Plant P and K was determined after wet digestion by inductively coupled argon plasma emission spectrometry (ICP). Grain samples for 1000-grain weight determinations were air-dried, counted with an electronic seed counter, and weighed.

In 2001, 1.5 m^2 pre-harvest samples were also taken: at the beginning of stem elongation, at the beginning of flowering (ten 1.14 m segments of rows per plot, with two row left on the outside as guard rows), at the end of flowering and at the medium milk stage. From the beginning of flowering on, ears were manually clipped off for a separate analysis.

The estimation of soil water use was based on soil water measurements (capacitive method) at the beginning and at the end of spring-summer growth period (1st April and 31st July). Water use efficiency in grain production was determined dividing grain yield by cubic meter of water used (soil water use plus precipitation for the same period). Not all plots were equipped with capacitance probes in 2000, and thus soil water measurement for N low and N high treatment was not taken separately. For the 2001 soil water measurements all plots were equipped with capacitance probes and separate measurements for the two N treatments could be obtained.

A statistical analysis was performed by use of a general linear model (SAS, 1989). When significant differences were found (P=0.05) least significant differences (LSDs) were calculated. For testing differences between the soil water content under high and low nitrogen application treatment a Wilcoxon rank-sum test was performed (SAS, 1989). In the text of the present work, differences are considered as not significant, unless explicitly mentioned.

4.3 Results and discussion

Average daily temperature, precipitation, irrigation amount and withheld precipitation for each growing spring and summer season are given in table 10. In April and May 2000, temperature and precipitation were above average, followed by a relatively hot and dry June and a relatively cold and rainy July. Temperature and precipitation in the growing spring season of 2001 were near average except for May and July that were warmer and dryer than average. The difference in external water supply between the irrigated plots and the rain-shelter plots was 244 mm in 2000 and 214 mm in 2001.

In the area of the present study since 1961, 30 % of all monthly precipitations in May exceeded the precipitation recorded for May 2000, but 70 % the precipitation in May 2001. For June, the percentages of monthly precipitations exceeding the precipitation recorded

Table 10 Monthly average maximum and minimum temperature, precipitation, amount of irrigated water and of rainwater withheld by sheltering during the spring-summer growing season of 2000 and 2001 and the 30-year average.

2000	April	May	June	July	August
Temperature					
Average Maximum (C°)	15.8	20.7	23.4	20.9	24.5
Average Minimum (C°)	4.0	8.6	10.2	10.9	12.3
Preciptation (mm)	74	104.3	60.9	137.1	69.8
Irrigation (mm)		150			
Withheld rainwater (mm)		94.3			
2001					
Temperature					
Average Maximum (C°)	11.8	20.8	19.5	23.8	24.5
Average Minimum (C°)	2.4	8.9	8.9	11.6	12.6
Preciptation (mm)	52.6	60.2	104.5	57.7	114.5
Irrigation (mm)		160			
Withheld rainwater (mm)		54.9	10.2		
1961-90					
Temperature					
Average Maximum (C°)	12.5	17.3	20.3	22.4	22.1
Average Minimum (C°)	2.6	6.7	9.9	11.4	11.2
Preciptation (mm)	55.8	88.7	105	98.7	95.1

during the trial years are 80 % and 34 %, and for July 25 % and 83 % in 2000 and 2001, respectively.

Depletion of plant available soil water (PASW). In the year 2000 trial, the amount of PASW at site A was around 155 mm down to 90 cm soil depth, and at site B around 115 mm / 90 cm. In 2001, PASW was around 170 mm / 90 cm and around 100 mm / 90 cm for site A and site B, respectively.

Figure 10 and 11 compare the monthly depletion of PASW of the two sites during the growing period of winter wheat in 2000 and in 2001. At both sites, depletion of PASW was slowed down by irrigation or accelerated by the rain-shelter treatment compared to the control treatment during the application of WT in May. After the WT was terminated in the beginning of June, the level of depletion reached quickly a similar level on all treatments. In the pattern of depletion in the soil profile, a conspicuous difference between the two sites can be recognized. At site B, depletion is more pronounced above 50 cm soil depth than below 50 cm, whereas at site A, PASW was depleted to a comparable extent in all soil depths throughout the profile. In 90 cm, depletion continuously increased from May to July at site A

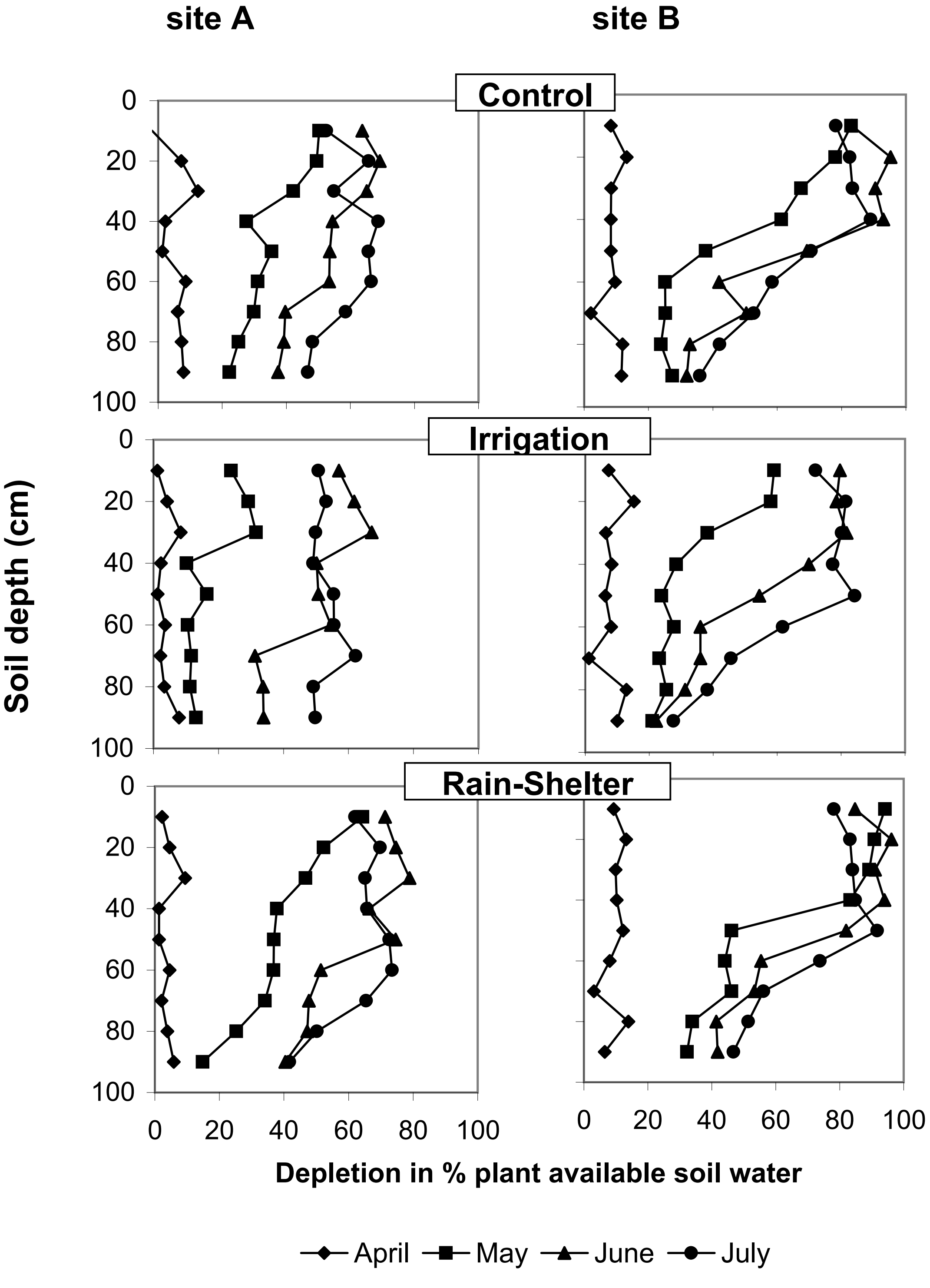

Figure 10 Depletion of plant available soil water at different soil depths of two sites in 2000 for three different water supply regimes. Values are the median depletion of plant available soil water of each month.

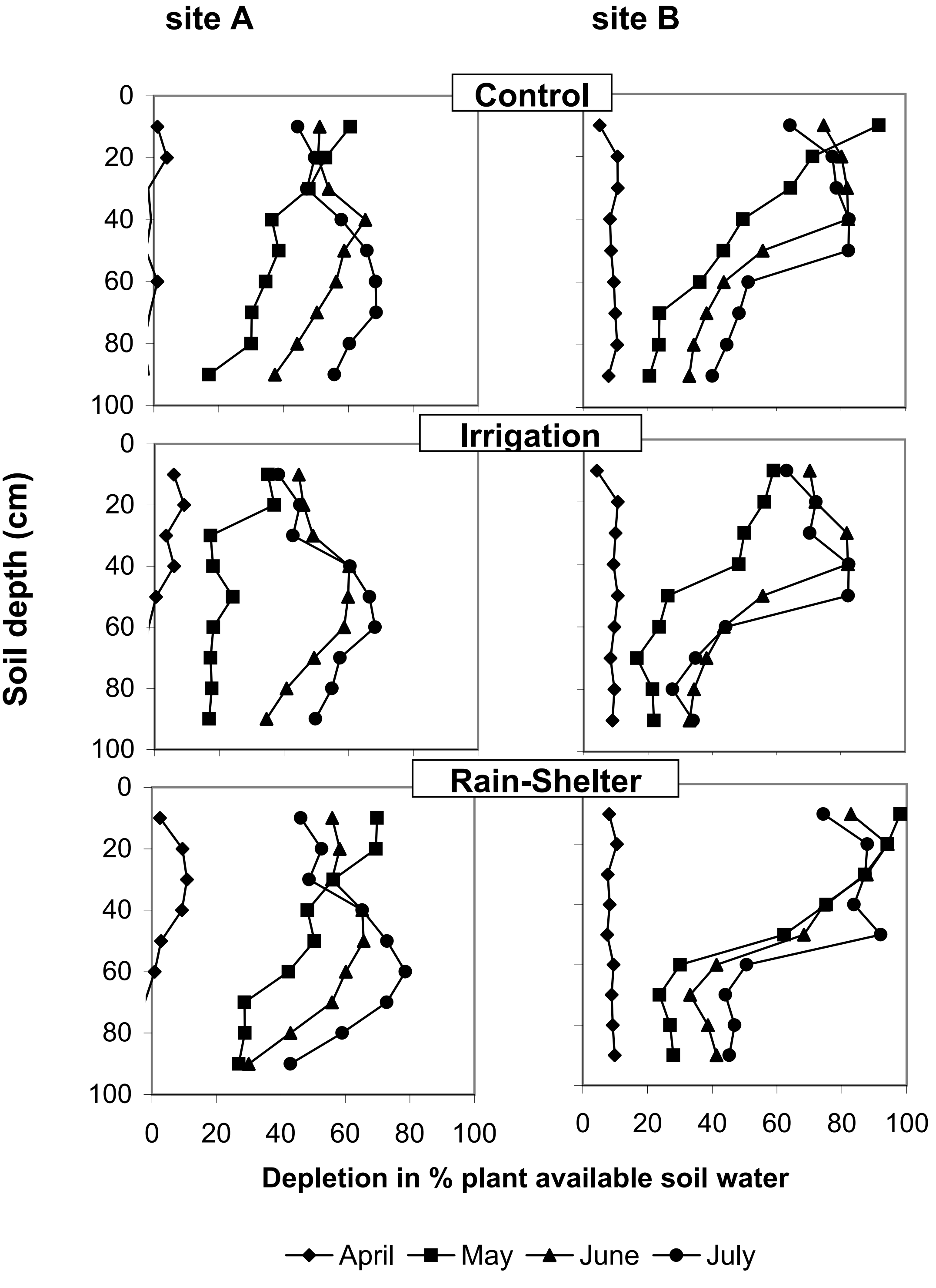

Figure 11 Depletion of plant available soil water at different soil depths of two sites in 2001 for three different water supply regimes. Values are the median depletion of plant available soil water of each month.

suggesting that layers below 90 cm may also have contributed to the water consumption of the plants. At site B, the difference in depletion between May, June and July was little and thus only a small contribution to the water consumption of the plant by layers below 90 cm may be assumed. If soil water depletion is related to root growth, the findings for the site of low plant available soil water could be consistent with Stoffel et al. (1995) who observed in a study conducted in the vicinity of the present work that on average 84 % of the roots on sandy-textured soil are found in the topsoil (0 – 30 cm). They concluded, however, that root growth was not always correlated with soil texture but rather with factors such as management (preceding crop) and weather (especially rainfall distribution). The findings on the A sites would be in agreement with Kmoch et al. (1957) who reported for winter wheat on fine sandy loam that favorable moisture conditions increase rooting depth growth.

A maximum monthly depletion (MMD) of usually more than 70 % of the PASW of the first 50 cm was observed at site B, whereas the MMD of the PASW of the first 50 cm at site A was always less than 75%. The difference in MMD of the PASW from 60 cm to 90 cm between the two sites was less pronounced than from 0 cm to 50 cm and ranged from 36 % to 57 % at site B and from 54 to 65 % at site A. MMD was higher on the rain-sheltered treatment than on the control treatment (except for site A in 2001 on the low N treatment), which in turn was higher than the maximum depletion of the irrigation treatment. The MMD values as presented in our study are averages in time and depth and thus not comparable to the values observed by Cabelguenne and Debaeke (1998), who reported individual maximum water depletion values. It can however be confirmed that for individual observations, a depletion beyond PASW occurred, i.e. a depletion of up to 130 % of the PASW at the B sites and up to 105 % at the A sites down to 40 cm soil depth (data not shown), which is still not comparable to values up to 200 % observed by Cabelguenne and Debaeke (1998) as the result of more than 10 experimental years under a more severe climate.

A comparison of the two experimental years has to take into account that the location of the trials was not identical. Yet, similar distribution of the depletion of PASW below 30 cm for both years can be recognized. Between 0 and 30 cm of soil depth, differences between the two years were more pronounced, although they do not entirely reflect the precipitation patterns as one may anticipate. For example, the generally less important depletion of PASW between 0 and 30 cm in June 2001 compared to June 2000 can be explained by an above average precipitation in June 2001 whereas the above average precipitation in July 2000 did not replenish soil water as perhaps expected.

Table 11 shows the difference in depletion of PASW between the low and high nitrogen

Table 11 Differences between low and high fertilizer application (low N treatment minus high N treatment) in the monthly % depletion of plant available soil water in 2001.

	site A										site B									
	Control																			
	soil depth (cm)																			
	10	20	30	40	50	60	70	80	90	all	10	20	30	40	50	60	70	80	90	all
March	1.4	3.4	3.4	0.9	-0.5	-1.0	-0.6	-0.5	-0.3	0.7	3.6	2.0	3.6	2.3	0.6	-0.8	-1.3	-1.0	3.6	1.4
April	2.0	3.4	2.6	0.3	-0.9	-5.1*	-0.2	-7.0**	-0.8	-0.6	2.7	2.2	1.9	1.2	-0.1	-1.1	-1.3	-0.7	3.7	0.9
May	6.3*	6.5*	3.4	1.1	-0.4	-2.5	0.5	-3.4	-2.3	1.0	3.1	-7.7**	-0.1	3.6	2.3	-0.8	-1.8	-0.9	7.9**	0.6
June	9.0**	5.7*	3.4	2.1	0.6	-2.9	0.2	-4.7*	-3.9	1.1	3.4	-2.3	-1.1	1.4	3.7	0.4	-1.2	-1.1	6.4*	1.1
July	7.0**	7.1**	7.6**	8.7**	3.4	-3.1	3.4	-5.6*	-5.7*	2.5	3.5	-4.7*	-3.1	2.5	3.7	3.1	0.4	2.2	3.6	1.2
all	6.3**	5.8**	4.4**	3.3*	0.8	-3.0*	1.0	-4.6**	-3.3*	1.2	3.3*	-3.5*	-0.6	2.3	2.6	0.5	-0.9	-0.1	5.5*	1.0
	Irrigation																			
March	1.0	2.2	1.4	0.1	-0.1	0.0	0.1	0.3	0.3	0.6	0.2	-0.8	2.5	2.3	2.8	0.2	-2.9	0.8	-3.0	0.2
April	5.9*	5.2*	4.9*	2.2	-1.9	-1.8	0.0	1.7	1.2	1.9	-0.4	0.3	2.4	2.1	2.7	-1.9	-2.4	0.7	-2.1	0.1
May	9.3**	10.8**	10.0**	2.2	-0.5	-0.5	0.3	3.6*	3.9*	4.3*	-1.7	-5.6*	3.2	2.0	1.4	-1.8	-3.2	2.6	-2.7	-0.6
June	5.0*	4.9*	5.1*	1.8	-0.7	-0.4	2.3*	3.8*	3.7*	2.8*	-0.4	-2.1	-0.4	0.0	0.2	-0.9	-1.3	1.0	-1.0	-0.6
July	2.4*	2.3	5.9**	6.3**	-2.2	-1.3	-0.9	1.3	1.6	1.7	-0.5	-4.2*	-2.5	-2.9	-3.2	-2.8	-2.0	1.2	-0.8	-2.0
all	5.3**	5.6**	6.3**	3.1*	-1.2	-0.8	0.5	2.6*	2.6*	2.7*	-0.7	-3.2*	0.5	0.2	0.1	-1.7	-2.2	1.4	-1.7	-0.8
	Rain-shelter																			
March	2.1	1.1	2.1	1.3	0.4	-0.5	-0.7	-0.6	-2.1	0.3	-0.9	-3.2	-1.9	0.5	0.6	2.0	1.3	1.8	6.2*	0.7
April	2.6	2.1	1.8	1.2	-0.1	-1.1	-1.2	-0.7	-2.0	0.3	1.3	-2.8	-0.1	-2.9	2.0	2.9	2.7	6.4*	3.1	1.4
May	3.5*	0.2	0.0	1.4	0.9	-0.3	-0.7	-0.4	-2.2	0.3	-0.2	-3.3	1.4	-2.9	3.1	2.5	2.2	5.6*	3.4	1.3
June	6.6**	0.4	-0.5	0.6	1.6	0.2	-0.5	0.5	-2.1	0.8	0.2	-3.2	-0.8	-3.1	2.4	0.8	1.3	2.4	3.0	0.3
July	1.9	-0.4	-1.8	1.4	8.7**	1.8	0.2	2.2*	-2.1	1.3	-0.1	-4.4*	-3.2*	-3.1	3.1	0.2	-0.4	2.3	2.7	-0.3
all	3.7**	0.5	0.3	1.2	1.9*	0.0	-0.6	0.1	-2.1	0.6	0.1	-3.5*	-0.8	-2.8*	2.6	1.5	1.2	3.7*	3.2*	0.6

* Significant at $P = 0.05$ ** Significant at $P = 0.01$

fertilizer application treatments for the year 2001 (monthly depletion of PASW on the low N treatment minus PASW depletion on the high N treatment). The depletion of PASW did not remarkably differ between the two N treatments at site B and below 30 cm soil depth at site A. In the topsoil of site A, however, especially under the irrigation treatment, depletion of PASW was higher on the low N treatment than on the high N treatment and often highly significant differences of more than 10 % depletion of PASW between the two N-treatments were found.

These findings are not in agreement with many other works. Warder et al. (1963), for example, reported no difference in soil moisture consumption between the two fertilizer treatments on loam soil (but more moisture use by fertilized wheat than by unfertilized wheat on clay). Jensen and Sletten (1965) found only small increases of the seasonal use of water by winter wheat when the amounts of applied N were increased on silty clay loam. Brown (1971) showed that water use by winter wheat was substantially increased by N fertilization on silt loamy loess. Only Hanks and Tanner (1952) observed, on sand and under corn crop and only for a few instances, that less soil moisture was used on high fertility plots than on low fertility plots even though greater yields were obtained on the high fertility plots.

The more important biomass with a higher vegetative cover on the N high plots compared to the low N plots at site A and thus a reduced soil water evaporation appears to be one reason for a higher soil water content in the first 30 cm on the high N plots. This, however, is unlikely to be the only explanation for this difference: Visually, no difference between the two N treatments as for the time and extent of the vegetative cover could be observed. All treatments at site A had an exceptionally high biomass yield in 2001, and the vegetative cover of all treatments reduced presumably soil evaporation to a quite similar extent. Also, if soil evaporation was the cause of the different soil water content between the two fertilizer treatments, the effect should be expected to be more important at site B, where the different soil cover was visually conspicuous and the biomass difference between the two fertilizer treatments, especially on the irrigated plots, was relatively more important. On the other hand, Kmoch et al. (1957) reported a stimulated root growth in all depths due to favorable soil moisture conditions and N fertilization, which might result in a decrease of the relative importance of the first 30 cm of rooting zone as water reservoir for the plant and thus explain to a certain extent the observation made in the present trial.

Grain yield. In 2001, the average grain yield of the whole field was 10.8 Mg ha^{-1} and thus markedly higher than the average yield of 7.4 Mg ha^{-1} in 2000 (table 12). Grain yield as

Table 12 Grain yield, straw yield, and harvest index as affected by site, fertilizer treatments and water supply treatments.

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	n.s	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	

ns: nonsignificant at $P = 0.05$ † least significant difference between two sites

affected by site, fertilizer and water supply treatments is also illustrated in figure 12. The important yield increase from 2000 to 2001 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 in comparison with 2001. The critical water demand period for maximum yield appears to start after booting until the end of milk ripeness, and especially the growth stages heading and blooming (Bruns and Croy, 1983; Singh, 1981) It could be shown that water stress during heading or blooming reduced yield by more than 50 % as summarized from different works by Kirkham and Kanemasu (1983). The data in this experiment suggest, however, the factor site as the primary effect that accounted for variability of yield while precipitation appeared to affect the overall yield level in a given year. A yield increase from 2000 to 2001 was observed at both sites on all treatments, but 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 on the rain-shelter treatment in 2000). The differences were always significant when WT data were pooled, but only in a few cases within WT. The response of grain yield to the application of additional 60 kg ha^{-1} on grain yield appeared to be dependent on site and water supply, however for different reasons. At the site of high plant available soil water, in 2001, a very high yield was already obtained on the low N treatment and thus, the margin of potential yield increase from low N to high N treatment was small, whereas in 2000, the potential to increase yield was still considerable. In both years, the highest yield increases, at the sites of high plant available soil water, were obtained, on the rain-shelter treatment, i.e. when water supply was reduced during stem elongation and heading. These findings suggest that on sites of high plant available soil water a higher N application should be considered when external water supply during stem elongation and heading is below average. At the sites of low plant available soil water, the response of grain yield to WT underscored the importance of sufficient external water supply for efficient N use on sites of low plant available soil water as already reported by others (Eck, 1988; Schneider et al., 1969; Jensen and Sletten, 1965). Yield increases with applied N increase at the B sites were comparable to the yield increases at the A sites, when water supply was adequate, i.e on the irrigation treatment.

As water supply increased during stem elongation and booting from rain-shelter to control and from control to irrigation to irrigation treatment an increase in grain yield at site B, but not always at site A was observed. In fact, at site A, an increased external water supply caused in some cases a grain yield reduction. Thus, irrigation was only beneficial on the sandy soils

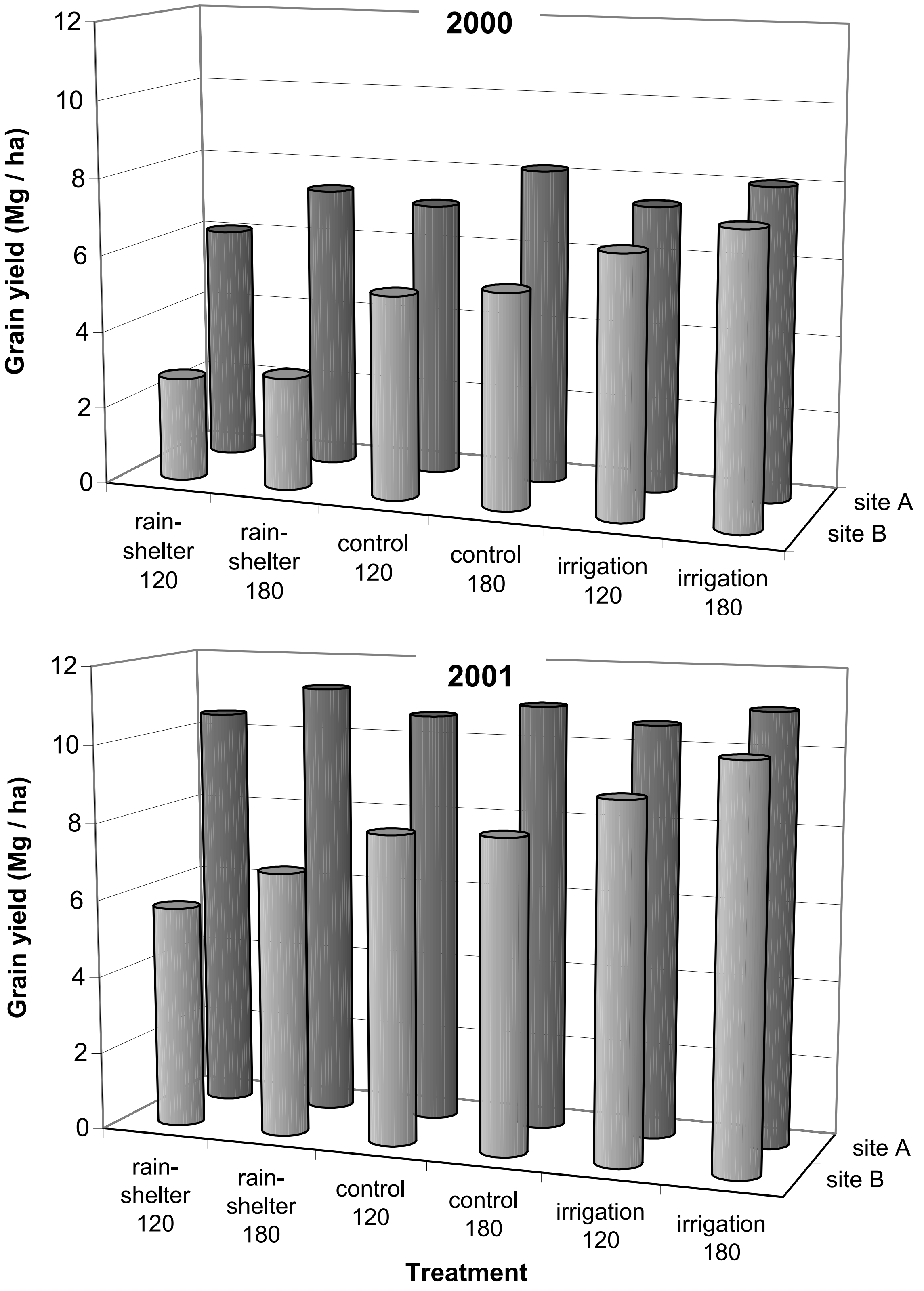

Figure 12 Effect of fertilizer treatments (120 and 180 kg N ha^{-1}), water supply treatments and site on grain yield in 2000 and 2001.

although irrigation occurred during a less critical water demand period. Good soil moisture in early growth stages stimulates however vegetative growth (Bruns and Croy, 1983; Warder et al., 1963), which is important to achieve a high yield potential. Thus, if stress is prevented until heading, there is still potential for maximum yields if precipitation occurs during heading and grain filling, while if plants are stressed earlier, the yield potential is lost which is in agreement with the findings by Eck (1988). Yield variability of winter wheat can therefore be considerably reduced when water supply is sufficient as it is also reported for corn grain yield by Machado et al. (2000).

The effect of the factor site on grain yield was interacting with WT but not with NT (table 13). As a result, the significant difference between the two sites on the rain-shelter treatment (3.8 Mg ha^{-1} in 2000 and 4.6 Mg ha^{-1} in 2001) decreased to nonsignificant differences between the two sites on the irrigation treatment (0.6 Mg ha^{-1} in 2000 and 1.2 Mg ha^{-1} in 2001). At the A sites, the differences in grain yield between rain-shelter and irrigation treatment was of a similar order than the grain yield difference due to NT, i.e. around 1 Mg ha^{-1} and no difference between the two WT, and around 1 Mg ha^{-1} and 0.5 Mg ha^{-1} between the two NT, in 2000 and 2001, respectively. At the B sites, the difference between rain-shelter and irrigation treatment was far more important than the average increase caused by a higher

Table 13 Variance ratios (*F*) of the interaction effect of site, N fertilizer application (NT) and water supply treatment (WT) on the plant characteristics and quality of winter wheat.

2000

Source	D.F.	Grain yield	Straw yield	Harvest index	Heads/ sqm	Seed weight	N grain	P grain	K grain	N uptake	P uptake	K uptake
site X NT	1	2.09	0.13	0.81	0.44	0.89	0.04	0.04	0.06	3.62	0.64	1.43
site X WT	2	16.32**	7.01**	8.16**	0.66	1.52	7.85**	4.01*	0.75	6.42**	7.55**	2.55
NT X WT	2	0.02	1.66	1.96	0.70	0.43	0.93	0.51	0.14	0.06	0.01	0.22
site X WT X NT	2	0.82	0.54	0.02	0.26	4.33*	0.07	0.13	0.93	0.71	0.60	0.11
(WT X NT) / site A	2	0.18	0.08	0.86	0.40	1.35	0.68	0.10	1.18	0.14	0.28	0.02
(WT X NT) / site B	2	0.90	3.59*	1.20	0.66	4.04*	0.74	0.66	0.83	0.86	0.37	0.63

2001

source	D.F.	Grain yield	Straw yield	Harvest index	Heads/ sqm	Seed weight	N grain	P grain	K grain	N uptake	P uptake	K uptake
site X NT	1	0.07	2.38	0.00	0.35	0.04	0.00	0.88	0.00	0.63	1.80	0.39
site X WT	2	5.11**	3.90**	2.72	1.50	0.75	0.02	0.54	0.09	2.18	1.45	2.51
NT X WT	2	0.25	2.38	4.74*	0.21	0.05	0.11	0.11	0.03	2.81	1.59	2.91
site X WT X NT	2	0.09	0.20	0.40	2.12	1.04	0.00	0.78	0.01	0.19	0.47	0.63
(WT X NT) / site A	2	0.14	2.72	2.82	3.21	0.86	0.04	0.40	0.02	0.61	0.32	0.73
(WT X NT) / site B	2	0.17	0.69	2.13	0.63	0.45	0.07	0.03	0.01	3.12**	2.24	2.85

* significant at $P = 0.05$ ** significant at $P = 0.01$

N application, i.e. around 4.2 Mg ha^{-1} and 3.4 Mg ha^{-1} for the two WT in comparison with around 0.3 Mg ha^{-1} and 0.8 Mg ha^{-1} for the NT, in 2000 and 2001, respectively.

If the 60 kg N ha^{-1} increment is divided by yield increase (in kg) to obtain the increment efficiency, the maximum efficiency for each kg of N applied, at the A sites, was found on the rain-shelter treatments (21.0 kg in 2000, and 12.8 kg in 2001). At the B sites in 2000, the maximum grain yield increase for each kg of the N increment applied was on the irrigation treatment (12.7 kg kg^{-1}), and, in 2001, on the irrigation and, surprisingly on the rain-shelter treatment (both 18.0 kg kg^{-1}). In 2000, on average across the WT, the increment was more efficiently used at site A (16.5 kg kg^{-1}) than at site B (5.3 kg kg^{-1}), but in 2001, the increment was more efficiently used at site B (12.5 kg kg^{-1}) than at site A (8.7 kg kg^{-1}).

Straw yield and harvest index (HI). Straw yield was higher on the high N plots than on the low N plots but differences were usually nonsignificant within WT (table 12). At the B sites, but also 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. Significant differences in straw yield between WT were found at the B sites. At the A sites, a steady increase of straw yield from rain-shelter to control to irrigation treatment could only be observed on the high N plots. The differences between the two sites in straw yield were much larger in 2001 than in 2000, and in both years the smallest difference between the two sites was always found on the irrigation treatment.

Since the effect of NT on straw yield was comparable to its effect on grain yield, HI was little influenced by NT. The effect of WT and of the factor site on grain yield differed, however, from their respective effect on straw yield. Besides, there was an interacting effect of site and WT on grain and straw yield in both experimental years, of site and WT on HI in 2000, and in 2001, there was an interacting effect of NT and WT on HI (table 13). Thus the response of HI to WT and site was erratic.

Biomass development. Pre-harvest biomass data are only available for 2001. Figure 13 compares the effect of WT and of NT on the development of the biomass growth at the two sites under the different external water supply treatments. The biomass growth curves of the rain-sheltered and of the control treatment of site A are flattened during anthesis (BBCH growth stage 61 to 69 (Meier, 1997)) compared to the curves of the respective irrigation treatment. The biomass growth curves of the corresponding treatments of site B, however, stayed flattened beyond anthesis in comparison with site B irrigation treatment and all treatments at site A. This again illustrates the importance of sufficient water supply during vegetative growth at sites of low plant available soil water to maintain a potential for high yield, whereas at sites of high plant available soil water the effect is relatively small. On the

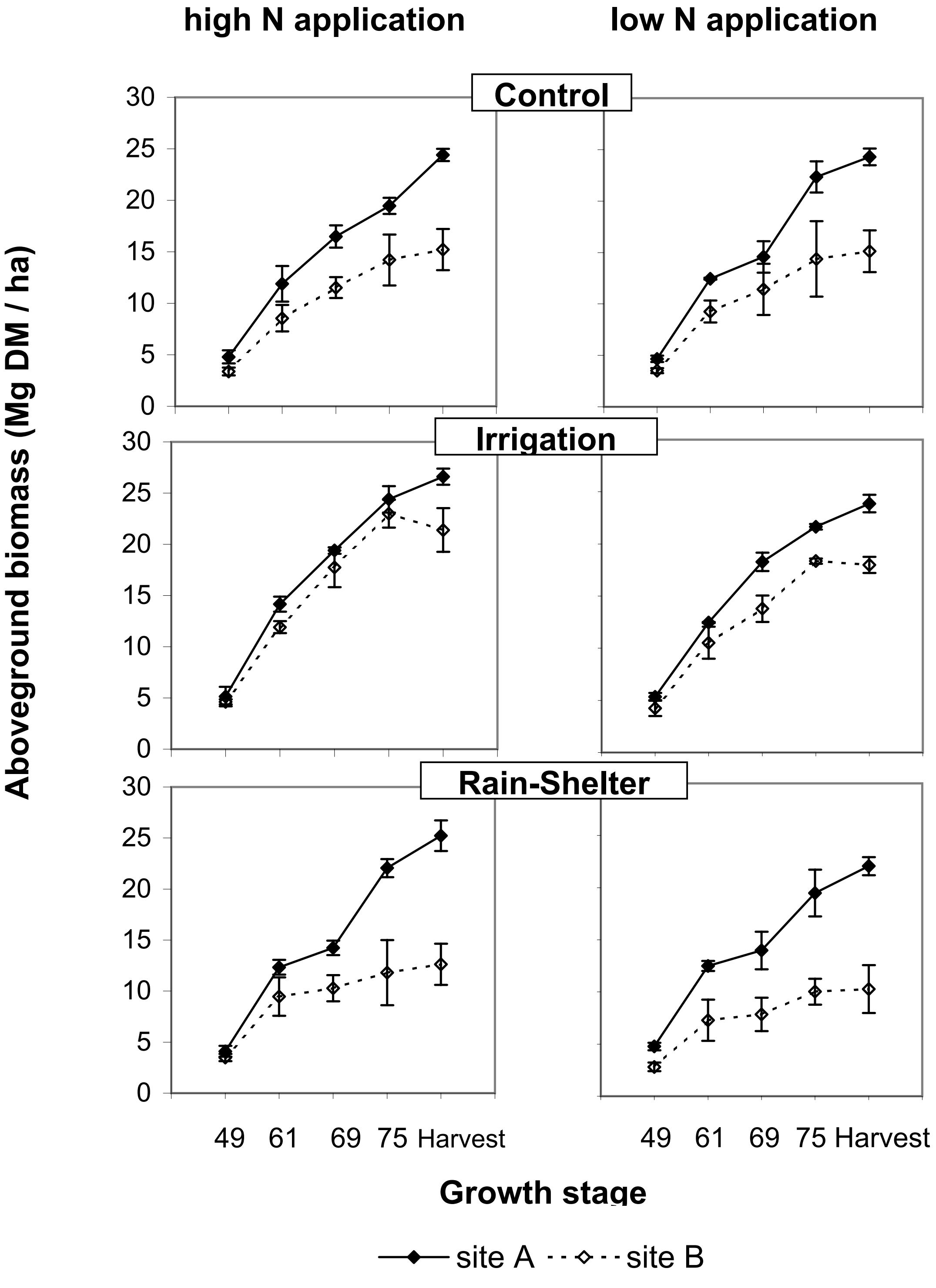

Figure 13 Aboveground biomass growth (with S.E.) at Krohberg, 2001. The growth stages are based on Meier (1997)

irrigation treatment, the biomass development of the two sites was comparable, especially where high N was applied. The biomass deficit at harvest between the two sites on the irrigation treatment is attributable to the relatively large difference in straw yield between the two sites rather than to differences in grain yield.

Heads per square meter and seed weight. At the A sites, in most cases, more heads per square meter on the low N treatment than on the high N treatment was found (table 14). This is not consistent with the findings of Eck (1988) who observed an increased head number by increased applied N on clay loam. At the B sites, the response to NT was erratic. At both sites, the number of heads was smallest on the rain-shelter treatment and increased from the control to the irrigation treatment. The findings are not in agreement with Robins and Domingo

Table 14 Heads per square meter and seed weight as affected by site, fertilizer treatments, and water supply treatments.

Fertilizer	**Heads 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	

ns: nonsignificant at $P = 0.05$ † least significant difference between two sites

(1962) who found, for spring wheat grown on sandy loam, that severe moisture stress prior to heading greatly increased the number of heads per unit area due to second growth. The numbers of heads 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, but not on the rain-shelter treatment at site B and the irrigation treatment at site A in 2000. WT did not consistently affect seed weight. Seed weights were significantly higher at site A than at site B within WT in 2001, but in 2000 only within the rain-shelter treatment or when pooled across WT.

Black (1982) and Robins and Domingo (1962) reported a high correlation between heads per unit area and spring wheat yield. This can quite often not be confirmed in the present study, in particular at the site of high plant available soil water or if the additional amount of applied N was the cause for yield increase. The increased seed weight on the high N treatment rarely compensated the decrease in heads square meter and thus, it can be assumed that the yield increase was mainly due to a considerably larger grain number on the high N treatment than on the low N treatment.

Grain N,P,K. Grain N concentration (gN) was generally higher on the high N treatment than on the low N treatment (table 15). At both sites in 2000 and in 2001 at site B, gN decreased from rain-shelter to control and from control to irrigation treatment. In 2000, gN on 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. Thus, an increase of N fertilizer at this site may be indicated when external water supply during stem elongation and booting is above average to meet standard requirements for high quality flour.

Grain P concentration (gP) was influenced only by site and higher at the B sites than at the A sites. Differences between the two sites were small within the irrigation treatment. WT and NT affected gP only little. An effect of NT on grain K concentration (gK) could also not be detected, but as for WT, a steady increase in gK from rain-shelter to control to irrigation treatment was observed. Significant site differences in gK can only be reported for 2001, with higher gK at site B than at site A.

N,P,K uptake. The increase in grain and straw yield, and a higher plant grain N concentration straw N concentration (data not shown) on the high N treatment compared to the low N treatment was also reflected in an increased N uptake on the high N treatment (table 16). N uptake was more important at site A than at site B. Although the factor site was inversely related with gN than with biomass, its effect on biomass could not be offset by its effect on

Table 15 N, P, and K content in grain as affected by site, fertilizer treatments and water supply treatments.

Fertilizer	N (g kg^{-1})					P (g kg^{-1})					K (g kg^{-1})				
(kg ha^{-1})	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD
2000, site A															
120	21.4	20.9	24.5	22.3	1.6	3.8	3.8	3.9	3.8	ns	4.5	4.8	4.1	4.5	0.2
180	23.5	23.9	27.6	25.0	1.5	3.8	3.8	3.9	3.8	ns	4.5	4.7	4.1	4.5	0.2
Average	22.5	22.4	26.1	23.6	2.0	3.8	3.8	3.9	3.8	ns	4.5	4.8	4.1	4.5	0.1
LSD	1.3	1.6	2.2	2.0		ns	ns	ns	ns		ns	ns	ns	ns	
2000, site B															
120	21.7	19.6	27.1	23.1	2.0	4.2	3.8	4.3	4.1	0.21	4.7	4.8	4.2	4.5	0.3
180	25.1	22.1	29.0	25.6	1.9	4.3	3.8	4.1	4.1	0.31	4.6	4.9	4.0	4.5	0.3
Average	23.4	20.8	28.1	24.3	2.0	4.3	3.8	4.2	4.1	0.22	4.6	4.9	4.1	4.5	0.2
LSD	0.7	ns	1.7	2.5		ns	ns	ns	ns		ns	ns	ns	ns	
LSD †	ns	ns	1.8	ns		0.2	ns	0.3	0.2		ns	ns	ns	ns	
2001, site A															
120	21.7	21.0	21.5	21.4	ns	3.7	3.9	3.7	3.8	ns	4.4	4.6	4.3	4.4	0.2
180	21.8	23.0	22.4	22.4	ns	3.8	3.9	3.8	3.9	ns	4.3	4.6	4.2	4.4	ns
Average	21.8	22.0	22.0	21.9	ns	3.8	3.9	3.7	3.8	ns	4.3	4.6	4.2	4.4	0.2
LSD	ns	1.8	ns	0.9		ns	ns	ns	ns		ns	ns	ns	ns	
2001, site B															
120	21.5	18.5	23.8	21.3	ns	3.9	3.9	4.1	3.9	ns	4.7	4.9	4.6	4.7	ns
180	22.5	21.4	25.4	23.1	ns	4.0	4.1	4.1	4.1	ns	4.5	4.8	4.5	4.6	ns
Average	22.0	19.9	24.6	22.2	2.9	3.9	4.0	4.1	4.0	ns	4.6	4.9	4.6	4.7	0.2
LSD	ns	2.8	ns	ns		ns	ns	ns	ns		ns	ns	ns	ns	
LSD †	ns	ns	ns	ns		ns	ns	0.3	0.1		0.1	0.3	0.2	0.1	

ns: nonsignificant at $P = 0.05$ † least significant difference between two sites

Table 16 N, P and K uptake (above-ground) as affected by site, fertilizer treatments, and water supply treatments.

Fertilizer	N ($kg\ ha^{-1}$)					P ($kg\ ha^{-1}$)					K ($kg\ ha^{-1}$)				
($kg\ ha^{-1}$)	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD	Control	Irrigation	Shelter	Average	LSD
2000, site A															
120	191.6	193.3	181.7	188.9	ns	32.3	33.8	28.5	31.5	ns	98.5	104.6	68.9	90.7	ns
180	246.4	250.8	255.2	250.8	ns	36.0	36.5	34.9	35.8	ns	124.1	127.2	89.4	113.6	ns
Average	219.0	222.0	218.4	219.8	ns	34.1	35.2	31.7	33.7	ns	111.3	115.9	79.2	102.1	ns
LSD	ns	ns	ns	28.7		ns	ns	ns	4.2		ns	ns	ns	ns	
2000, site B															
120	133.9	162.1	97.7	129.1	9.2	25.3	29.7	15.3	22.9	5.2	52.0	84.2	30.6	54.1	27.2
180	167.8	202.8	108.4	156.4	12.5	28.2	33.0	15.5	24.9	5.6	62.6	100.2	31.4	62.7	24.9
Average	150.8	182.4	103.0	142.8	8.0	26.7	31.4	15.4	23.9	4.2	57.3	92.2	31.0	58.4	22.1
LSD	ns	ns	ns	ns		ns	ns	ns	ns		ns	ns	ns	ns	
LSD †	37.6	ns	38.5	26.2		4.8	ns	5.2	4.3		21.9	ns	13.0	17.7	
2001, site A															
120	314.2	294.8	293.3	300.8	ns	54.8	55.7	50.2	53.6	ns	200.8	201.1	156.3	186.0	ns
180	319.3	363.9	348.7	343.9	ns	57.1	63.2	59.5	59.9	ns	234.6	279.9	214.4	243.0	ns
Average	316.7	329.4	321.0	322.4	ns	55.9	59.4	54.9	56.8	ns	217.7	240.5	185.3	214.5	ns
LSD	ns	ns	ns	28.3		ns	ns	ns	5.0		ns	ns	49.7	40.0	
2001, site B															
120	206.0	205.2	157.5	189.5	ns	39.2	44.5	28.5	37.4	11.5	84.6	105.2	54.4	81.4	40.6
180	222.6	275.6	216.3	238.1	ns	42.4	55.0	37.9	45.1	ns	80.6	160.1	73.3	104.7	64.6
Average	214.3	240.4	186.9	213.8	ns	40.8	49.7	33.2	41.2	9.0	82.6	132.7	63.9	93.1	37.4
LSD	ns	ns	ns	36.6		ns	ns	ns	ns		ns	ns	ns	ns	
LSD †	25.3	61.2	54.1	26.8		ns	ns	9.8	5.5		40.9	64.8	39.4	30.6	

ns: nonsignificant at $P = 0.05$ † least significant difference between two sites

gN. A similar observation is made for WT at the B sites where the decrease in gN from rain-shelter to control to irrigation treatment could not entirely compensate for the increase in biomass (except within the low N treatment at site B in 2001) and N uptake increased with increasing water supply. At the A sites, since both, changes in gN and changes in biomass, were not closely linked to changes in WT, results were erratic. In most cases and in particular at site A, N removed by the plants exceeded the amount of applied N fertilizer, in particular in 2001. Within WT, P and K uptake was always higher on high N treatments than on low N treatments (except on control treatment at site B in 2001 for K) and increased from rain-shelter to control and from control to irrigation treatment, with the exception of the high N at treatment at site A in 2001. P and K uptake were significantly higher at the A sites than at the B sites.

Water use efficiency (WUE). Soil water use was initially assumed to be similar for both NT (Jensen and Sletten, 1965; Warder et al., 1963) and thus, soil water monitoring devices were shared between the two NT 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 are considered during a limited period of time, but when estimated for the entire spring and summer growing season and for the rooting zone, differences were relatively small (less than 6 %) and had only little effect on the outcome of the water use efficiency calculation. Thus, the two different approaches in 2000 and in 2001 do no exclude a comparison between the two experimental years.

WUE was around 1.2 kg grain m^{-3} water higher in 2001 than in 2000 (table 17). 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). Within WT, a more efficient use of soil water was observed on the high N treatment every time in which a yield increase occurred compared to the low N treatment. The observation of an increased WUE when yield increase also occurred due to higher N application is consistent with findings in other works (Eck, 1988; Jensen and Sletten, 1965; Warder et al., 1963; Hanks and Tanner, 1952) as a consequence of a strongly increased biomass production.

Between WT, the rain-shelter treatment resulted in the largest WUE at the A sites. Irrigation reduced WUE compared to control at both sites, but to a lesser extent at site B than at site A and thus, the differences in WUE between the two sites were smaller on the irrigation treatment than on the other WT.

Since soil water depletion data suggested a water extraction at the A sites below the 90 cm monitored in this study, the difference in WUE between the two sites, therefore, will certainly

Table 17 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, fertilizer treatments and water supply treatments. Data are based on records from April to July.

	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

† assuming an additional consumption of 35 mm during the spring-summer growing season from layers below 90 cm soil depth

be smaller than presented in table 17. For example, assuming an additional consumption of 35 mm of soil water during the spring growing season at the A sites (Haberle and Svoboda, 2000; Entz et al., 1992), the WUE of site A would be reduced by a mean 0.12 kg grain m^{-3} in 2000 and 0.24 kg grain m^{-3} in 2001.

The comparison of the findings with other works on the effect of water supply on WUE is problematical due to different climatic conditions, soil and timings of drought stress and thus results are conflicting. Withholding irrigation or inducing water stress increased WUE (Singh and Kumar, 1981), but Johnson et al. (1984) reports that withholding water decreased WUE. Heitholt (1989) and Johnson et al. (1987) reported that WUE was greatest under moderate water stress, but decreased if water stress was not imposed or if the stress was severe.

The results of the present study complements findings in other works insofar as it demonstrated that the effect of water supply on WUE is also dependent on water holding capacity of the soil. The sufficient water supply at the site of high plant available soil water during stem elongation and booting resulted in an early and dense cover of vegetation and thus, most of the evapotranspiration was transpiration and not evaporation from the soil surface.

The average soil water use in 2001, on the whole field scale, was similar to the soil water use in 2000, but the difference between the two sites was more important in 2001 (41 mm) than in 2000 (16 mm) (table 17). A higher soil water use on sites of high plant available soil water than on sites of low plant available soil water was also observed by Singh et al. (1975). Highest soil water consumption was on the rain-shelter treatment at the B sites in both experimental years, and at the A site on the rain-shelter treatment in 2000, but on control in 2001. Lowest soil water consumption was always found on the irrigation treatment. Evidently, soil water consumption and the difference between the two sites are underestimated, if considerable water consumption had occurred from layers below 90 cm.

Water use efficiency considerations based on only soil water use diminish the difference between the two sites (except on the rain-shelter treatment), and in 2001, the use of soil water was even more efficient at site B than at site A.

Soil mineral N (N_{min}). N_{min} data are only available for 2001. Table 18 shows the main and interaction effects of site, NT and WT on N_{min}. N_{min} differences at different sampling times can primarily be attributed to site and in many cases also to WT, whereas NT did not produce a significant effect on N_{min}.

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, but a higher soil mineral N was found at site B than at site A, in particular at 31 – 60 cm soil depth (figure 14 and 15).

In the topsoil (0-30 cm), the increase in N_{min} until the middle of June was followed by a decrease until the end of June. Subsequently, N_{min} remained on a relatively low level or further declined at site A, whereas 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

Table 18 Variance ratios (*F*) of the main and interaction effects of site, water supply treatment (WT), and nitrogen fertilizer treatment (NT) on soil mineral N content at two depths.

		0 - 30 cm					**31 - 60 cm**				
source	D.F.	02-Apr	18-May	12-Jun	26-Jun	25-Jul	02-Apr	18-May	12-Jun	26-Jun	25-Jul
site	1	4.49*	21.63**	70.97**	2.41	43.61**	42.93**	7.67*	6.04*	4.28*	15.09**
WT	2	0.72	12.22**	26.02**	6.39**	1.66	0.36	5.25*	5.30*	3.63*	3.66*
site X WT	2	0.4	1.15	4.16*	0.6	1.73	0.15	1.92	1.66	1.71	2.55
NT	1	0.98	0.11	0.31	0.25	0.31	0.37	0.03	0.05	0.09	0.01
site X NT	1	2.69	0.47	3.86	0.02	0.00	0.18	0.03	0.43	0.06	0.09
NT X WT	2	0.10	0.26	3.31	0.37	0.11	0.44	0.08	0.72	0.13	0.34
site X WT X NT	2	0.50	0.98	0.55	0.86	0.13	2.91	0.40	0.02	0.04	0.47
WT / site A	2	1.26	7.35**	6.99**	2.66	0.04	0.07	3.45	1.73	1.08	3.29
NT / site A	1	0.60	0.13	1.33	0.32	2.33	0.63	0.00	0.77	0.94	4.51
(WT X NT) / site A	2	1.44	2.31	4.79	1.86	1.74	1.28	0.59	0.49	0.92	1.40
WT / site B	2	0.40	5.93**	18.87**	3.48	1.73	0.39	3.61	4.13*	2.82	3.10
NT / site B	1	2.01	0.30	2.39	0.04	0.10	0.01	0.03	0.07	0.00	0.01
(WT X NT) / site B	2	0.05	0.08	0.50	0.07	0.08	1.97	0.20	0.35	0.01	0.39

* significant at $P = 0.05$ **significant at $P = 0.01$

were always considerably higher at site B than at site A. Differences between corresponding plots of the two sites appeared to be somewhat more pronounced on the high N treatment than on the low N treatment. Differences between the two sites decreased as the external water supply increased from rain-shelter to control to irrigation. A reduced water supply during stem elongation and booting seems therefore to increase the risk of N leaching, especially on the sites of low plant available soil water. On the rain-sheltered treatments and high N application, maximum differences in N_{min} between the two sites of more than 80 kg N ha^{-1} in the middle of June and more than 90 kg N ha^{-1} at the end of July were found. In the subsoil (31-60 cm) of the control and irrigation treatment, the differences between the two sites were generally less important than in the topsoil, except for the rain-shelter treatment where differences were still considerable. An increase in N_{min} after the end of July at site B, but not at site A, was also observed in the subsoil.

4.4 Conclusion

Between the three factors, i.e. site, precipitation and N fertilization, site is the primary effect that accounts for variability of grain yield while precipitation, and in particular its distribution during the growing season, affects the overall yield level in a given year. Increased N fertilization generally increases yield but in particular on coarse-structured sites, its efficiency

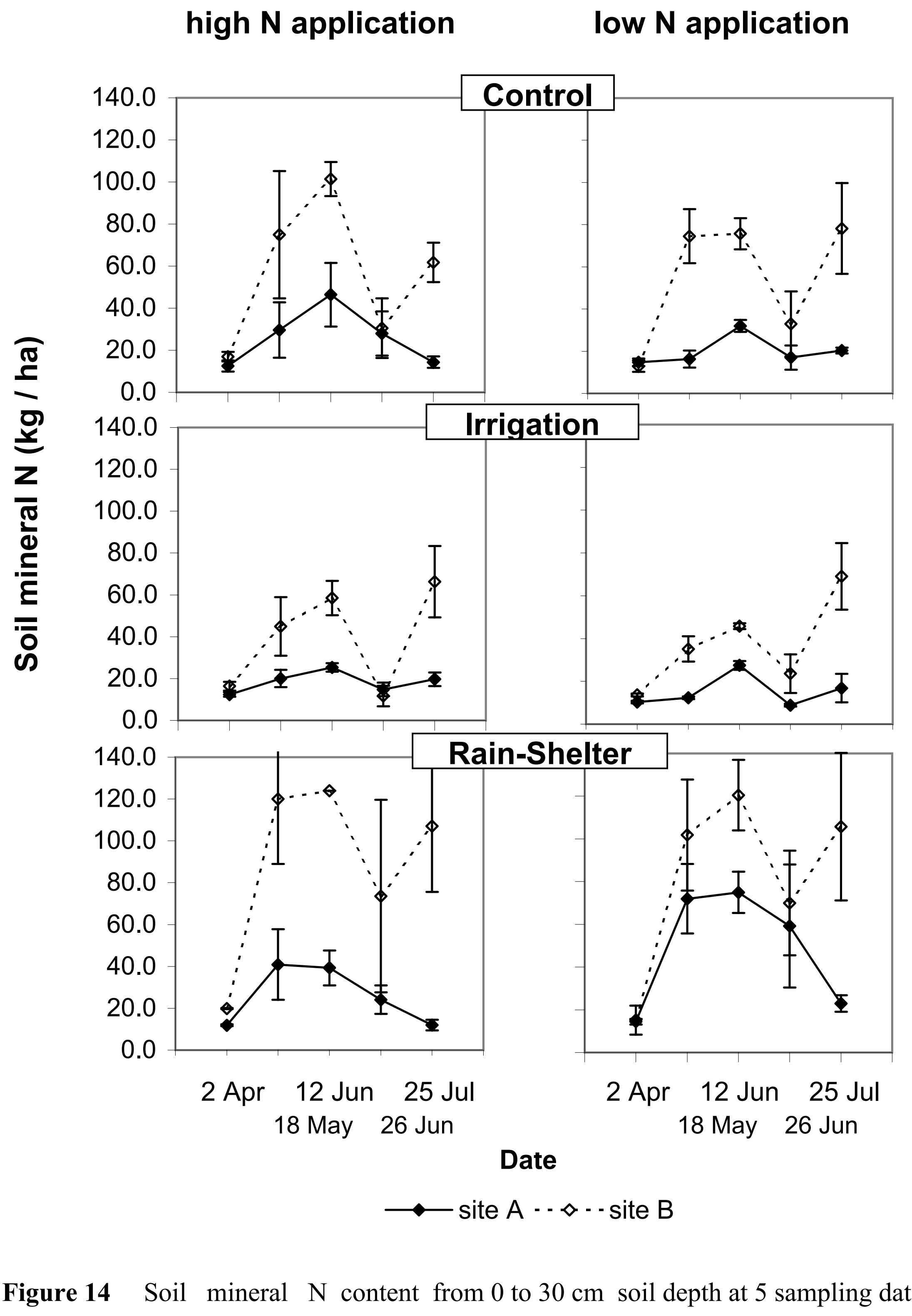

Figure 14 Soil mineral N content from 0 to 30 cm soil depth at 5 sampling dates during spring-summer growing season 2001. N fertilizer was applied on April 4, April 26, May 5 and May 24.

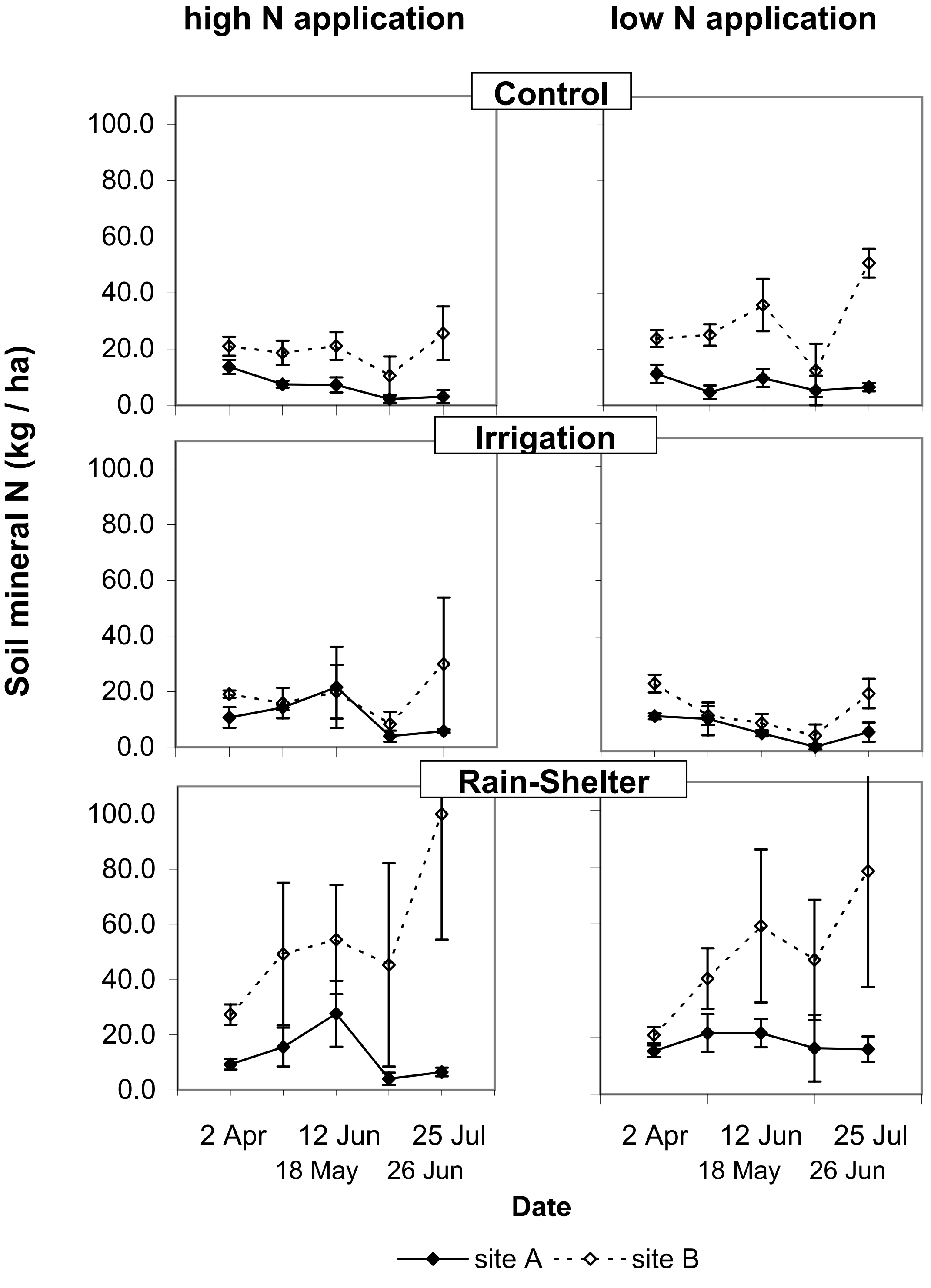

Figure 15 Soil mineral N content from 31 to 60 cm soil depth at 5 sampling dates during spring-summer growing season 2001. N fertilizer was applied on April 4, April 26, May 5 and May 24.

can come to nothing if climatic conditions are unfavourable. Stress during tillering and jointing limits yield potential that is not regained when stress is relieved. However, if stress is prevented until heading by a sufficient precipitation, there is still potential for maximum yields if sufficient precipitation occurs during heading and grain filling. Crop management should consider annual variability of yield in addition to soil conditions and site-specific N fertilization should be adapted to the actual progress of plant growth. A below average water supply (precipitation or irrigation) during tillering and jointing on sites of high plant available soil water may eventually result in higher yield expectation and thus suggest higher N fertilization. On coarse-structured sites, only if rainfall during jointing is considerably above average, an increase in the amount of applied N to obtain higher yield and grain quality on sandy sites may be indicated, but generally decreased N uptake under unfavourable weather conditions, a higher N_{min} content during and after the trial, and a reduced rooting capacity advocate a low-level N fertilization strategy on sites of low plant available soil water. Also, if limited irrigation is to be used in wheat production on sites of low plant available soil water, it can be used more efficiently by preventing stress during tillering and jointing than during heading and grain filling because rainfall records in the area show that the amount of rainfall is more important during June or July than during May.

5 GENERAL DISCUSSION

A typical precision agriculture goal is to divide a field into spatially homogeneous sections that can be managed uniformly. This goal may be difficult to realize because there often appears to be a lack of consistency in the patterns of yield variability from year to year.

In the present study grain yields were significantly related to available water capacity (factor site) for both years but the relationship varies. Thus, variations in seasonal weather can impact relationships between soil water and grain yield.

The magnitude of the impact of precipitation and plant available soil water on grain yield is, however, dependent on climatic and soil conditions and therefore, results from other works are conflicting. In Britain, Weir et al. (1984) who assembled data on winter wheat grown on approximately 1000 fields each year during two years identified soil type as major cause of yield variability. However, no individual soil factor, including plant available soil water, was found to account for the large yearly standard deviation of 20 % of the mean yield. They confirmed suggestions by Gales (1983) that wheat yield in Britain is rarely affected by water stress and that yield loss causing stress only occurs on soils retaining very little moisture and in extremely dry summers. Many other authors found that the amount and in particular the distribution of precipitation is the primary factors determining winter wheat yields (Nielsen and Halvorson, 1991; Eck, 1988; Kirkham and Kanemasu, 1983; Singh, 1981; Schneider et al., 1969; Jensen and Sletten, 1965).

For example, Dirks and Bolton (1981) attributed up to 80 % of the variability in corn yields to monthly precipitation and temperature by means of correlations and regression analysis in a 13-yr field study. Similarly, Asghari and Hanson (1984) developed empirical models to predict corn yields with monthly heat units and precipitation as independent variables. Yamoah et al. (1998) showed that biological windows (an index based on soil temperature and soil moisture that indicates the number of days favourable or detrimental to crop growth) in combination with May air temperature explained more than 80 % of the variability in corn and soybean yields in a 12-yr span

Other works reported that the amount of plant available water had greater influence on the variations in yield than the growing season rainfall (Singh et al., 1975; Read and Warder, 1974; Baier and Robertson, 1968).

The results of the present study have shown that the response of winter wheat to water shortage or abundance and N fertilitization is site-specific, i.e. in the presented case dependent on plant availability of soil water. At the sites of low plant available soil water, reduced water supply between stem elongation and heading as induced by rain-sheltering resulted in considerable grain yield reduction compared to the control plots, 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 the effect produced by reduced water supply on grain yield ranged from moderate yield reduction to yield increase, and, on the irrigation treatment, from very small yield increase to a small yield reduction which was very likely caused by waterlogging.

During the two-year trial, climatic factors and particularly the distribution of precipitation appear to be superimposed on the yield variability due to 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 sandy soils although it occurred during a less critical water demand period. Good soil moisture in early growth stages stimulates however vegetative growth (Bruns and Croy, 1983; Warder et al., 1963), which is important to achieve a high yield potential. A similar effect was reported by Eck (1988).

The importance of sufficient water for the efficient N fertilizer application is already reported in other works (Rhoads, 1984; Black, 1982; Musick and Dusek, 1980; Schneider et al., 1969). Read and Warder (1974) reported that the rainfall during the growing season had a greater influence than stored soil water on the yield of spring wheat grown on unfertilized plots, but the amount of stored soil water had a greater influence on the effect of fertilizer on yield variation than did summer rainfall. But, as has been shown in the present study, the response of grain yield to the application of additional 60 kg N ha^{-1} on grain yield appears also to be dependent on site and water supply, however for different reasons for each site. At the site of high plant available soil water 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}, while in 2000, the potential to increase yield was still considerable, only theoretically however, due to the unfavourable weather conditions. At this site, the highest yield increase in both years was obtained, when 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 aerial conditions. At the site of low plant available soil water, the response of grain yield to the application of additional 60 kg N ha^{-1} underscores the importance of sufficient external water supply for efficient N use at these sites. Yield increases comparable to the sites of high plant available soil water were obtained, when water supply was adequate.

It must also be taken into account that the role of water is not only limited to the time during spring and summer growth as might be concluded from the present study. A number of investigations have been made on the nitrogen relations of crops as affected by rainfall during the preceding winter months and showed a decreasing yield with increasing winter rainfall (Sinclair et al., 1992; Black, 1966).

Lord et al. (1997) inferred from their findings that increased yields were correlated with increased soil water use. The present work has shown that this is only true if we compare different sites whereas within each site, in particular at the sites of low plant available soil water this conclusion cannot always be supported. However in agreement with Lord et al. (1997) it can be concluded from the data of the present study that an increased water use does not necessarily cause an increase in yield. As it has been shown in this study, it is equally possible that coarse soil structure may have restricted the density and depth of rooting into the subsoil, thereby effectively reducing soil water available to the crop. Further research is needed to take into account confounded factors since appropriate management response to variation in yield requires the identification of the true limitation.

The findings suggest that on sites of high plant available soil water a higher N application can be considered when external water supply by precipitation during stem elongation and heading is reduced. At sites of low plant available soil water an increase of N fertilizer may be indicated to increase grain yield but also to meet the German standard requirements for high quality flour when external water supply during stem elongation and heading is above average. When water supply during this period is, however, reduced at the latter site, a further reduction of N application should be considered to avoid N leaching since the rain-shelter treatment in this study resulted in a considerably higher soil mineral N content compared to the other treatments during the trial. Admittedly, there is little room for manoeuvre for the farmer if N is applied at the same times as in this study (i.e. at the beginning of the spring growing season, at the beginning of stem elongation, at the two-node stage and at the beginning of heading). Thus, it is only at the last application that the farmer may reduce or increase the N rate according to the past weather.

A larger above-ground 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, and thereby reducing 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 growth of the vegetative parts of plants, thereby saving a greater proportion of the available water for the stage of grain development. In this regard, one could theoretically increase the efficiency of water use and nitrogen fertilization in production of grain by withholding some of the nitrogen 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 nitrogen fertilizer to the soil so as to be effective under dry conditions that prevail. Black (1966) suggested for such cases to spray nitrogen on plant in form of urea as a means of application might prove satisfactory for the small quantities of nitrogen 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 as in this study occurs. Rainfall records in the area show that, during May, an amount of average monthly rainfall as important as on the irrigation treatment of the present study have never happened and that an amount of average monthly rainfall as little as induced by rain-sheltering occurred only once since 1961.

Also, the prevailing impact of site on yield in this study is certainly due to the choice of sites with regard to significant soil-textural differences. As the soil texture composition becomes similar, the difference between sites will most likely weaken and result into a lack of consistency in the pattern of within-field variability as usually observed (Stafford et al., 1999; Dampney et al., 1997). The effect of plant available soil water on grain yield is also small when the evaporative demand in the growing season is low.

In a recent study on a texturally and topographically heterogeneous field, Machado et al. (2000) found that four major factors i.e. water supply, texture, soil NO_3-N, elevation and diseases evaluated in this study explained 43 – 71 % of the variability in corn grain yields suggesting that there are more variables that influence crop yields under conditions of low evaporative demand.

The present study has shown that evapotranspiration merely based on a total water use balance as presented in this study (precipitation + irrigation – water withheld by rain-sheltering + change in soil water content) is not a good indicator of production, if no further details are given as 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 treatments 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), but grain yield in 2001 was clearly high on all treatments than in 2000. Also, while within each year a higher total water use at the sites of low plant available soil water are concomitant of increased yield, this was not true for the sites of high plant available soil water, where in quite a few cases yield decreased with increasing water supply.

Although only N fertility has been examined in the present study, also other approaches to adjust management practises to heterogeneous plant available soil water conditions can be considered. Variable-rate planting techniques, for example, are being developed and some equipment is already available that adjusts seeding density based on GIS data sets but more experimental results are needed to determine if farmers can produce more from poorer soil areas by reducing planting density. Switching to a wheat variety that is more drought tolerant on areas with low water storage capacities may also result in higher overall grain yields.

On one hand, precision farming has created a critical need for spatial data on crop yield and related soil characteristics. On the other hand soil resource variability is a result of interactions among soil parent material, climate, and local processes possibly much to complex to fully understand and thus the question arises on the necessity of soil mapping for precision farming. Firstly, available soil maps, while a source of helpful data, may not have all information useful for precision agriculture and secondly not at scales necessary to successfully implement the knowledge of soil properties and their relationships in a landscape to take advantage of site-specific management. Also, the production of soil maps are not without cost. In homogeneous fields, soil maps may be redundant and spatial yield variability is rather due to other causes. In heterogeneous fields as in the present study yield variability related to soil hydraulic properties occur in distances as short as 10 m. Acquiring data in two dimensions quickly forces one to confront the squared relation between resolution and cost – doubling the linear resolution requires four times as many samples and becoming cost prohibitive.

Due to complexity of soil and plant relation, modified by climatic and topographic factors, precision management systems can be envisioned that use simple input and output relations such as models that emphasizes on yield maps and weather records corrected by on-the-go information rather than employing theoretical models of cause and effect that are usually only applicable in a well-defined environment.

Crop yield maps contain a wealth of corollary information about spatial variability of soil properties that affect yield. The data for yield maps can be acquired on the ground by appropriate yield monitoring instrumentation or, even more efficiently, by means of remote sensing. The variability revealed by yield mapping results from integration of all the factors responsible for crop growth and development. In addition, yield mapping is, perhaps, the only method that has been available commercially for several years that is able to provide a dense spatial data set at very low cost. Admittedly, examination of sequences of yield maps has revealed not only large variations in yield in a given season but also a lack of consistency in the pattern of variability from season to season within fields. However, crop simulation models that take into account weather variability can help make sense of such data by relating historic yield maps with historic weather records. The latter are split into temporal units creating patterns from seeding to before harvest. This information can be retrieved at any time and be compared with actual weather data. Long-time statistical forecasts are then integrated (some will criticize this model for the unpredictability of weather, but a similar uncertainty is also attached to soil-plant models). 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.

6 SUMMARY

Site-specific agriculture aims at optimising inputs on field and farm level. The approach should benefit the farmer in terms of net return and the environment through lower emission levels. Variations in grain yields are often significantly related to changes in available water capacity within one field but the temporal variation often overrules the spatial variation.

The objective of the present study was to evaluate the impact of varying plant available soil water and precipitation (or irrigation) conditions on yield and various plant characteristics of winter wheat. Knowledge of these variables and of the effect that they have on variations in the response to fertilizer is necessary when planning a fertilizer program.

The two-year trial was conducted in the tertiary foothills of the Bavarian Alps. A completely randomised two-factorial experiment was set up with two different N fertilizer treatments (180 N kg ha^{-1} and 120 N kg ha^{-1}) and three different water supply treatments (stress by rain-sheltering, irrigation, and control, i.e. rain-fed only). The experiment was conducted simultaneously on two sites of different plant available soil water within one field in each experimental year. Soil water content and soil water matric suction were regularly measured in different depths by portable capacitance probes and tensiometers, respectively.

A speedy and cheap method to calibrate Diviner capacitance sensors in heterogeneous fields was developed that highly increased the relation between gravimetrically obtained soil moisture and instrument readings in the trial fields.

At both sites, depletion of plant available soil water was slowed down by irrigation or accelerated by the rain-shelter treatment compared to the control treatment during the application of the water supply treatment. After the water supply treatment was terminated in the beginning of June, the level of depletion reached quickly a similar level on all treatments of each site. A conspicuous difference between the two sites could be recognized in the pattern of depletion of plant available soil water.

The depletion of plant available soil water was similar for both N treatments except for the topsoil at the site of high plant available soil water where a stronger depletion was found on the low N treatment than on the high N treatment.

The important yield increase from 2000 to 2001 on all treatments can readily be explained by the unfavourable distribution of precipitation in 2000. The high N treatment generally yielded more than the low N treatment but the response of grain yield to higher N application appeared to be dependent on site and water supply.

At the sites of high plant available soil water, the differences in grain yield between rain-shelter and irrigation treatment were of a similar order than the grain yield differences due to the application of additional N. At the sites of low plant available soil water, the differences in grain yield between rain-shelter and irrigation treatment were far more important than the average increase caused by a higher N application. The maximum efficiency for each kg of N applied at the sites of high plant available soil water was found on the rain-shelter treatments whereas at sites of low plant available soil water the maximum grain yield increase for each kg of the N increment applied was on the irrigation treatment. The importance of sufficient water supply during vegetative growth at sites of low plant available soil water to maintain a potential for high yield was also demonstrated in this study..

All plant characteristics examined in this study except for N and K concentration in grain were affected by site. Many were also affected by the water supply treatment but only seed weight and N concentration in grain were affected by N fertilization. N removed by the plants exceeded in most cases the amount of applied N fertilizer.

Water use efficiency was higher in 2001 than in 2000. Water was more efficiently used at sites of high plant available soil water than at the sites of low plant available soil water. Within the water supply treatment, a more efficient use of soil water was observed on the high N treatment every time in which a yield increase occurred compared to the low N treatment. The results of the present study also complements findings in other works insofar as they demonstrated that the effect of water supply on water use efficiency is also dependent on the water holding capacity of the soil.

Differences in soil mineral N at the various sampling times could primarily be attributed to site and to the water supply treatment, whereas the N fertilization treatment did not produce a significant effect on soil mineral N. A reduced water supply during stem elongation and booting seems to increase the risk of N leaching at the sites of low plant available soil water.

Soil water matric suction is predominantly affected by site. Variables computed on the basis of average monthly soil water matric suction generally perform better in identifying yield variability than variables based on the average matric suction of the entire spring-summer growing period. The quality and character of correlations between soil water matric suction and yield varied considerably between years which can in part be attributed to yearly rainfall patterns.

In conclusion, between the three factors, i.e. site, water supply (precipitation and irrigation) and N fertilization, site is the primary effect that accounts for variability of grain yield while water supply, and in particular its distribution during the growing season, affects the annual yield level in a given year. Increased N fertilization within the water supply treatment generally increases yield, but in particular on coarse-structured sites, N efficiency can come to nothing if climatic conditions are unfavourable. Stress during tillering and jointing limits yield potential that is not regained when stress is relieved. However, if stress is prevented until heading by a sufficient precipitation, there is still potential for maximum yields even on sites of low plant available soil water if sufficient precipitation occurs during heading and anthesis. A below average water supply during tillering and jointing on sites of high plant available soil water may eventually result in higher yield expectation and thus, may suggest a higher N fertilization. On coarse-structured sites, only if rainfall during tillering and jointing is considerably above average, an increase in the amount of applied N to obtain higher yield and grain quality may be indicated, but generally decreased N uptake, a higher soil mineral N content during and after the trial, and a reduced rooting capacity advocate a low-level N fertilization strategy on sites of low plant available soil water.

7 RESUME

L'agriculture de précision vise à optimiser la gestion des intrants au niveau du champ et de la ferme. De cette approche devrait bénéficier l'agriculteur en termes de revenu et l'environnement par des niveaux d'émission plus bas. La variabilité du rendement du grain dans un seul champ s'explique souvent par une variation du réservoir du sol en eau disponible pour les plantes. Pourtant, la variabilité temporelle du rendement dépasse souvent la variabilité spatiale, et ainsi l'application modulée d'engrais devient très complexe.

L'objectif de cette étude était d'expérimenter les effets de la variation du réservoir en eau disponible dans un champ et de la variabilité des précipitations (ou irrigation) sur la production du blé d'hiver. Une meilleure connaissance de ces variables et de leurs effets sur la variabilité de la productivité est nécessaire pour planifier une application modulée d'engrais.

La présente étude de deux ans fut située dans les collines tertiaires des Alpes bavaroises. L'expérience fut constituée d'un dispositif de deux facteurs complètement randomisé avec deux niveaux d'application d'engrais (180 N kg ha^{-1} et 120 N kg ha^{-1}) et trois niveaux d'apport d'eau (abri-pluies; irrigation; et témoin, c.-à-d. alimenté par pluie seulement). Chaque année l'expérience fut parallèlement conduite sur deux stations d'un champs avec des réservoirs différents en eau disponible. Un suivi de la teneur et de la tension de l'eau du sol fut régulièrement effectué avec une sonde capacitive portable et des tensiomètres. Une méthode rapide et avantageuse de calibrage des sondes capacitives dans des champs hétérogènes fut développée ce qui a fortement amélioré la capacité d'estimation de l'humidité du sol par la sonde capacitive.

L'épuisement du réservoir en eau disponible du sol fut accéléré par les abris-pluies et ralenti par l'irrigation par rapport au traitement témoin sur les deux stations. Peu après la fin de l'application de l'abri et de l'irrigation, le niveau de l'épuisement a rapidement regagné une teneur comparable en eau dans toutes les parcelles au niveau de chaque station. Par contre, une différence significative a pu être observée entre les deux stations. L'épuisement en eau du sol ne fut guère différent entre les deux niveaux d'application d'engrais, à l'exception des 30 premiers centimètres du sol de la station à basse capacité en eau disponible.

Le gain de rendement du blé en 2001 par rapport à 2000 peut être expliqué par une distribution défavorable de la précipitation en 2000. Le rendement du traitement recevant plus d'engrais azoté fut plus élevé que celui du traitement recevant moins d'engrais, mais l'ampleur de l'effet variait en fonction de la station et du niveau d'apport d'eau.

Sur la station disposant d'une haute capacité en eau disponible, l'écart entre les rendements du grain dans les parcelles irriguées et ceux des parcelles sous abri était comparable à l'écart dû à l'application de deux quantités différentes d'engrais azoté, tandis que sur la station présentant une basse capacité en eau disponible l'écart des rendements entre ces deux traitements d'apport d'eau était beaucoup plus important que celui lié à l'application accrue d'azote. La productivité maximale par kilogramme d'azote appliqué se trouvait sur les parcelles sous abri de la station de haute capacité en eau disponible, mais au niveau de la station de basse capacité en eau disponible sur les parcelles irriguées. La présente étude a aussi mis en évidence l'importance d'un ravitaillement adéquat en eau pendant la croissance végétative pour maintenir un potentiel de rendement maximal.

Tous les paramètres examinés dans cette étude, hormis la concentration en azote et en potassium dans les graines, furent influencés de manière significative par la station, et souvent aussi par le niveau d'apport d'eau. Par contre uniquement le poids des graines et la concentration en azote dans les graines furent influencés par le niveau d'application en engrais azoté. Généralement, l'azote enlevé par la récolte excédait la quantité d'engrais azoté appliquée.

Une meilleure efficacité de l'utilisation de l'eau fut trouvée en 2001 qu'en 2000. L'eau a été plus efficacement utilisée à la station disposant d'une haute capacité en eau disponible qu'à la station disposant d'une basse capacité en eau disponible. Dans chacun des traitements d'apport d'eau, on a pu observer une utilisation plus efficace d'eau chaque fois que l'application accrue d'azote engendrait une augmentation du rendement. Les résultats de la présente étude complètent aussi les résultats obtenus dans d'autres études par la mise en évidence d'une modification de l'efficacité de l'utilisation de l'eau lors d'une variation du réservoir en eau disponible.

La variabilité dans la teneur en azote minéral dans le sol a surtout pu être attribuées à la station, et à un moindre degré aux différents traitements d'apport d'eau. Par contre, peu d'effet de la quantité d'azote appliquée a pu être constaté sur l'azote minéral dans le sol. Les résultats indiquent un risque accru de lessivage d'azote sur une station de basse capacité en eau disponible si le ravitaillement en eau entre les stades phénologiques de l'élongation de la tige et le stade de la montaison n'est pas assuré de forme adéquate.

La station fut également la cause principale de la variabilité de la tension de l'eau du sol. Une plus forte corrélation fut constatée entre la variabilité du rendement et des valeurs calculées sur la base des moyennes mensuelles des relevés des tensiomètres, qu'entre la variabilité du rendement et les valeurs calculées sur les données de toute la période de croissance de

printemps et d'été. Toutefois, la qualité et le caractère des corrélations entre la tension de l'eau de sol et le rendement variait considérablement entre les deux années, ce qui peut en partie être attribué à la différence dans la distribution annuelle des précipitations.

En conclusion, dans le cadre de la présente étude, entre les trois variables examinées, c.-à-d. la station, l'apport d'eau (par précipitations ou irrigation) et la fertilisation azotée, c'est la station qui est la première cause de la variabilité du rendement du grain. Par contre, l'apport d'eau, et en particulier sa distribution pendant la saison de croissance, influence le niveau du rendement de l'année. Une fertilisation azotée accrue augmente généralement le rendement du grain, mais, sur des stations à texture grossière, l'effet de la fertilisation peut être neutralisé si les conditions climatiques sont défavorables. Un déficit en eau pendant les stades phénologiques du tallage et de l'élongation de la tige réduit considérablement le potentiel d'un bon rendement qui ne peut plus être compensé par la plante dans les stades ultérieurs. Par contre, si jusqu'à l'épiaison un bon apport d'eau est donné, le potentiel d'un rendement maximal persiste. Ceci peut être réalisé si une précipitation favorable se produit pendant l'épiaison et la fleuraison. Sur une station à texture fine et à haute capacité en eau disponible, l'apport d'eau en dessous de la moyenne pendant le tallage et l'élongation des tiges semble produire un potentiel de rendement plus élevé et par conséquent une augmentation d'engrais azoté peut être prise en considération. Sur une station à texture grossière, l'augmentation de l'application d'engrais azoté pour obtenir une augmentation du rendement et une qualité plus élevée du blé est seulement possible si les précipitations pendant l'élongation de la tige jusqu'à l'épiaison demeurent considérablement au-dessus de la moyenne, mais, généralement, une stratégie d'application réduite d'engrais semble économiquement plus efficace et écologiquement plus appropriée.

8 ZUSAMMENFASSUNG

Ziel teilflächenspezifischer Landwirtschaft ist die Optimierung der Einträge auf Schlag- und Betriebsebene. Dieser Ansatz soll durch höhere Erträge und geringere Austräge sowohl dem Landwirt als auch der Umwelt dienen. Schwankungen im Ertrag stehen häufig in Beziehung zu Änderungen in der pflanzenverfügbaren Wasserkapazität des Bodens, doch sind die zeitlichen Schwankungen häufig bedeutender als die räumlichen.

Ziel der vorliegenden Arbeit war es daher in einem Versuch den variablen Einfluß von pflanzenverfügbarem Wasser und Niederschlag (oder Bewässerung) auf den Ertrag und Mineralstoffgehalte von Winterweizen zu untersuchen. Die Kenntnis dieser Zusammenhänge und ihrer Einflüsse auf die unterschiedliche Wirksamkeit von N-Dünger ist die Voraussetzung für die Planung einer effizienten Düngestrategie.

Der Versuch erstreckte sich über zwei Jahre und wurde im Gebiet des tertiären Hügellandes der bayrischen Voralpen durchgeführt. Ein vollkommen randomisierter zweifaktorieller Versuch mit zwei Düngestufen (120 kg N ha^{-1} und 180 kg N ha^{-1}) und drei Wasserversorgungsstufen (Abdeckung, Bewässerung und Kontrolle, d.h. nur Regen) wurde an zwei Standorten innerhalb eines Schlages mit unterschiedlichen pflanzenverfügbaren Wasserkapazitäten durchgeführt. Der Bodenwassergehalt und die Matrixspannung wurden durch Messungen in verschiedenen Tiefen mit einem tragbaren Sensor (kapazitive Sonde), bzw. mit Tensiometern regelmässig verfolgt.

Eine rasche und kostengünstige Methode zur Kalibrierung des Sensors in heterogenen Feldern wurde entwickelt, die die Beziehung zwischen dem Wassergehalt in gravimetrischen Bodenproben und der von dem Sensor gemessenen Frequenz erheblich verbesserte.

Der Verbrauch des pflanzenverfügbaren Wassers im Boden wurde im Vergleich zur Kontrolle durch Abdeckung gesteigert und durch Bewässerung reduziert, doch schon kurz nach Ende der Anwendung von Bewässerung und Abdeckung erlangte der Vorrat an pflanzenverfügbarem Wasser ein vergleichbares Niveau auf allen Parzellen innerhalb eines Standortes. Zwischen den zwei Standorten bestand allerdings ein offensichtlicher Unterschied in dem Verlauf des Wasserverbrauches während des Beobachtungszeitraumes.

Der Verbrauch an pflanzenverfügbarem Wasser war auf den Parzellen beider Stickstoffstufen ähnlich. Nur im Oberboden des Standortes mit viel pflanzenverfügbarem Wasser wurde ein stärkerer Wasserverbrauch in den Parzellen der niedrigen Stickstoffstufe als in denen der hohen Stickstoffstufe beobachtet.

Der beträchtlich höhere Kornertrag im Jahr 2001 im Vergleich zum Jahr 2000 kann durch die ungünstigere Niederschlagsverteilung im Jahre 2000 erklärt werden. Der Ertrag auf den hoch gedüngten Parzellen war im allgemeinen höher als auf den niedrig gedüngten Parzellen, doch hing die Wirkung letztendlich vom Standort und der Wasserversorgung ab. Auf dem Standort mit viel pflanzenverfügbarem Wasser war der Ertragsunterschied zwischen den bewässerten und den überdachten Parzellen in ähnlicher Größenordnung wie die Steigerung duch die erhöhte Düngung. Auf dem Standort mit wenig pflanzenverfügbarem Wasser war der Unterschied zwischen diesen beiden Wasserversorgungsstufen weitaus größer als die durchschnittliche Ertragszunahme durch höhere Düngung. Die maximale Wirksamkeit pro kg N wurde auf dem Standort mit viel pflanzenverfügbarem Wasser auf den überdachten Parzellen gefunden, während auf dem Standort mit wenig pflanzenverfügbarem Wasser die höchste N-Düngeeffizienz auf den bewässerten Parzellen gemessen wurde. Die Bedeutung die der Wasserversorgung während des vegetativen Wachstums für die Erhaltung eines maximalen Ertragspotentials zukommt wird erörtert.

Mit Ausnahme der N- und K-Konzentration im Korn war bei allen untersuchten Parametern ein signifikanter Unterschied zwischen den Standorten feststellbar. In vielen Fällen wurde ebenso ein Unterschied zwischen den Wasserversorgungsstufen gefunden, doch nur bei Korngewicht und bei der N-Konzentration im Korn waren Unterschiede zwischen den beiden N-Düngestufen zu erkennen. Der N-Entzug durch die Ernte überstieg in den meisten Fällen die gedüngte N-Menge.

Im Jahr 2001 war die Wassernutzungseffizienz höher als im Jahr 2000. Wasser wurde effizienter genutzt auf Standorten mit viel pflanzenverfügbarem Wasser als auf Standorten mit wenig pflanzenverfügbarem Wasser. Die vorliegende Arbeit vervollständigt andere Studien insofern, als sie auch einen Zusammenhang zwischen Wassernutzungseffizienz und der Menge an pflanzenverfügbarem Wasser eines Standortes aufgezeigt.

Unterschiede im N_{min}-Gehalt des Bodens zu verschieden Zeitpunkten der Probeentnahme konnten vor allem dem Faktor Standort zugeordnet werden, doch häufig auch der Wasserversorgung. Die N-Düngungsstufen dagegen zeigten keine signifikant unterschiedliche Wirkung auf den N_{min}- Gehalt. Eine verringerte Wasserversorgung während des Schossens bis zum Ährenschieben scheint die Gefahr der N-Auswaschung auf Standorten mit geringem pflanzenverfügbarem Wasser zu erhöhen.

Die Bodenwasserspannung wurde hauptsächlich durch den Standort beeinflußt. Variablen die über die Saugspannungswerte der einzelnen Monate berechnet wurden waren in der Regel besser geeignet zur Charakterisierung der Ertragsvariabilität innerhalb eines Schlages als Variablen, die auf den Messungen der gesamten Frühjahrs-Sommer-Wachstumsphase beruhten. Die erheblichen Schwankungen in der Qualität und in der Art des Zusammenhangs zwischen Saugspannung und Ertrag konnte auf die unterschiedliche Verteilung des Niederschlags in den Versuchsjahren zurückgeführt werden.

Im Rahmen der in dem Versuch untersuchten Faktoren und Bedingungen scheint folglich der Faktor Standort die wesentliche Ursache für Ertragsschwankungen zu sein, wogegen Niederschlag, und vor allem seine Verteilung, das jährliche Ertragsniveau bestimmt. Eine erhöhte N-Düngung erhöht im allgemeinen den Ertrag, kann aber unter ungünstigen klimatischen Bedingungen, insbesondere auf grobtexturierten Böden, wirkungslos sein. Wasserstress während der Bestockung und des Schossens beschränkt das Ertragspotential, welches später nicht mehr kompensiert werden kann. Ist jedoch eine ausreichende externe Wasserversorgung bis zum Ährenschieben gegeben, bleibt auch auf Standorten mit wenig pflanzenverfügbarem Wasser ein Ertragspotential vorhanden, das bei günstiger Wasserversorgung während des Ährenschiebens und der Blüte in maximale Erträge umgesetzt werden kann. Auf Standorten mit viel pflanzenverfügbarem Wasser kann dagegen eine unterdurchschnittliche Wasserzufuhr während der Bestockung und des Schossens möglicherweise zu erhöhten Erträgen führen und eine erhöhte N-Düngung erscheint dann angebracht. Auf grobtexturierten Böden ist eine erhöhte N-Düngung nur dann sinnvoll, wenn die Wasserzufuhr während der Bestockung und des Schossens weit über dem Durchschnitt liegt, doch spricht auf diesen Standorten in der Regel die im allgemeinen reduzierte N-Aufnahme, ein höherer N_{min}–Gehalt nach dem Versuch und eine geringere Durchwurzelung für eine N-Düngestrategie mit reduzierter N-Menge.

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Annex

A. 1 – A. 8

(All significant correlations of each year between grain yield and variables derived from matric suction measurements based on seasonal or monthly measurements. Variation = considering failed tensiometer readings as matric suction > 800 hPa)

A. 1 Correlations between yield and variables based on matric suction measurements of the entire growing season

2000
ENTIRE GROWING SEASON
both sites (N=50)

grain				straw				biomass			
var	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**
> 400	20	-0.58	<.0001	> 400	20	-0.65	<.0001	> 400	20	-0.62	<.0001
> 500	20	-0.52	0.0001	> 500	20	-0.59	<.0001	> 500	20	-0.56	<.0001
sum	20	-0.47	0.0006	> 300	20	-0.53	<.0001	sum	20	-0.51	0.0002
> 300	20	-0.46	0.0007	sum	20	-0.53	<.0001	> 300	20	-0.50	0.0002
> 100	20	-0.43	0.002	average	20	-0.48	0.0005	> 100	20	-0.46	0.0008
> 600	20	-0.40	0.004	> 100	20	-0.47	0.0007	average	20	-0.44	0.001
average	20	-0.39	0.006	> 600	20	-0.45	0.001	> 600	20	-0.43	0.002
> 400	60	0.38	0.007	> 200	20	-0.41	0.003	> 200	20	-0.39	0.005
> 200	20	-0.37	0.009	> 200	60	0.29	0.04	> 400	60	0.34	0.02
> 200	60	0.37	0.009	> 400	60	0.29	0.04	> 200	60	0.33	0.02
> 300	60	0.37	0.009	> 300	60	0.28	0.05	> 300	60	0.33	0.02
> 500	60	0.33	0.02	miss.	20	0.26	0.07				
median	60	0.32	0.02								
sum	60	0.31	0.03								
average	60	0.31	0.03								
miss.	20	0.29	0.04								

site of high plant available soil water (N=18)

> 600	20	-0.66	0.003	> 600	20	-0.73	0.0005	> 600	20	-0.75	0.0004
> 100	20	-0.63	0.005	> 400	20	-0.70	0.001	> 400	20	-0.66	0.003
average	90	-0.59	0.01	> 500	20	-0.69	0.002	sum	20	-0.66	0.003
miss.	20	0.55	0.02	sum	20	-0.67	0.002	> 100	20	-0.64	0.004
sum	90	-0.55	0.02	average	20	-0.63	0.005	> 500	20	-0.62	0.006
sum	20	-0.55	0.02	median	20	-0.62	0.006	average	90	-0.59	0.01
> 200	90	-0.54	0.02	> 300	20	-0.62	0.007	> 200	20	-0.58	0.01
> 200	20	-0.53	0.02	> 700	20	-0.59	0.01	> 300	20	-0.57	0.01
> 400	20	-0.52	0.03	> 100	20	-0.58	0.01	average	20	-0.56	0.02
> 300	90	-0.52	0.03	> 200	20	-0.56	0.02	sum	90	-0.55	0.02
> 400	90	-0.51	0.03	average	90	-0.53	0.02	> 300	90	-0.53	0.02
> 100	92	-0.50	0.04	sum	90	-0.50	0.04	> 200	90	-0.53	0.03
				> 300	90	-0.49	0.04	> 700	20	-0.52	0.03
								> 400	90	-0.51	0.03
								median	20	-0.47	0.05

site of low plant available soil water (N=32)

> 500	20	-0.86	<.0001	> 400	20	-0.83	<.0001	> 400	20	-0.85	<.0001
> 400	20	-0.84	<.0001	> 500	20	-0.81	<.0001	> 500	20	-0.84	<.0001
average	20	-0.80	<.0001	> 300	20	-0.78	<.0001	average	20	-0.80	<.0001
> 300	20	-0.80	<.0001	average	20	-0.78	<.0001	> 300	20	-0.80	<.0001
sum	20	-0.76	<.0001	sum	20	-0.74	<.0001	sum	20	-0.76	<.0001
> 100	20	-0.68	<.0001	> 100	20	-0.69	<.0001	> 100	20	-0.70	<.0001
> 600	20	-0.65	<.0001	> 200	20	-0.62	0.0001	> 600	20	-0.64	<.0001
> 200	20	-0.63	0.0001	> 600	20	-0.61	0.0002	> 200	20	-0.63	<.0001
median	20	-0.62	0.0001	median	20	-0.57	0.0006	median	20	-0.60	0.0002
average	60	-0.50	0.004	average	60	-0.50	0.004	average	60	-0.50	0.003
> 100	60	-0.49	0.005	sum	60	-0.48	0.005	sum	60	-0.49	0.005
sum	60	-0.48	0.006	median	60	-0.45	0.009	> 100	60	-0.47	0.006
median	60	-0.45	0.01	> 100	60	-0.44	0.01	median	60	-0.46	0.009

A. 2 Correlations between yield and variables based on matric suction measurements of the entire growing season. Variation = considering failed tensiometer readings as matric suction > 800 hPa .

2000
ENTIRE GROWING SEASON
-- variation --
both sites (N=50)

grain				straw				biomass			
var	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**
sum	20	-0.47	0.0006	sum	20	-0.53	<.0001	sum	20	-0.51	0.0002
average	20	-0.39	0.006	average	20	-0.48	0.0005	average	20	-0.44	0.001
> 400	60	0.38	0.007	> 400	20	-0.36	0.009	> 400	60	0.34	0.02
> 200	60	0.37	0.009	> 500	20	-0.31	0.03	> 200	60	0.33	0.02
> 300	60	0.37	0.009	> 300	20	-0.30	0.04	> 400	20	-0.33	0.02
> 500	60	0.33	0.02	> 200	60	0.29	0.04	> 300	60	0.33	0.02
median	60	0.32	0.02	> 400	60	0.29	0.04				
sum	60	0.31	0.03	> 300	60	0.28	0.05				
> 700	20	0.31	0.03								
average	60	0.31	0.03								
> 800	20	0.29	0.04								
miss.	20	0.29	0.04								
> 400	20	-0.28	0.05								
site of high plant available soil water (N=18)											
average	90	-0.59	0.01	sum	20	-0.67	0.002	sum	20	-0.66	0.003
> 800	20	0.55	0.02	average	20	-0.63	0.005	average	90	-0.59	0.01
miss.	20	0.55	0.02	median	20	-0.62	0.006	average	20	-0.56	0.02
sum	90	-0.55	0.02	average	90	-0.53	0.02	sum	90	-0.55	0.02
sum	20	-0.55	0.02	sum	90	-0.50	0.04	> 300	90	-0.53	0.02
> 200	20	-0.54	0.02	> 300	90	-0.49	0.04	> 200	20	-0.53	0.03
> 300	90	-0.52	0.03					> 400	90	-0.51	0.03
> 400	90	-0.51	0.03					median	20	-0.47	0.05
> 100	90	-0.50	0.04								
site of low plant available soil water (N=32)											
average	20	-0.80	<.0001	average	20	-0.78	<.0001	average	20	-0.80	<.0001
> 500	20	-0.77	<.0001	sum	20	-0.74	<.0001	sum	20	-0.76	<.0001
sum	20	-0.76	<.0001	> 300	20	-0.72	<.0001	> 500	20	-0.75	<.0001
> 300	20	-0.75	<.0001	> 500	20	-0.71	<.0001	> 300	20	-0.74	<.0001
> 400	20	-0.73	<.0001	> 400	20	-0.70	<.0001	> 400	20	-0.72	<.0001
> 100	20	-0.69	<.0001	> 100	20	-0.69	<.0001	> 100	20	-0.70	<.0001
median	20	-0.62	0.0001	> 200	20	-0.58	0.0005	median	20	-0.60	0.0002
> 600	60	-0.61	0.0002	median	20	-0.57	0.0006	> 200	20	-0.60	0.0003
> 200	20	-0.60	0.0003	> 600	60	-0.55	0.001	> 600	60	-0.59	0.0004
average	60	-0.50	0.004	average	60	-0.50	0.004	average	60	-0.50	0.003
> 100	60	-0.49	0.005	sum	60	-0.48	0.005	sum	60	-0.49	0.005
sum	60	-0.48	0.006	median	60	-0.45	0.009	> 100	60	-0.47	0.006
median	60	-0.45	0.01	> 100	60	-0.44	0.01	median	60	-0.46	0.009

A. 3 Correlations between yield and variables based on matric suction measurements of each month (April - July)

							2000 MONTHLY both sites (N=50)							
		grain					straw					biomass		
var	depth	month	R	P	var	depth	month	R	P	var	depth	month	R	P
> 400	20	June	-0.69	<.0001	> 400	20	June	-0.72	<.0001	> 400	20	June	-0.72	<.0001
> 300	20	June	-0.62	<.0001	> 300	20	June	-0.66	<.0001	> 300	20	June	-0.65	<.0001
> 500	20	June	-0.62	<.0001	> 400	20	May	-0.65	<.0001	> 500	20	June	-0.63	<.0001
> 400	20	May	-0.58	<.0001	> 500	20	June	-0.62	<.0001	> 400	20	May	-0.63	<.0001
sum	20	June	-0.53	<.0001	> 100	20	May	-0.57	<.0001	median	20	May	-0.55	<.0001
median	20	May	-0.52	0.0001	average	20	May	-0.57	<.0001	sum	20	June	-0.55	<.0001
> 100	20	May	-0.50	0.0002	median	20	May	-0.56	<.0001	> 100	20	May	-0.54	<.0001
average	20	May	-0.50	0.0002	> 300	20	May	-0.56	<.0001	average	20	May	-0.54	<.0001
> 500	20	May	-0.49	0.0003	> 500	20	May	-0.55	<.0001	> 300	20	May	-0.53	<.0001
> 300	20	May	-0.49	0.0004	sum	20	June	-0.54	<.0001	> 500	20	May	-0.53	<.0001
sum	20	May	-0.47	0.0006	sum	20	May	-0.54	<.0001	sum	20	May	-0.51	0.0001
> 200	20	June	-0.43	0.002	> 200	20	May	-0.48	0.0004	> 200	20	May	-0.45	0.001
> 600	60	June	-0.41	0.003	median	20	June	-0.46	0.0008	median	20	June	-0.43	0.002
> 200	20	May	-0.41	0.003	> 600	60	June	-0.42	0.002	> 600	60	June	-0.42	0.002
median	20	June	-0.38	0.007	> 200	20	June	-0.40	0.004	> 200	20	June	-0.42	0.002
> 400	60	July	0.38	0.007	average	20	June	-0.39	0.006	> 200	60	June	0.34	0.02
> 200	60	June	0.36	0.01	> 600	60	May	-0.36	0.01	> 600	60	May	-0.34	0.02
> 300	60	June	0.36	0.01	> 200	60	June	0.31	0.03	> 400	60	July	0.34	0.02
> 400	20	July	0.36	0.01	> 400	20	July	0.30	0.03	average	20	June	-0.33	0.02
> 400	60	June	0.36	0.01	> 300	60	June	0.30	0.04	> 400	20	July	0.33	0.02
> 500	60	July	0.35	0.01	> 400	60	July	0.29	0.04	> 300	60	June	0.33	0.02
> 200	60	May	0.35	0.01	miss.	20	July	0.29	0.04	> 400	60	June	0.32	0.02
> 300	60	July	0.35	0.01	> 300	20	July	0.29	0.04	> 300	60	July	0.31	0.03
> 200	60	July	0.35	0.01						> 200	60	July	0.31	0.03
> 500	60	June	0.34	0.02						miss.	20	July	0.31	0.03
median	60	July	0.32	0.02						> 200	60	May	0.31	0.03
sum	60	June	0.32	0.02						> 500	60	June	0.30	0.03
> 100	60	May	0.32	0.02						> 300	20	July	0.30	0.03
miss.	20	July	0.31	0.03						median	60	July	0.30	0.04
> 500	20	July	0.31	0.03						> 500	60	July	0.29	0.04
> 600	60	May	-0.31	0.03						sum	60	June	0.29	0.04
> 300	60	May	0.31	0.03						> 100	60	May	0.28	0.05

A. 3 cont.

2000 MONTHLY both sites (N=50)														
		grain					straw					biomass		
var	depth	month	R	P	var	depth	month	R	P	var	depth	month	R	P
median	60	June	0.31	0.04						> 500	20	July	0.28	0.05
> 300	20	July	0.30	0.03										
average	60	June	0.30	0.04										
miss.	20	June	0.29	0.04										
> 600	60	June	0.29	0.04										
average	60	July	0.29	0.04										
sum	60	July	0.29	0.04										
> 400	60	May	0.28	0.05										

A. 3 cont.

2000
MONTHLY
site of high plant available soil water (N=18)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
> 600	60	June	-0.78	0.0001	> 400	20	June	-0.82	<.0001	> 400	20	June	-0.84	<.0001
> 400	20	June	-0.75	0.0004	> 500	20	June	-0.82	<.0001	> 500	20	June	-0.84	<.0001
> 500	20	June	-0.75	0.0004	> 300	20	June	-0.72	0.0008	> 600	60	June	-0.77	0.0002
sum	20	June	-0.74	0.0005	> 400	20	May	-0.71	0.001	sum	20	June	-0.76	0.0003
> 100	20	June	-0.65	0.004	sum	20	June	-0.70	0.001	> 300	20	June	-0.73	0.0006
median	90	June	-0.65	0.004	> 600	60	May	-0.69	0.002	> 600	60	May	-0.67	0.002
> 300	20	June	-0.64	0.004	> 600	60	June	-0.68	0.002	> 400	20	May	-0.66	0.003
> 700	20	June	-0.63	0.01	sum	20	May	-0.68	0.002	> 700	20	June	-0.65	0.003
> 400	90	June	-0.62	0.01	> 200	20	May	-0.68	0.002	average	90	July	-0.65	0.004
average	90	May	-0.61	0.01	median	20	June	-0.67	0.004	> 200	20	May	-0.64	0.004
median	20	April	0.60	0.01	> 500	20	May	-0.65	0.003	median	90	July	-0.64	0.004
average	20	April	0.60	0.01	> 100	20	May	-0.65	0.004	median	90	June	-0.64	0.005
sum	20	April	0.60	0.01	average	20	June	-0.65	0.01	> 100	20	May	-0.63	0.005
average	90	June	-0.59	0.01	average	90	July	-0.63	0.005	sum	20	May	-0.62	0.006
average	90	July	-0.58	0.01	median	90	July	-0.62	0.01	> 500	60	May	-0.62	0.006
median	90	July	-0.58	0.01	> 300	20	May	-0.61	0.01	> 100	20	June	-0.59	0.01
> 200	20	June	-0.58	0.01	median	20	May	-0.61	0.01	> 400	90	June	-0.59	0.01
> 300	90	June	-0.57	0.01	> 700	20	June	-0.60	0.01	average	90	June	-0.59	0.01
sum	90	May	-0.57	0.01	> 500	60	May	-0.60	0.01	sum	90	June	-0.58	0.01
sum	90	June	-0.57	0.01	average	20	May	-0.60	0.01	> 500	20	May	-0.58	0.01
> 500	60	May	-0.56	0.02	median	90	June	-0.56	0.02	median	20	June	-0.57	0.02
> 600	60	May	-0.56	0.02	sum	90	June	-0.53	0.02	> 200	20	June	-0.56	0.02
median	90	May	-0.54	0.02	average	60	May	-0.53	0.03	> 300	90	June	-0.55	0.02
> 200	20	July	-0.52	0.03	average	90	June	-0.52	0.03	average	90	May	-0.55	0.02
> 100	90	June	-0.52	0.03	> 400	90	June	-0.51	0.03	median	20	May	-0.55	0.02
> 100	20	May	-0.52	0.03	sum	600	May	-0.50	0.03	average	20	June	-0.54	0.03
miss.	20	June	0.52	0.03	> 100	20	June	-0.49	0.04	> 300	20	May	-0.53	0.02
> 200	20	May	-0.51	0.03	> 200	20	June	-0.49	0.04	average	20	May	-0.52	0.03
> 100	20	May	-0.51	0.03	> 700	20	May	-0.48	0.04	> 100	90	June	-0.52	0.03
> 400	20	May	-0.50	0.03	> 300	90	June	-0.48	0.04	sum	90	May	-0.52	0.03
> 600	60	May	-0.48	0.05	miss.	90	July	-0.47	0.05	> 200	20	July	-0.51	0.03
					> 100	90	June	-0.47	0.05	> 600	60	May	-0.50	0.04

A.3 cont.

2000

MONTHLY

site of high plant available soil water (N=18)

grain					straw					biomass				
var	depth	month	R	P	var	depth	month	R	P	var	depth	month	R	P
										average	60	May	-0.49	0.04
										> 300	90	July	-0.49	0.04
										median	90	May	-0.49	0.04

site of low plant available soil water (N=32)

grain					straw					biomass				
var	depth	month	R	P	var	depth	month	R	P	var	depth	month	R	P
median	20	May	-0.88	<.0001	> 300	20	May	-0.84	<.0001	median	20	May	-0.87	<.0001
> 300	20	May	-0.86	<.0001	average	20	May	-0.84	<.0001	> 300	20	May	-0.86	<.0001
average	20	May	-0.85	<.0001	median	20	May	-0.83	<.0001	average	20	May	-0.86	<.0001
> 400	20	May	-0.85	<.0001	> 400	20	May	-0.82	<.0001	> 400	20	May	-0.84	<.0001
> 500	20	May	-0.81	<.0001	sum	20	May	-0.78	<.0001	> 500	20	May	-0.81	<.0001
sum	20	May	-0.80	<.0001	> 500	20	May	-0.78	<.0001	sum	20	May	-0.80	<.0001
> 200	20	May	-0.73	<.0001	> 100	20	May	-0.74	<.0001	> 100	20	May	-0.75	<.0001
> 100	20	May	-0.73	<.0001	> 200	20	May	-0.73	<.0001	> 200	20	May	-0.74	<.0001
median	20	June	-0.70	<.0001	median	20	June	-0.65	<.0001	median	20	June	-0.68	<.0001
> 400	20	June	-0.66	<.0001	> 400	20	June	-0.64	<.0001	> 400	20	June	-0.66	<.0001
> 300	20	June	-0.66	<.0001	> 300	20	June	-0.64	<.0001	> 300	20	June	-0.66	<.0001
average	20	June	-0.65	<.0001	average	20	June	-0.63	0.0001	average	20	June	-0.65	<.0001
> 500	20	June	-0.60	0.0003	> 600	60	May	-0.54	0.002	> 500	20	June	-0.57	0.0006
> 600	60	May	-0.59	0.0004	> 500	20	June	-0.53	0.002	> 600	60	May	-0.57	0.0007
sum	20	June	-0.56	0.0008	sum	20	June	-0.53	0.002	sum	20	June	-0.55	0.001
average	60	July	-0.55	0.001	average	60	July	-0.53	0.002	average	60	July	-0.55	0.001
median	60	June	-0.55	0.002	median	60	June	-0.53	0.003	median	60	June	-0.55	0.002
sum	60	July	-0.54	0.002	sum	60	July	-0.52	0.002	sum	60	July	-0.54	0.002
average	60	June	-0.52	0.003	average	60	June	-0.50	0.005	average	60	June	-0.52	0.003
> 200	20	June	-0.51	0.003	median	60	July	-0.48	0.005	median	60	July	-0.50	0.004
median	60	July	-0.50	0.004	> 200	20	June	-0.47	0.006	> 200	20	June	-0.50	0.004
> 100	60	June	-0.47	0.006	sum	60	May	-0.47	0.007	sum	60	May	-0.47	0.007
sum	60	May	-0.46	0.008	average	60	May	-0.47	0.007	average	60	May	-0.47	0.007
average	60	May	-0.46	0.008	> 100	20	June	-0.46	0.008	> 100	20	June	-0.47	0.007
> 100	20	June	-0.46	0.008	median	60	May	-0.43	0.01	> 100	60	June	-0.45	0.009
median	60	May	-0.41	0.02	> 100	60	June	-0.42	0.02	median	60	May	-0.42	0.02
> 600	60	June	-0.38	0.03	miss.	20	July	0.40	0.02	> 600	60	June	-0.39	0.03
sum	60	June	-0.36	0.04	> 600	60	June	-0.38	0.03	sum	60	June	-0.38	0.03
> 100	60	July	-0.36	0.05	sum	60	June	-0.38	0.03	> 100	20	July	-0.37	0.04
> 100	60	May	-0.35	0.05	> 100	20	July	-0.38	0.03	miss.	20	July	0.36	0.04

A. 4 Correlations between yield and variables based on matric suction measurements of each month (April - July)
Variation = considering failed tensiometer readings as matric suction > 800 hPa .

2000
MONTHLY
-- variation --
both sites (N=50)

		grain					**straw**					**biomass**		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
> 300	20	July	0.54	<.0001	> 100	20	May	-0.58	<.0001	> 100	20	May	-0.56	<.0001
sum	20	June	-0.53	<.0001	> 400	20	May	-0.57	<.0001	> 400	20	May	-0.56	<.0001
> 400	20	May	-0.52	0.0001	average	20	May	-0.57	<.0001	median	20	May	-0.55	<.0001
median	20	May	-0.52	0.0001	median	20	May	-0.56	<.0001	sum	20	June	-0.55	<.0001
> 100	20	May	-0.52	0.0001	sum	20	June	-0.54	<.0001	average	20	May	-0.54	<.0001
average	20	May	-0.50	0.0002	sum	20	May	-0.54	<.0001	> 300	20	July	0.53	<.0001
> 400	20	July	0.49	0.000	> 300	20	July	0.51	0.000	sum	20	May	-0.51	0.0001
sum	20	May	-0.47	0.001	> 300	20	May	-0.51	0.000	> 300	20	May	-0.48	0.0004
> 200	20	July	0.44	0.001	> 500	20	May	-0.47	0.001	> 400	20	July	0.47	0.0005
> 300	20	May	-0.44	0.001	median	20	June	-0.46	0.001	> 500	20	May	-0.45	0.0009
> 500	20	July	0.42	0.002	> 200	20	May	-0.44	0.001	> 200	20	July	0.44	0.002
> 500	20	May	-0.42	0.003	> 400	20	July	0.44	0.001	median	20	June	-0.43	0.002
median	20	June	-0.38	0.01	> 200	20	July	0.42	0.003	> 200	20	May	-0.42	0.003
> 200	20	May	-0.38	0.01	average	20	June	-0.39	0.006	> 500	20	July	0.40	0.004
> 400	60	July	0.38	0.01	> 500	20	July	0.37	0.008	> 200	60	June	0.34	0.02
> 200	60	June	0.36	0.01	> 400	20	June	-0.37	0.008	> 400	60	July	0.34	0.02
> 300	60	June	0.36	0.01	> 300	20	June	-0.32	0.03	average	20	June	-0.33	0.02
> 400	60	June	0.36	0.01	> 200	60	June	0.31	0.03	> 300	60	June	0.33	0.02
> 500	60	July	0.35	0.01	> 500	20	June	-0.30	0.04	> 400	20	June	-0.33	0.02
> 200	60	May	0.35	0.01	> 300	60	June	0.30	0.04	> 400	60	June	0.32	0.02
> 200	60	July	0.35	0.01	> 400	60	July	0.29	0.04	> 600	20	July	0.31	0.03
> 300	60	July	0.35	0.01	> 600	20	July	0.29	0.04	> 300	60	July	0.31	0.03
> 500	60	June	0.34	0.02	> 800	20	July	0.29	0.04	> 200	60	July	0.31	0.03
> 700	20	June	0.33	0.02	> 700	20	July	0.29	0.04	> 800	20	July	0.31	0.03
> 600	20	July	0.33	0.02	miss.	20	July	0.29	0.04	> 700	20	July	0.31	0.03
median	60	July	0.32	0.02						miss.	20	July	0.31	0.03
sum	60	June	0.32	0.02						> 200	60	May	0.31	0.03
> 100	60	May	0.32	0.02						> 500	60	June	0.30	0.03
> 700	20	July	0.31	0.03						median	60	July	0.30	0.04
> 800	20	July	0.31	0.03						> 500	60	July	0.29	0.04
miss.	20	July	0.31	0.03						> 700	20	June	0.29	0.04
> 300	60	May	0.31	0.03						sum	60	June	0.29	0.04
median	60	June	0.31	0.04						> 100	60	May	0.28	0.05
average	60	June	0.30	0.04										
miss.	20	June	0.29	0.04										
> 800	20	June	0.29	0.04										

A. 4 cont.

2000
MONTHLY
-- variation --
both sites (N=50)

		grain					**straw**					**biomass**		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
> 600	60	June	0.29	0.04										
average	60	July	0.29	0.04										
sum	60	July	0.29	0.04										
> 400	60	May	0.28	0.05										
							site of high plant available soil water (N=18)							
sum	20	June	-0.74	0.0005	sum	20	June	-0.70	0.001	sum	20	June	-0.76	0.0003
median	90	June	-0.65	0.004	sum	20	May	-0.68	0.002	average	90	July	-0.65	0.004
> 400	90	June	-0.62	0.006	median	20	June	-0.67	0.004	median	90	July	-0.64	0.004
average	90	May	-0.61	0.007	average	20	June	-0.65	0.005	median	90	June	-0.64	0.005
median	20	April	0.60	0.009	average	90	July	-0.63	0.005	sum	20	May	-0.62	0.006
average	20	April	0.60	0.009	median	90	July	-0.62	0.006	> 500	60	May	-0.62	0.006
sum	20	April	0.60	0.009	median	20	May	-0.61	0.007	> 400	90	June	-0.59	0.01
average	90	June	-0.59	0.01	> 500	60	May	-0.60	0.009	average	90	June	-0.59	0.01
average	90	July	-0.58	0.01	average	20	May	-0.60	0.009	sum	90	June	-0.58	0.01
median	90	July	-0.58	0.01	median	90	June	-0.56	0.02	median	20	June	-0.57	0.02
> 200	90	June	-0.58	0.01	sum	90	June	-0.53	0.02	> 200	90	June	-0.56	0.02
> 300	90	June	-0.57	0.01	average	60	May	-0.53	0.03	> 300	90	June	-0.55	0.02
sum	90	May	-0.57	0.01	average	90	June	-0.52	0.03	average	90	May	-0.55	0.02
sum	90	June	-0.57	0.01	> 400	90	June	-0.51	0.03	median	20	May	-0.55	0.02
> 500	60	May	-0.56	0.02	sum	60	May	-0.50	0.03	average	20	June	-0.54	0.03
median	90	May	-0.54	0.02	> 200	90	June	-0.49	0.04	average	20	May	-0.52	0.03
> 200	90	July	-0.52	0.03	> 300	90	June	-0.48	0.04	> 100	90	June	-0.52	0.03
> 100	90	June	-0.52	0.03	miss.	90	July	-0.47	0.05	sum	90	May	-0.52	0.03
> 800	20	June	0.52	0.03	> 100	90	June	-0.47	0.05	> 200	90	July	-0.51	0.03
miss.	20	June	0.52	0.03						> 600	60	May	-0.50	0.04
> 100	90	May	-0.51	0.03						average	60	May	-0.49	0.04
> 300	20	July	0.50	0.04						> 300	90	July	-0.49	0.04
> 600	60	May	-0.48	0.05						median	90	May	-0.49	0.04

A. 4 cont.

2000
MONTHLY
-- variation --
site of low plant available soil water (N=32)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
median	20	May	-0.88	<.0001	> 100	20	May	-0.86	<.0001	> 300	20	May	-0.87	<.0001
> 300	20	May	-0.86	<.0001	> 300	20	May	-0.86	<.0001	median	20	May	-0.87	<.0001
average	20	May	-0.85	<.0001	average	20	May	-0.84	<.0001	> 100	20	May	-0.86	<.0001
> 400	20	May	-0.84	<.0001	median	20	May	-0.83	<.0001	average	20	May	-0.86	<.0001
> 100	20	May	-0.83	<.0001	> 400	20	May	-0.82	<.0001	> 400	20	May	-0.84	<.0001
sum	20	May	-0.80	<.0001	> 200	20	May	-0.79	<.0001	> 500	20	May	-0.80	<.0001
> 500	20	May	-0.80	<.0001	> 500	20	May	-0.78	<.0001	sum	20	May	-0.80	<.0001
> 200	20	May	-0.78	<.0001	sum	20	May	-0.78	<.0001	> 200	20	May	-0.79	<.0001
median	20	June	-0.70	<.0001	> 400	20	June	-0.66	<.0001	median	20	June	-0.68	<.0001
> 400	20	June	-0.67	<.0001	> 300	20	June	-0.66	<.0001	> 400	20	June	-0.68	<.0001
> 300	20	June	-0.67	<.0001	median	20	June	-0.65	<.0001	> 300	20	June	-0.68	<.0001
average	20	June	-0.65	<.0001	average	20	June	-0.63	0.0001	average	20	June	-0.65	<.0001
> 600	20	May	-0.65	<.0001	> 600	20	May	-0.61	0.0002	> 600	20	May	-0.64	<.0001
> 500	20	June	-0.63	0.0001	> 500	20	June	-0.58	0.0005	> 500	20	June	-0.61	0.0002
sum	20	June	-0.56	0.0008	> 100	20	June	-0.55	0.001	sum	20	June	-0.55	0.001
average	60	July	-0.55	0.001	sum	20	June	-0.53	0.002	average	60	July	-0.55	0.001
median	60	June	-0.55	0.002	average	60	July	-0.53	0.002	> 100	20	June	-0.55	0.001
sum	60	July	-0.54	0.002	median	60	June	-0.53	0.003	median	60	June	-0.55	0.002
> 100	20	June	-0.53	0.002	sum	60	July	-0.52	0.002	sum	60	July	-0.54	0.002
> 200	20	June	-0.53	0.002	> 200	20	June	-0.52	0.003	> 200	20	June	-0.53	0.002
average	60	June	-0.52	0.003	average	60	June	-0.50	0.005	average	60	June	-0.52	0.003
median	60	July	-0.50	0.004	median	60	July	-0.48	0.005	median	60	July	-0.50	0.004
> 100	60	June	-0.47	0.006	sum	60	May	-0.47	0.007	sum	60	May	-0.47	0.007
sum	60	May	-0.46	0.008	average	60	May	-0.47	0.007	average	60	May	-0.47	0.007
average	60	May	-0.46	0.008	> 400	20	July	0.45	0.009	> 100	60	June	-0.45	0.009
> 600	20	June	-0.44	0.01	> 600	20	June	-0.45	0.01	> 600	20	June	-0.45	0.01
median	60	May	-0.41	0.02	> 300	20	July	0.44	0.01	> 400	20	July	0.43	0.01
> 400	20	July	0.40	0.02	median	60	May	-0.43	0.01	median	60	May	-0.42	0.02
> 300	20	July	0.38	0.03	> 100	60	June	-0.42	0.02	> 300	20	July	0.41	0.02
sum	60	June	-0.36	0.04	> 200	20	July	0.41	0.02	> 200	20	July	0.39	0.03
> 100	60	July	-0.36	0.05	miss.	20	July	0.40	0.02	sum	60	June	-0.38	0.03
> 100	60	May	-0.35	0.05	> 800	20	July	0.40	0.02	miss.	20	July	0.36	0.04
					> 700	20	July	0.40	0.02	> 700	20	July	0.36	0.04
					> 500	20	July	0.40	0.02	> 800	20	July	0.36	0.04
					> 600	20	July	0.40	0.02	> 600	20	July	0.36	0.04
					sum	60	June	-0.38	0.03	> 500	20	July	0.36	0.04
										> 100	60	July	-0.35	0.05

A. 5 Correlations between yield and variables based on matric suction measurements of the entire growing season

2001
ENTIRE GROWING SEASON
both sites (N=36)

grain				straw				biomass			
var	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**
> 100	90	0.49	0.002	> 100	90	0.51	0.001	> 100	90	0.51	0.001
> 200	60	0.47	0.004	> 200	90	0.41	0.01	> 200	90	0.43	0.008
> 300	60	0.47	0.004	> 300	60	0.39	0.02	> 300	60	0.43	0.009
> 200	90	0.45	0.006	> 200	60	0.38	0.02	> 200	60	0.42	0.01
> 400	60	0.44	0.008	> 400	60	0.37	0.03	> 400	60	0.40	0.02
average	60	0.39	0.02	sum	90	0.36	0.03	sum	90	0.37	0.02
sum	60	0.38	0.02	average	90	0.35	0.04	average	90	0.37	0.03
sum	90	0.38	0.02	> 300	90	0.33	0.05	average	60	0.36	0.03
> 100	60	0.38	0.02	average	60	0.33	0.05	sum	60	0.35	0.04
average	90	0.38	0.02	miss.	60	0.32	0.05	> 300	90	0.35	0.04
> 300	90	0.36	0.03	sum	60	0.32	0.06	> 100	60	0.34	0.04
> 500	60	0.33	0.05	> 500	60	0.32	0.06	> 500	60	0.33	0.05
> 400	90	0.31	0.06	> 100	60	0.31	0.07	miss.	60	0.31	0.07
miss.	20	0.29	0.08	> 400	90	0.29	0.08	> 400	90	0.31	0.07
site of high plant available soil water (N=18)											
> 700	90	-0.53	0.02	> 100	20	-0.58	0.01	> 100	20	-0.63	0.01
> 100	20	-0.52	0.03	median	20	-0.52	0.03	median	20	-0.53	0.02
> 500	20	-0.49	0.04	> 400	60	-0.47	0.05				
				> 100	60	-0.47	0.05				
site of low plant available soil water (N=18)											
miss.	90	-0.51	0.03	miss.	90	-0.53	0.02	miss.	90	-0.52988	0.02

A. 6 Correlations between yield and variables based on matric suction measurements of the entire growing season. Variation = considering failed tensiometer readings as matric suction > 800 hPa .

2001
ENTIRE GROWING SEASON
-- variation --
both sites (N=36)

grain				**straw**				**biomass**			
var	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**	**var**	**depth**	**R**	**P**
> 100	90	0.49	0.002	> 100	90	0.51	0.001	> 100	90	0.51	0.001
> 200	60	0.47	0.004	> 200	90	0.41	0.01	> 200	90	0.43	0.008
> 300	60	0.47	0.004	> 300	60	0.39	0.02	> 300	60	0.43	0.009
> 200	90	0.45	0.006	> 200	60	0.38	0.02	> 200	60	0.42	0.01
> 400	60	0.44	0.008	> 400	60	0.37	0.03	> 400	60	0.40	0.02
average	60	0.39	0.02	> 300	20	0.36	0.03	> 300	20	0.38	0.02
> 300	20	0.39	0.02	sum	90	0.36	0.03	sum	90	0.37	0.02
sum	60	0.38	0.02	average	90	0.35	0.04	average	90	0.37	0.03
sum	90	0.38	0.02	> 400	20	0.34	0.04	average	60	0.36	0.03
> 100	60	0.38	0.02	> 300	90	0.33	0.05	sum	60	0.35	0.04
average	90	0.38	0.02	average	60	0.33	0.05	> 300	90	0.35	0.04
> 300	90	0.36	0.03					> 400	20	0.35	0.04
> 400	20	0.34	0.04					> 100	60	0.34	0.04
> 500	60	0.33	0.05								
site of high plant available soil water (N=18)											
> 700	90	-0.53	0.02	median	20	-0.52	0.03	median	20	-0.53	0.02
				> 100	20	-0.51	0.03				
				> 200	60	-0.47	0.05				
				> 100	60	-0.47003	0.05				
site of low plant available soil water (N=18)											
miss.	90	-0.51	0.03	miss.	90	-0.53	0.02	miss.	90	-0.53	0.02

A. 7 Correlations between yield and variables based on matric suction measurements of each month (April - July)

2001
MONTHLY
both sites (N=36)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
median	60	July	0.65	<.0001	sum	20	July	0.66	<.0001	sum	20	July	0.66	<.0001
sum	20	July	0.65	<.0001	> 200	20	June	0.63	<.0001	median	60	July	0.65	<.0001
> 300	60	July	0.64	<.0001	median	60	July	0.63	<.0001	sum	60	July	0.63	<.0001
sum	60	July	0.64	<.0001	sum	60	July	0.61	<.0001	> 200	20	June	0.63	<.0001
> 200	60	July	0.63	<.0001	> 300	20	June	0.61	<.0001	> 300	60	July	0.63	<.0001
average	60	July	0.61	<.0001	> 300	60	July	0.60	0.0001	average	60	July	0.61	<.0001
> 200	20	June	0.59	0.0001	average	60	July	0.60	0.0001	> 200	60	July	0.60	<.0001
miss.	20	July	0.57	0.0003	> 200	60	July	0.57	0.0003	> 300	20	June	0.58	0.0002
> 100	60	July	0.54	0.0007	miss.	20	July	0.57	0.0003	miss.	20	July	0.58	0.0002
> 400	60	July	0.53	0.001	sum	60	April	0.52	0.001	> 400	60	July	0.53	0.0009
> 300	20	June	0.51	0.001	> 400	60	July	0.52	0.001	> 100	60	July	0.53	0.0009
> 100	20	June	0.51	0.001	sum	90	July	0.52	0.001	sum	90	July	0.52	0.001
sum	90	July	0.50	0.002	> 100	60	July	0.51	0.002	sum	60	April	0.51	0.001
average	90	July	0.48	0.003	> 100	90	July	0.51	0.002	> 100	90	July	0.50	0.002
> 100	90	July	0.47	0.004	median	90	May	-0.50	0.002	> 100	20	June	0.49	0.003
> 200	90	July	0.47	0.004	> 100	20	June	0.46	0.005	average	90	July	0.47	0.004
median	90	July	0.47	0.004	median	90	July	0.46	0.005	median	90	July	0.47	0.004
sum	60	April	0.47	0.004	average	90	July	0.46	0.005	> 200	90	July	0.46	0.004
miss.	90	May	-0.45	0.006	> 200	90	July	0.45	0.006	average	20	June	0.45	0.006
average	20	June	0.44	0.007	average	20	June	0.45	0.006	median	90	May	-0.45	0.006
> 100	90	June	0.40	0.01	> 500	60	July	0.43	0.008	> 500	60	July	0.43	0.01
average	20	July	0.40	0.01	average	20	July	0.40	0.02	average	20	July	0.41	0.01
> 500	60	July	0.39	0.02	median	90	April	-0.40	0.02	> 100	90	June	0.41	0.01
sum	20	June	0.39	0.02	> 100	90	June	0.40	0.02	miss.	90	May	-0.40	0.02
median	20	July	0.38	0.02	median	20	July	0.38	0.02	median	20	July	0.39	0.02
> 300	90	July	0.38	0.02	average	90	May	-0.37	0.03	sum	20	June	0.36	0.03
> 400	90	July	0.36	0.03	miss.	90	May	-0.36	0.03	> 300	90	July	0.36	0.03

A. 7 cont.

							2001 MONTHLY both sites (N=36)							
		grain					straw					biomass		
var	depth	month	R	P	var	depth	month	R	P	var	depth	month	R	P
median	90	May	-0.34	0.04	> 300	90	July	0.34	0.04	median	90	April	-0.36	0.03
					sum	20	June	0.34	0.04	> 400	90	July	0.34	0.04
					median	60	April	-0.34	0.04	average	90	May	-0.34	0.04
					median	20	June	0.33	0.05	median	20	June	0.34	0.05
							site of high plant available soil water (N=18)							
> 100	20	July	-0.58	0.01	median	90	May	-0.61	0.007	> 100	90	May	-0.65	0.003
miss.	20	July	0.58	0.01	> 100	90	May	-0.59	0.01	miss.	20	July	0.54	0.02
> 100	90	May	-0.56	0.01	median	60	May	-0.55	0.02	median	90	May	-0.54	0.02
> 700	90	July	-0.53	0.02	average	60	May	-0.53	0.02	> 100	20	July	-0.53	0.02
> 600	20	July	-0.49	0.04	average	90	May	-0.53	0.02	> 200	60	July	-0.50	0.04
> 500	20	July	-0.48	0.05	sum	90	May	-0.53	0.03	> 100	60	May	-0.49	0.04
					> 100	60	May	-0.52	0.03	median	60	May	-0.48	0.04
					> 200	60	July	-0.51	0.03	sum	90	May	-0.47	0.05
					sum	20	May	-0.49	0.04	average	90	May	-0.47	0.05
					miss.	90	July	-0.48	0.04					
					sum	60	May	-0.48	0.04					

A 7 cont.

2001
MONTHLY
site of high plant available soil water (N=18)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
> 100	20	June	0.65	0.004	> 200	20	June	0.71	0.001	> 100	20	June	0.68	0.002
miss.	20	June	-0.64	0.004	> 100	20	June	0.69	0.001	miss.	20	June	-0.67	0.002
sum	20	July	0.61	0.007	miss.	20	June	-0.68	0.002	> 200	20	June	0.66	0.003
> 200	20	May	-0.59	0.01	> 200	20	May	-0.67	0.002	> 200	20	May	-0.64	0.004
> 200	20	June	0.58	0.01	> 100	20	May	-0.67	0.003	> 100	20	May	-0.63	0.005
> 300	60	July	0.57	0.01	miss.	20	July	0.62	0.006	sum	20	July	0.60	0.008
> 100	20	May	-0.57	0.01	average	20	May	-0.62	0.007	miss.	20	July	0.58	0.01
median	60	July	0.57	0.01	sum	20	July	0.59	0.01	average	20	May	-0.56	0.01
sum	60	July	0.53	0.02	median	20	May	-0.56	0.02	> 300	60	July	0.55	0.02
miss.	20	July	0.52	0.03	> 300	20	May	-0.55	0.02	median	60	July	0.53	0.02
> 200	60	July	0.52	0.03	> 100	90	June	0.53	0.02	median	20	May	-0.51	0.03
miss.	90	July	-0.50	0.03	> 300	60	July	0.53	0.03	sum	60	July	0.50	0.03
average	60	July	0.50	0.04	sum	20	May	-0.52	0.03	> 300	20	May	-0.50	0.04
average	20	July	0.49	0.04	median	60	July	0.50	0.03	average	20	July	0.50	0.04
average	20	May	-0.49	0.04	median	20	June	0.50	0.04	> 100	90	June	0.49	0.04
median	20	July	0.48	0.04	average	20	July	0.49	0.04	median	20	July	0.49	0.04
miss.	90	May	-0.47	0.05	miss.	90	May	-0.48	0.04	miss.	90	May	-0.48	0.04
					median	20	July	0.48	0.04	> 200	60	July	0.47	0.05

A 7 cont.

2001

MONTHLY

site of high plant available soil water (N=18)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
> 100	20	June	0.65	0.004	> 200	20	June	0.71	0.001	> 100	20	June	0.68	0.002
miss.	20	June	-0.64	0.004	> 100	20	June	0.69	0.001	miss.	20	June	-0.67	0.002
sum	20	July	0.61	0.007	miss.	20	June	-0.68	0.002	> 200	20	June	0.66	0.003
> 200	20	May	-0.59	0.01	> 200	20	May	-0.67	0.002	> 200	20	May	-0.64	0.004
> 200	20	June	0.58	0.01	> 100	20	May	-0.67	0.003	> 100	20	May	-0.63	0.005
> 300	60	July	0.57	0.01	miss.	20	July	0.62	0.006	sum	20	July	0.60	0.008
> 100	20	May	-0.57	0.01	average	20	May	-0.62	0.007	miss.	20	July	0.58	0.01
median	60	July	0.57	0.01	sum	20	July	0.59	0.01	average	20	May	-0.56	0.01
sum	60	July	0.53	0.02	median	20	May	-0.56	0.02	> 300	60	July	0.55	0.02
miss.	20	July	0.52	0.03	> 300	20	May	-0.55	0.02	median	60	July	0.53	0.02
> 200	60	July	0.52	0.03	> 100	90	June	0.53	0.02	median	20	May	-0.51	0.03
miss.	90	July	-0.50	0.03	> 300	60	July	0.53	0.03	sum	60	July	0.50	0.03
average	60	July	0.50	0.04	sum	20	May	-0.52	0.03	> 300	20	May	-0.50	0.04
average	20	July	0.49	0.04	median	60	July	0.50	0.03	average	20	July	0.50	0.04
average	20	May	-0.49	0.04	median	20	June	0.50	0.04	> 100	90	June	0.49	0.04
median	20	July	0.48	0.04	average	20	July	0.49	0.04	median	20	July	0.49	0.04
miss.	90	May	-0.47	0.05	miss.	90	May	-0.48	0.04	miss.	90	May	-0.48	0.04
					median	20	July	0.48	0.04	> 200	60	July	0.47	0.05

A. 8 Correlations between yield and variables based on matric suction measurements of each month (April - July).

Variation = considering failed tensiometer readings as matric suction > 800 hPa .

2001
MONTHLY
-- variation --
both sites (N=36)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
median	60	July	0.65	<.0001	sum	20	July	0.66	<.0001	sum	20	July	0.66	<.0001
sum	20	July	0.65	<.0001	> 600	60	July	0.65	<.0001	median	60	July	0.65	<.0001
> 300	60	July	0.64	<.0001	median	60	July	0.63	<.0001	> 600	60	July	0.64	<.0001
sum	60	July	0.64	<.0001	> 400	20	July	0.62	<.0001	sum	60	July	0.63	<.0001
> 200	60	July	0.63	<.0001	sum	60	July	0.61	<.0001	> 300	60	July	0.63	<.0001
average	60	July	0.61	<.0001	> 500	20	July	0.60	0.0001	> 400	20	July	0.62	<.0001
> 600	60	July	0.60	0.000	> 300	60	July	0.60	0.0001	average	60	July	0.61	<.0001
> 100	20	July	0.59	0.000	average	60	July	0.60	0.0001	> 200	60	July	0.60	<.0001
> 400	20	July	0.57	0.000	> 200	60	July	0.57	0.0003	> 500	20	July	0.59	0.0001
> 800	20	July	0.57	0.000	> 800	20	July	0.57	0.0003	> 800	20	July	0.58	0.0002
> 700	20	July	0.57	0.000	miss.	20	July	0.57	0.0003	miss.	20	July	0.58	0.0002
miss.	20	July	0.57	0.000	> 700	20	July	0.57	0.0003	> 700	20	July	0.58	0.0002
> 500	20	July	0.55	0.001	> 100	20	July	0.53	0.0009	> 100	20	July	0.56	0.0004
> 100	60	July	0.54	0.001	sum	60	April	0.52	0.001	> 400	60	July	0.53	0.0009
> 300	20	July	0.53	0.001	> 400	60	July	0.52	0.001	> 100	60	July	0.53	0.0009
> 400	60	July	0.53	0.001	sum	90	July	0.52	0.001	> 300	20	July	0.52	0.001
sum	90	July	0.50	0.002	> 100	60	July	0.51	0.002	sum	90	July	0.52	0.001
average	90	July	0.48	0.003	> 100	90	July	0.51	0.002	sum	60	April	0.51	0.001
> 100	90	July	0.47	0.004	> 300	20	July	0.51	0.002	> 100	90	July	0.50	0.002
> 200	20	July	0.47	0.004	median	90	May	-0.50	0.002	average	90	July	0.47	0.004
median	90	July	0.47	0.004	median	90	July	0.46	0.005	median	90	July	0.47	0.004
sum	60	April	0.47	0.004	average	90	July	0.46	0.005	> 200	20	July	0.46	0.004
miss.	90	May	-0.45	0.006	> 200	90	July	0.45	0.006	average	20	June	0.45	0.006
average	20	June	0.44	0.007	average	20	June	0.45	0.006	median	90	May	-0.45	0.006
> 200	20	July	0.41	0.01	> 500	60	July	0.43	0.008	> 500	60	July	0.43	0.01
> 100	90	June	0.40	0.01	average	20	July	0.40	0.02	average	20	July	0.41	0.01

A. 8 cont.

2001
MONTHLY
-- variation --
both sites (N=36)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
average	20	July	0.40	0.01	median	90	April	-0.40	0.02	> 100	90	June	0.41	0.01
> 500	60	July	0.39	0.02	> 100	90	June	0.40	0.02	> 200	20	July	0.40	0.02
sum	20	June	0.39	0.02	> 200	20	June	0.39	0.02	miss.	90	May	-0.40	0.02
median	20	July	0.38	0.02	median	20	July	0.38	0.02	> 200	20	June	0.39	0.02
> 300	90	July	0.38	0.02	> 200	20	July	0.38	0.02	median	20	July	0.39	0.02
> 200	20	June	0.37	0.03	average	90	May	-0.37	0.03	sum	20	June	0.36	0.03
> 100	20	June	0.37	0.03	miss.	90	May	-0.36	0.03	> 300	90	July	0.36	0.03
> 400	90	July	0.36	0.03	> 300	90	July	0.34	0.04	median	90	April	-0.36	0.03
median	90	May	-0.34	0.04	sum	20	June	0.34	0.04	> 400	90	July	0.34	0.04
					median	60	April	-0.34	0.04	average	90	May	-0.34	0.04
					median	20	June	0.33	0.05	median	20	June	0.34	0.05
										> 100	20	June	0.33	0.05

site of high plant available soil water (N=18)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
miss.	20	July	0.58	0.01	median	90	May	-0.61	0.007	> 100	90	May	-0.65	0.003
> 800	20	July	0.58	0.01	> 100	90	May	-0.59	0.01	miss.	20	July	0.54	0.02
> 700	20	July	0.58	0.01	median	60	May	-0.55	0.02	> 800	20	July	0.54	0.02
> 100	90	May	-0.56	0.01	average	60	May	-0.53	0.02	> 700	20	July	0.54	0.02
> 700	90	July	-0.53	0.02	average	90	May	-0.53	0.02	median	90	May	-0.54	0.02
					sum	90	May	-0.53	0.03	> 600	20	July	0.51	0.03
					> 100	60	May	-0.52	0.03	> 200	60	July	-0.50	0.04
					> 200	60	July	-0.51	0.03	> 100	60	May	-0.49	0.04
					> 600	20	July	0.50	0.03	median	60	May	-0.48	0.04
					sum	20	May	-0.49	0.04	sum	90	May	-0.47	0.05
					miss.	90	July	-0.48	0.04	average	90	May	-0.47	0.05
					sum	60	May	-0.48	0.04					
					> 100	20	June	-0.47	0.05					

A. 8 cont.

2001
MONTHLY
-- variation --
site of low plant available soil water (N=18)

		grain					straw					biomass		
var	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**	**var**	**depth**	**month**	**R**	**P**
> 800	20	June	-0.64	0.004	> 800	20	June	-0.68	0.002	> 800	20	June	-0.67	0.002
> 600	20	June	-0.64	0.004	> 600	20	June	-0.68	0.002	> 600	20	June	-0.67	0.002
> 700	20	June	-0.64	0.004	> 700	20	June	-0.68	0.002	> 700	20	June	-0.67	0.002
miss.	20	June	-0.64	0.004	miss.	20	June	-0.68	0.002	miss.	20	June	-0.67	0.002
sum	20	July	0.61	0.007	> 200	20	May	-0.63	0.005	sum	20	July	0.60	0.008
> 300	60	July	0.57	0.01	> 700	20	July	0.62	0.006	> 200	20	May	-0.60	0.008
median	60	July	0.57	0.01	> 800	20	July	0.62	0.006	miss.	20	July	0.58	0.01
> 200	20	May	-0.55	0.02	miss.	20	July	0.62	0.006	> 700	20	July	0.58	0.01
> 100	20	July	0.54	0.02	> 600	20	July	0.62	0.006	> 800	20	July	0.58	0.01
> 300	20	July	0.54	0.02	> 100	20	May	-0.62	0.006	> 600	20	July	0.58	0.01
sum	60	July	0.53	0.02	average	20	May	-0.62	0.007	> 100	20	May	-0.58	0.01
> 100	20	May	-0.52	0.03	> 500	20	July	0.59	0.01	average	20	May	-0.56	0.01
> 800	20	July	0.52	0.03	sum	20	July	0.59	0.01	> 300	20	July	0.55	0.02
> 700	20	July	0.52	0.03	> 400	20	July	0.57	0.01	> 500	20	July	0.55	0.02
> 600	20	July	0.52	0.03	median	20	May	-0.56	0.02	> 300	60	July	0.55	0.02
miss.	20	July	0.52	0.03	> 300	20	July	0.55	0.02	median	60	July	0.53	0.02
> 200	60	July	0.52	0.03	> 100	90	June	0.53	0.02	> 400	20	July	0.53	0.02
miss.	90	July	-0.50	0.03	> 300	60	July	0.53	0.03	> 100	20	July	0.52	0.03
> 200	20	July	0.50	0.04	sum	20	May	-0.52	0.03	median	20	May	-0.51	0.03
average	60	July	0.50	0.04	median	60	July	0.50	0.03	> 200	20	July	0.50	0.03
average	20	July	0.49	0.04	> 200	20	July	0.50	0.03	sum	60	July	0.50	0.03
> 500	20	July	0.49	0.04	median	20	June	0.50	0.04	average	20	July	0.50	0.04
average	20	May	-0.49	0.04	> 300	20	May	-0.50	0.04	> 100	90	June	0.49	0.04
median	20	July	0.48	0.04	> 100	20	July	0.49	0.04	median	20	July	0.49	0.04
> 400	20	July	0.48	0.04	average	20	July	0.49	0.04	miss.	90	May	-0.48	0.04
miss.	90	May	-0.47	0.05	miss.	90	May	-0.48	0.04	> 200	60	July	0.47	0.05
					median	20	July	0.48	0.04					

LEBENSLAUF

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1969 – 1982	Grundschule und Gymnasium in Karlsruhe
	Abschluß: Abitur
1982 – 1983	Matrose der Philippine Maritime Company
1983 – 1989	Studium der Forstwissenschaft an der Georg-August-Universität Göttingen, einschließlich Praktikum beim Office National des Forêts (Châlons s/Marne);
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1989 – 1990	Zivildienst beim Bund für Umwelt und Naturschutz, Radolfzell
1990 – 1991	Praktikum bei der Bezirksstelle für Naturschutz und Landschaftsplege in Karlsruhe
1991 – 1992	Japanisch-Sprachschule in Tokyo (DAAD-Stipendium)
1992 – 1993	Praktikum am PREC-Institute (Umweltgutachten und –planung), Tokyo (DAAD-Stipendium)
1994 – 1996	Entwicklungshelfer des DED in Niger
1996 - 1998	Fellowship der Texas A & M Universität;
	Abschluß: Master of Soil and Plant Science (Schwerpunkte: Bodenkunde und Statistik)
seit 1998	Doktorand am Lehrstuhl für Pflanzenernährung der TU München
2000 - 2002	Leitung eines Forstprojektes der Food and Agriculture Organization of the United Nations (FAO) in Niger