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Characterising site-specific water availability

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1 General Introduction

Crop yield was shown to vary spatially within one field giving a relatively stable pattern of yield distribution over years and different crops (Bhatti et al., 1999; Sadler et al. 2000a). Fields can thus be divided into higher and lower yielding zones. That observation gave room to the hypothesis that these lower and higher yielding zones are related to the potential site-specific yield. With conventional uniform crop management this means that input factors such as N fertiliser were either suboptimally supplied, optimally supplied or over supplied. The remaining N may contribute to nitrate leaching towards the groundwater or to gaseous N losses from the soil. Varying the amount of N fertiliser according to the potential site-specific uptake may offer prospects to increase the input efficiency (Moore and Tyndale-Biscoe, 1999) and eventually yield. In agreement with the definition of Eckert et al. (2000), precision agriculture can thus be part of sustainable agriculture in Germany, as the detrimental effects on ecology may be reduced with productivity being maintained.

Nutrient and water availability represent the predominant site-specific factors for plant growth. At Scheyern in the tertiary hills of southern Germany, where this investigation was realised, soil analysis showed that the soils contained sufficient amounts of potassium and phosphorus (Auerswald et al., 1997). The same authors showed that site-specific water availability was the limiting factor influencing plant development and yield, which was also reported in other regions (Vachaud et al., 1985; Ide et al., 1987; Shaffer et al., 1993). However, a characteristic is still needed to measure the site-specific water availability (Mulla, 1991; Sadler et al., 2000b). In precision agriculture a characteristic should either give information of an area or be a simple means that can be easily determined at numerous sites within a field (Lark, 2001). The focus of this study was put on simple means determined at a point which could be used as a reference for area-based characteristics.

Soil texture was suggested as a characteristic of site-specific water availability (Funk and Maidl,1997), as it is closely related to the water holding capacity of a soil. With an annual precipitation of 700 to 900 mm at Scheyern, however, the soil water reservoir at the beginning of the growing season may not be the only factor influencing plant development. Instead, rainfall distribution within the growing season of a crop may rather be decisive for plant performance and yield. In southern Germany dry periods can occur in summer. Periods of water limitation were shown to increase spatial variability in plant growth and yield (Auerswald et al. 1997; Sadler et al. 2000b). Generally the extent of upward and lateral fluxes (Monteith, 1988; Rejd et al., 1984; Sadras and Milroy, 1996; Tardieu and Kraterij, 1991) and the root distribution (Ritchie et al., 1972; Ritchie, 1981; Bruckler et al., 1991) within the profile may determine site-specific water availability. Lateral fluxes were shown to be important in the tertiary hills of southern Germany (Auerswald et al., 1997; Honisch and Sinowsky, 1997). The determination of lateral fluxes in the field, as suggested by Tigges et al. (1999), however, was only qualitative and could not be used for their quantification. Consequently, site-specific water availability could not be derived from a water balance. In this study two approaches were used for determining site-specific water availability.

In the first approach soil and plant water status were investigated. Soil water status was expressed as the soil matric potential determined with tensiometers, since it was shown to be closely related to the physiological response of a crop to soil drying (Ali et al., 1998; Jensen et al., 1998). Nevertheless, with the soil matric potential strongly varying within the soil profile owing to variation in soil texture (Rejd et al., 1984), landscape position (Honisch and Sinowsky, 1997), or soil bulk density (Tardieu and Kraterij, 1991), leaf water potential may be more suitable to measure soil water availability. As both the soil matric and the leaf water potential can be easily determined in the field, their potential as a characteristic of water availability was studied.

In the second approach water availability was derived from crop transpiration. Allen et al. (1989) showed that crop transpiration can be calculated on the basis of meteorological data and crop characteristics with the Penman-Monteith equation. Soil water availability, however, is not considered directly. In addition, input data for this equation refer to a large scale and can be correctly determined in plain areas (Jarvis and McNaughton, 1985). However, in southern Germany, where this investigation was realised, the landscape is hilly and areas for quantifying crop transpiration may be less than one hectare in precision agriculture. The Penman-Monteith equation may thus only be applied with caution. According to Winterhalter and Fabian (2000), errors in the determination of input data may cause substantial variation in evapotranspiration calculated from the Penman-Monteith equation. Consequently, it may offer only poor prospects of success for separating areas within one field in a hilly region differing rather gradually in crop transpiration.

In this study silicon (Si) was investigated with respect to its potential as a tracer of crop transpiration. It was shown to be closely related to crop transpiration (Handreck and Jones, 1968; Paltridge and de Vries, 1973; Adatia and Besford, 1986; Reay, 1987). Jones and Handreck (1965) as well as Schultz and French (1976) reported that crop transpiration could be calculated from the Si accumulation in above-ground dry matter and the Si concentration in soil solution. Raven (1983) suggested that this could be applied to all ‘dryland’ Gramineae.

However, in recent reports this simple relationship between Si accumulation and crop transpiration could not be confirmed in dryland gramineae (Mayland et al., 1991; Masle et al., 1992; Mayland et al., 1993).These contrasting results might be explained by the fact that Si accumulation may also be influenced by other factors independent of transpiration. Duda et al. (2001b) found that both transpiration and growth, the latter expressed as change in dry matter, influenced independently the Si accumulation in plant dry matter of wheat. The same authors showed that crop transpiration was closely related to the Si content changes in leaves. Therefore the latter parameter was investigated as a tracer of crop transpiration.

This study was divided into three parts in order to evaluate the various parameters as characteristics of site-specific water availability. Soil matric and leaf water potential were studied during the growing season of silage maize (1999) and winter wheat (2000) (chapter 2). In 2000 the potential of Si accumulation as a tracer of crop transpiration was studied in parallel (chapter 3). In order to evaluate the tracer’s suitability an accurate determination of crop transpiration was imperative. This aspect was therefore studied in a glasshouse experiment (chapter 4).

2 The Response of Midday Leaf Water Potential to Soil Drying, a Characteristic of Site-specific Water Availability

2.1 Abstract

Water availability was shown to cause spatial crop yield variation. In precision agriculture fertilisation should be varied spatially according to the site-specific water availability during growing season. But a parameter is still needed which reflects the effect of soil water availability on yield of a series of crops and which could be used for identifying management units. This study aimed at finding a characteristic of site-specific soil water availability.

Investigations were conducted in the tertiary hills of southern Germany with heterogeneous soils and undulating relief. Based on information about variation in soil texture, soil bulk density, elevation, and potential yield, five sites were selected within one field. Gravimetric water contents of the soil, soil matric potential, and leaf water potential were measured regularly during growing season of silage maize in 1999 and winter wheat in 2000. On the basis of gravimetric water contents, a simplified water balance was calculated. Above-ground biomass was determined at various developmental growth stages and at plant maturity.

Site-specific water availability could be indicated by neither soil matric potential nor leaf water potential. Differences in water availability between the sites became evident when the soil matric potential at 40 cm depth was correlated with the midday leaf water potential. The decrease in leaf water potential resulting from a 100-hPa decline in soil matric potential at 40 cm depth is called the ‘response’ of a site. The response ranged between 0.02 and 0.1 MPa*100 hPa^{-1} in maize and between 0.06 and 0.9 MPa*100 hPa^{-1} in wheat. These findings were further supported by the

results from the simplified water balance. In addition, the response was significantly, negatively correlated with the above-ground fresh biomass in maize ($R^2 = 0.77$ at $P \leq 0.05$) and in wheat ($R^2 = 0.48$ at $P \leq 0.05$).

The response is suggested as a sensitive criterion for characterising water availability in hilly landscapes at one site relative to others.

2.2 Introduction

Crop yield variability within one field was shown to give a relatively stable pattern of yield distribution (Timlin et al., 2001). This may be predominantly determined by site-specific variations in the nutrient and water availability. At Scheyern, in southern Germany, where this investigation was realised, soil analysis showed that the soil contained sufficient plant available phosphorus and potassium (Auerswald et al., 1997). It was therefore concluded that site-specific variations in water availability were the major cause for the spatial yield variability, as was also shown in other areas (Ide et al., 1987; Shaffer et al., 1993; Moore and Tyndale-Biscoe, 1999; Sadler et al., 2000a, b).

In precision agriculture fertilisation should be varied spatially according to the site-specific water availability during growing season (Tolk et al., 1998; Geesing et al., 2001; Timlin et al., 2001). Therefore a parameter is still needed which reflects the effects of soil water availability on yield of a series of crops and which could be used for identifying management units (Mulla, 1991; Sadler et al., 2000b).

Based on the concept of available soil water, Funk and Maidl (1997) suggested the soil texture as a criterion for assessing management units in precision agriculture. However, with an annual precipitation of 700 to 900 mm the amount of available soil water may be less important for crop performance in the field. Water availability additionally depends on root distribution in the profile (Ritchie et al., 1972; Ritchie, 1981; Bruckler et al., 1991; Roth et al., 1997) and can be substantially increased through upward and lateral fluxes (Rejd et al., 1984; Stone et al., 1985; Tardieu and Karterij, 1991). Significant lateral soil water fluxes were shown at Scheyern in the tertiary hills of southern Germany where this investigation was realised (Auerswald et al., 1997; Honisch and Sinowsky, 1997). The quantification of lateral fluxes, however, is difficult and was not yet shown. Therefore only a simplified water balance was calculated in this study in order to indicate the predominant fluxes determining soil water dynamics at selected sites within the field. Emphasis was put on the soil matric potential and the leaf water potential as indicators of soil water availability with respect to plant performance in the field.

The soil matric potential may be an even more suitable characteristic than the absolute amount of available soil water. Ali et al. (1998) found in wheat that the response of stomatal conductance and leaf extension to soil drying were more closely linked to the soil matric potential than to the volumetric water content. Similar results were reported by Jensen et al. (1998) for lupins. Nevertheless, the meaning of bulk soil matric potential may be limited in soils strongly heterogeneous in texture (Rejd et al., 1984) or bulk density (Tardieu and Katerij, 1991), as it may not reflect the situation of plant roots. In these cases, the leaf water potential might better indicate soil water availability, which was shown to parallel at least the development of physiological processes in various crops (Tardieu and Simonneau, 1998).

Since both soil matric potential and leaf water potential were simple means to determine water availability in the field, one important prerequisite for a characteristic in precision agriculture, this study aimed at evaluating their potential as indicators of water availability during growing season. A trial was conducted in a field, showing spatial yield variation, during growing season of maize (1999) and wheat (2000).

Based on information about variation in soil texture, soil bulk density, elevation, and potential yield, five sites were chosen within this field. At these sites water availability was characterised by two approaches: i) a simplified water balance and ii) the course of soil matric potential and leaf water potential.

2.3 Material and Methods

2.3.1. Location, weather conditions, experimental design, and site characteristics

This study was part of an interdisciplinary co-operation for ecosystem research (FAM, Forschungsverbund Agrarökosysteme München). Its global aim is to identify indicators of sustainable agriculture with precision agriculture being one approach. Experiments were conducted on the 143 ha Scheyern Experimental Farm in the tertiary hills of southern Germany. The annual precipitation was 899 and 919 mm in 1999 and 2000, respectively. During growing season of maize in 1999 (May to mid September) there was 570 mm of precipitation being above the six-year average (480 mm). The growing season for winter wheat in 2000 (mid March to July) was also more humid compared to the six-year average, with 462 mm of rainfall compared to 402 mm on average.

This investigation represents part of the data obtained in a two-year field trial aiming at testing uniform versus two approaches of site-specific crop management. The management strategies were realised in 7.5-m large strips subjected to uniform or site-specific crop management. The experiment was arranged in a randomised block design with seven replicates.

The intensive measurements for investigating water balance aspects were done in one plot at five selected sites, subjected to uniform crop management. The sites differed in soil texture, soil bulk density, and elevation (Table 1).

Table 1: Description of the five selected sites within the field. Data were taken from reference points of a 50 x 50 m^2 grid which were nearest to the sites. Relative yield was derived from a three-year-averaged yield record. AWC is the available water capacity within effective root zone according to Sinowsky (1995). Methods for determing soil texture and AWC were described by Sinowski et al. (1997) and Scheinost et al. (2001). For explanations of the soil horizons the interested reader may be refered to Sinowsky (1995) and Auerswald et al. (2001).

Site	Soil						Elevation	Rel. yield
	horizon	clay	silt	Sand	bulk density	AWC		
			%		g*cm^{-3}	mm*m^{-1}	m a.s.l.	%
‘North’	Ap	23	50	27	1.30	205	467	126
	xM1	19	50	31	1.59			
	M1	19	56	25	1.43			
	M2	18	57	25	1.54			
	M3	22	58	20	1.52			
West Hill’	Ap	23	47	30	1.33	146	473	96
	Bv	36	39	25	1.59			
	SwBv	35	32	33	1.66			
	SdBv	35	39	26	1.59			
‘East Hill’	Ap	23	55	22	1.46	173	469	90
	XBv1	29	48	23	-			
	Bv1	28	47	25	1.56			
	Bv2	27	47	26	-			
	IIBv1	27	28	45	-			
‘West’	Ap	24	51	25	1.46	144	472	84
	XBv1	21	54	25	1.65			
	Bv1	28	47	25	1.63			
	Bv2	22	38	40	1.60			
‘Valley South’	Ap	20	59	21	1.35	171	468	90
	AhBv	30	50	20	1.60			
	Bv	29	56	15	1.45			
	SwBv	25	50	25	1.58			
	SdBv	-		-	-			

In addition, the sites were located in different zones of relative yield according to a three-year averaged yield record (Table 1). Relative yield is the yield of one unit within a field as percentage of the average yield of the field. According to Sinowsky (1995) available water capacity in the rooting zone was above 140 mm at all of these sites, ranging between 144 and 205 mm. Availability of phosphorus and potassium was sufficient at all sites (Auerswald et al., 1997).

2.3.2 Crop management

Maize (*Zea mays* L., cv. Attribut) was sown on May 5 in 1999 at a seeding rate giving a final plant population of 9 ± 0.8 plants*m^{-2} in the plots. At sowing, 40 kg N*ha^{-1} and at 6-leaf stage (30 days after sowing (DAS)) 110 kg N*ha^{-1} were applied. Maize was used for silage, being harvested on September 17 in 1999 (133 DAS) when dry matter content of the plants was 35 %.

Winter wheat, cv. Petrus, was sown on October 22 in 1999 at a seeding rate of 320 seeds*m^{-2}. Mineral N fertiliser was split into three portions: 50 kg N*ha^{-1} at the start of growing season in March, 60 kg N*ha^{-1} at the second node stage, and 40 kg N*ha^{-1} at the end of booting. During tillering slurry was applied corresponding to 20 kg N * ha^{-1}. Plants were harvested on July 21 in 2000 (273 DAS).

2.3.3 Soil and plant water status, above-ground biomass

Gravimetric soil water content was determined in 20-cm increments down to 100 cm depth at an approximately two-week interval. Therefore soil samples were taken with two replicates which were composited to one mixed sample. Soil matric potential was measured weekly with tensiometers. Measurements were taken at 20, 40, 60, 80, and 100 cm depth with three replicates each.

Leaf water potential was determined in upper fully expanded leaves with the pressure chamber technique (Scholander et al., 1965) at predawn and midday. Measurements were made at approximately weekly intervals with three replicates, using a different plant for each replicate.

Above-ground biomass of maize was determined before harvest (130 days after sowing, DAS) by cutting plants above the ground within 1.3 m in a row. Three replicates were taken.

In wheat, above-ground biomass was determined with two or three replicates at 200 DAS (EC 32), 230 DAS (EC 50), 242 DAS (EC 61), and 258 DAS (EC 80) during growing season. Plants within 30 cm were cut above the ground in two rows 12.5 cm apart.

2.3.4 Statistical analysis

Statistical analyses were performed with SAS (SAS Institute Inc., Cary, NC, USA), version 6.2. Differences among class variables were tested by using ANOVA (SAS general linear model procedure). Significant differences between class variables were identified with LSMEANS multiple comparison for $P \leq 0.05$. Correlations and linear regressions were calculated with SAS REG procedure.

2.4 Results

2.4.1 Site-specific plant growth

Plant height of silage maize was similar at the various sites during growing season 1999. It rose from 0.75 m at 6 to 8-leaf stage (46 days after sowing, DAS) to 2.4 m at male flowering (94 DAS) averaged over all sites (data not shown). At plant maturity above-ground fresh biomass varied between 3.8 and 6.4 kg*m^{-2} at the various sites with the highest biomass at the site ‘North’ and the lowest biomass at the site ‘West’ (Table 2). Based on the average fresh biomass in the field, the relative fresh biomass varied between 73 and 124 %.

Throughout growing season 2000 above-ground fresh mass of wheat developed similarly at the various sites increasing from tillering to ear emergence and then remaining constant. At dough development, above-ground fresh biomass varied between 2.4 and 3.5 kg*m^{-2} within the field. It was significantly higher at the site ‘North’ than at the other sites and slightly lower ($P < 0.1$) at the site ‘West’ compared to the site ‘West Hill’ (Table 2). Based on the average fresh biomass in the field, the relative fresh biomass varied between 81 and 125 %.

Table 2: Above-ground fresh biomass at plant maturity of silage maize and winter wheat at the various sites within the field. Mean values ± standard deviation are given; values with different letters within the row are significantly different at $P \leq 0.05$ according to Tukey-test.

	Above-ground fresh biomass [kg*m^{-2}] at the various sites				
	‘North’	‘West Hill’	‘East Hill’	‘West’	‘Valley (South)’
Silage maize (1999)	6.4 ± 1.0 a	5.3 ± 0.2 ab	4.8 ± 0.2 b	3.8 ± 0.5 c	5.5 ± 0.3 ab
Winter wheat (2000)	3.5 ± 0.5 a	2.9 ± 0.1 b	2.6 ± 0.4 b	2.4 ± 0.3 b	2.6 ± 0.1 b

2.4.2 Site-specific water dynamics

The site-specific characteristics of water dynamics were derived from the variation of the changes in gravimetric water content. Figure 1 shows the results obtained for winter wheat in 2000. Similar results were found for maize in 1999 (data not shown). At the sites ‘North’ and ‘Valley (South)’, both located in depressions within the field, the gains and losses of soil water down to 1 m depth were generally high (Fig. 1). Still at the site 'North' the variation was high in all soil depths, while it mainly resulted from changes at 80 and 100 cm depth at the site 'Valley (South)', especially in 2000. In addition, gravimetric soil water contents at these two sites were 2 to 3 % higher compared to the other sites, averaged over time and depth (data not shown). In contrast, at the site 'West' the variation of the changes in gravimetric soil water content was small.

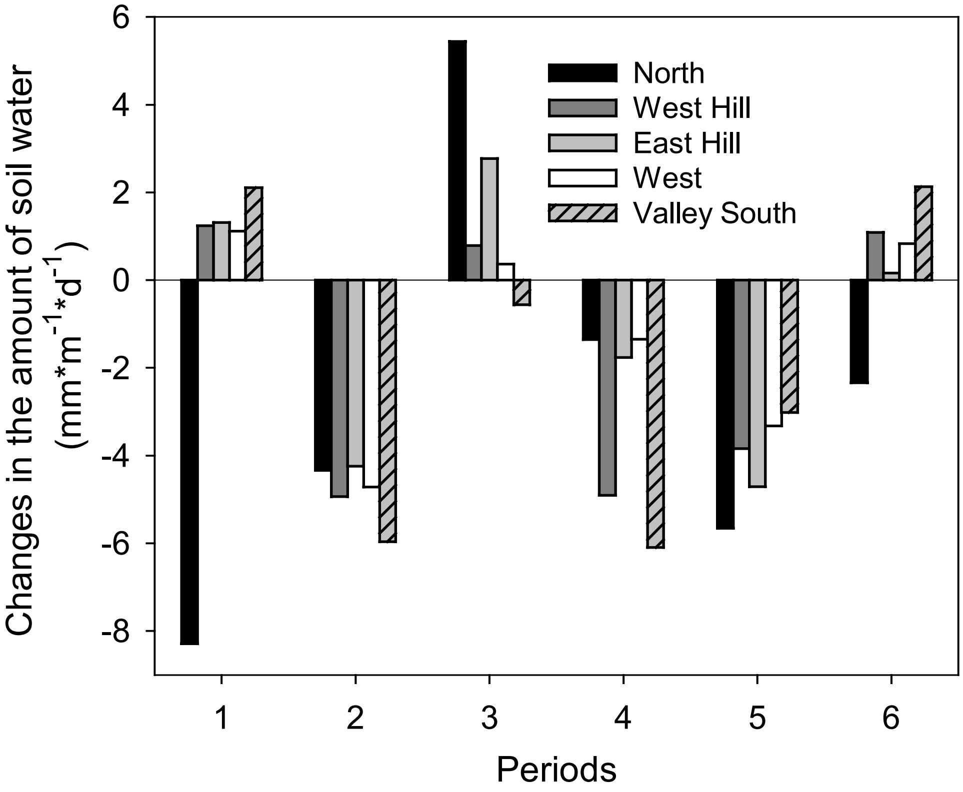

Fig. 1: Average changes per day in the amount of soil water in the profile during growing season 2000 of winter wheat. The different bars represent the various sites within the field. Period 1 to 6 correspond to the following times of the year 2000: period 1 = 3.4. – 20.4., period 2 = 20.4. – 11.5., period 3 = 11.5. – 23.5., period 4 = 23.5. – 31.5., period 5 = 31.5. – 21.6., period 6 = 21.6. – 6.7.

2.4.3 Site-specific water availability

Differences in water availability could be characterised by neither the soil matric potential nor the leaf water potential separately. The soil matric potential ranged between 0 and –800 hPa in all depths during growing season of maize (1999) and wheat (2000), showing a similar development at the various sites. The course of the soil matric potential during growing season 2000 is shown in Fig. 2 for the 40 cm depth. Significant site-specific differences in soil matric potential occurred occasionally, but the ranking of the sites varied from one time to the other. Consequently, no consistent site-specific differences in water availability could be deduced from the data.

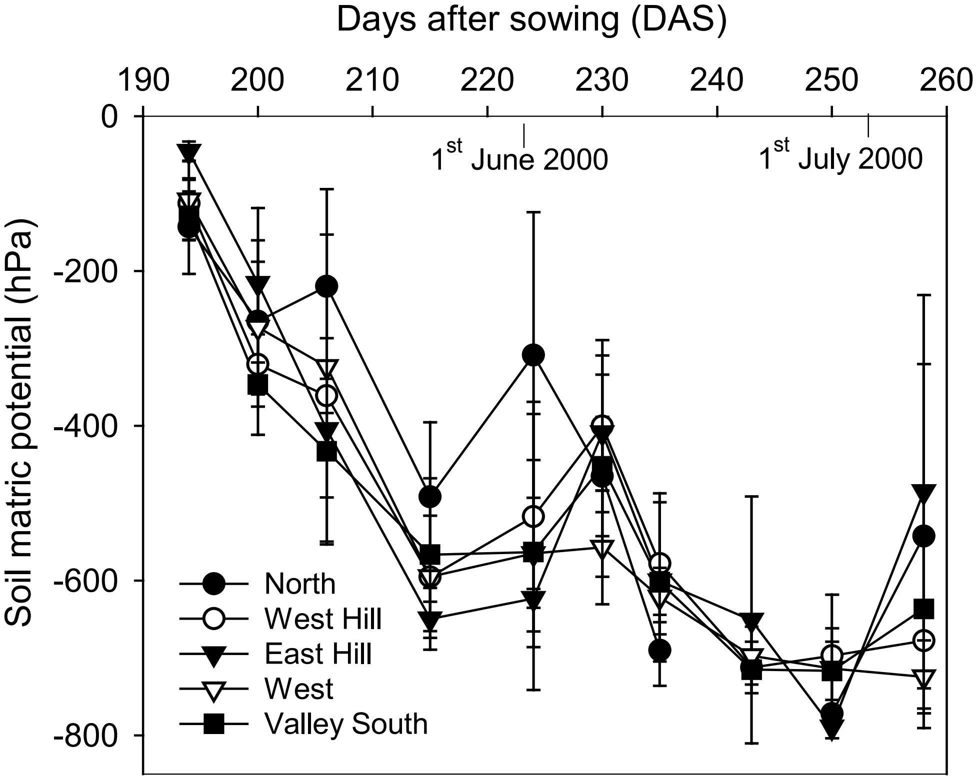

Fig. 2: Soil matric potential at 40 cm depth at the various sites during growing season 2000 of winter wheat. Mean values of three replicates are given. Vertical bars indicate the standard deviation.

The leaf water potential of maize remained nearly constant at predawn, ranging between -0.05 and –0.1 MPa, and decreased slightly from –0.5 to –1.2 MPa at midday during growing season 1999 (data not shown). In wheat (growing season 2000) the leaf water potential showed a decreasing tendency at predawn from –0.1 to –0.2 MPa averaged over all sites (data not shown). At midday it decreased gradually from –1.6 to –2.7 MPa during growing season (Fig. 3). Similar to the soil matric potential, no consistent site-specific differences could be derived from the data.

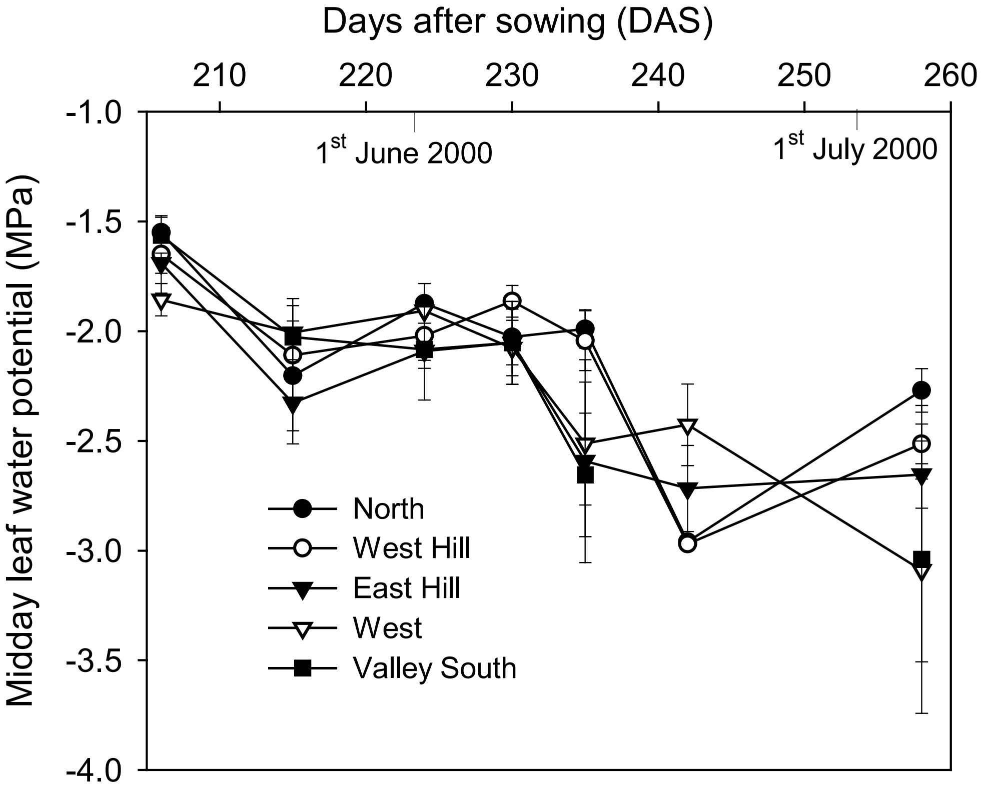

Fig. 3: Midday leaf water potential at the various sites during growing season 2000 of winter wheat. Mean values of three replicates are given. Vertical bars indicate the standard deviation.

However, in both years site-specific differences in water availability became evident when the midday leaf water potential was correlated to the soil matric potential at 40 cm depth, as shown for wheat in Fig. 4.

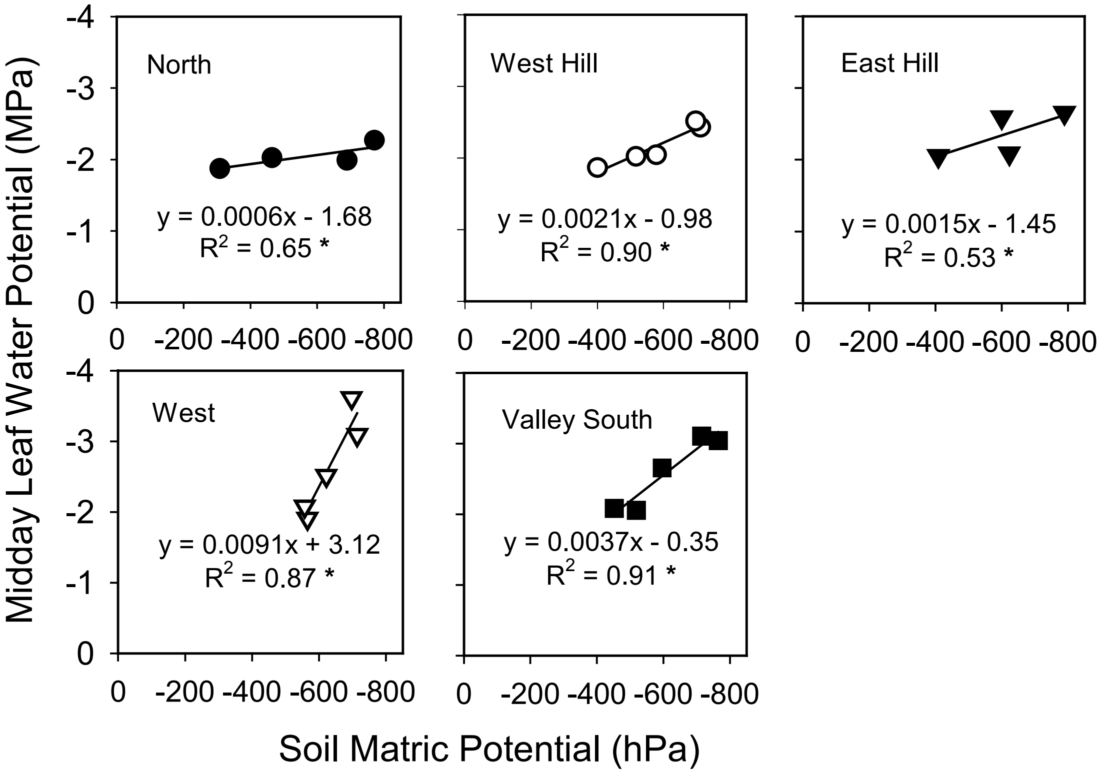

Fig. 4: Relationship between the soil matric potential at 40 cm soil depth and the midday leaf water potential, shown for each site. The equation of regression and the coefficient of determination are given. * indicates significance of the regression at $P \leq 0.05$.

At the site ‘North’ midday leaf water potential remained almost constant, while it distinctly declined at the site ‘West’ with decreasing soil matric potential at 40 cm soil depth (Fig. 4). The decrease in leaf water potential due to soil drying was intermediate at the other sites. Hence site-specific water availability during growing season could be expressed by the slope of the regression. The decrease in leaf water potential resulting from a 100-hPa decline in soil matric potential is called the response of a site. Figure 5 shows the site-specific response obtained during growing season in 1999 for maize and in 2000 for wheat. The values of the response obtained in wheat varied in a wider range than those found for maize (0.06 and 0.9 MPa*100 hPa^{-1} in wheat compared to 0.02 and 0.1 MPa*100 hPa^{-1} in maize). Nevertheless, site-specific differences were similar.

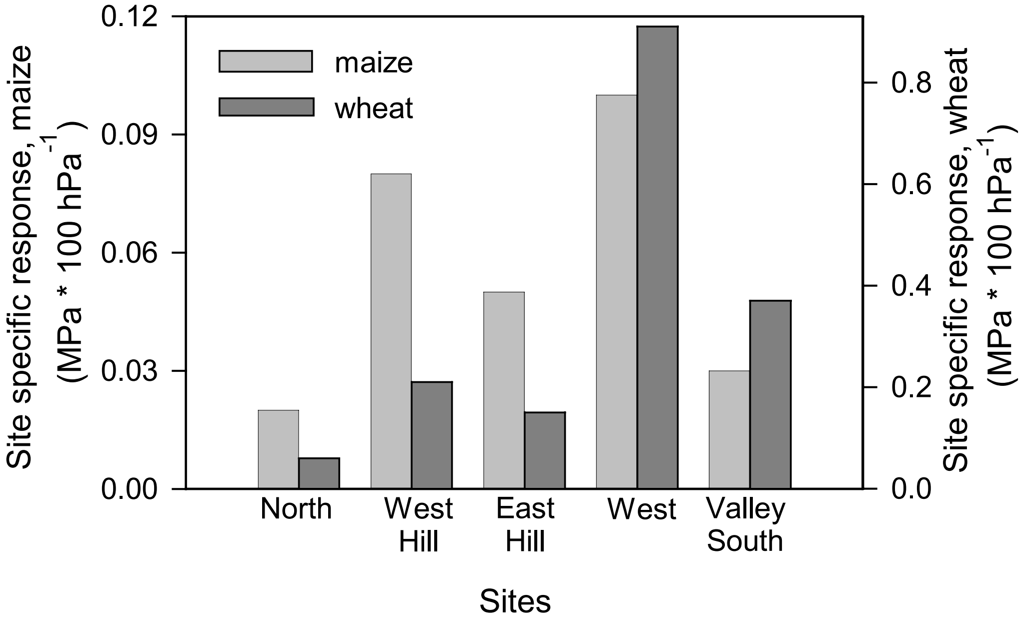

Fig. 5: Site-specific responses of the midday leaf water potential to a 100-hPa decline in soil matric potential at 40 cm depth in one field, shown for maize (left bar) from growing season 1999 and for winter wheat (right bar) from growing season 2000.

In wheat the site-specific response could also be calculated from the relationship between the predawn leaf water potential and the soil matric potential at 100 cm depth. Values are shown in Table 3. Site-specific differences were similar to the response, based on midday leaf water potential. In maize, the response of predawn leaf water potential to a 100-hPa decline in soil matric potential at 100 cm depth was not significantly different from zero at all sites; the data were therefore not shown in Table 3.

Table 3: The response, calculated from predawn leaf water potential and the soil matric potential at 100 cm soil depth, at the various sites within the field. * indicates a significant regression at $P \leq 0.05$; n.s. means non-significant.

Response (MPa*100 hPa^{-1}), based on predawn leaf water potential and the soil matric potential at 100 cm depth, at the various sites					
	'North'	'West Hill'	'East Hill'	'West'	'Valley (South)'
Winter wheat (2000)	0.002 (n.s.)	0.04 *	0.001 (n.s.)	0.12 *	0.06 *

On the basis of the presented data the 'response', based on midday leaf water potential and the soil matric potential at 40 cm depth, is suggested as an indicator of site-specific water availability, allowing its evaluation with respect to plant growth, since it was significantly, negatively correlated with above-ground fresh biomass at plant maturity either for maize or for wheat (Fig. 6).

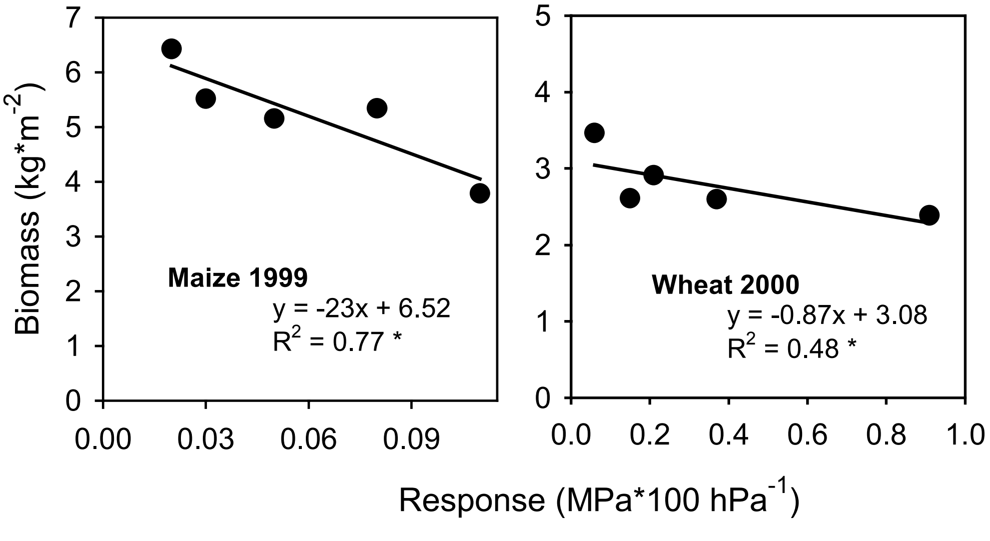

Fig. 6: Relationship between the site-specific response and final above-ground fresh biomass, shown for maize (growing season 1999) and wheat (growing season 2000). The equation of regression and the coefficient of determination are given. * indicates significance of the regression at $P \leq 0.05$.

2.5 Discussion

Site-specific water availability could be indicated by the response integrating the development of plant and soil water status during growing season into one term. The site-specific response was calculated from midday leaf water potential, since it thus reflects the situation of the assimilating plant. Predawn leaf water potential – though closely related to the soil water status, as found by Schmidhalter et al. (1998) – may rather indicate the extent of refilling during the night, as it was shown to be more related to soil water status of the wettest root zone, as found by Tardieu and Katerij (1991), Schmidhalter et al. (1992), Schmidhalter (1997), and Améglio et al. (1999). In our study the wettest root zone was found at 100 cm depth or even deeper soil layers. At these soil depths, however, only a small proportion of the root system might be expected, as can be derived from the studies of Wiesler (1991) and Stockle and Jara (2000) with maize and Ehlers (1975) and Beese et al. (1978) with wheat as well as from the study of Cabelguenne and Debaeke (1998) with both crops. Climatic demand could not be fulfilled from the low-root density zones, as also reported by Profitt et al. (1985), Tardieu and Katerij (1991), and Tardieu et al. (1992). The fact that in 1999 the response could only be calculated on the basis of midday leaf water potential but not based on predawn leaf water potential, gives therefore evidence to the midday-leaf water potential based response as a suitable indicator of plant water availability.

A low response, as obtained at the site ‘North’ in both years, represented high water availability which could be explained by its landscape position in a depression within the field. The simplified water balance indicated that the soil water content changed dynamically, which resulted in generally higher gains and losses of soil water in the profile compared to the other sites. This finding could be explained by lateral fluxes, as also suggested by Auerswald et al. (1997). The slightly higher soil water contents, observed at the site ‘North’ during growing season, might have resulted from the lateral fluxes to the site. As a consequence soil hydraulic conductivity might have been distinctly higher than at the other sites, since it was shown to change exponentially in loamy soils in the range of gravimetric or volumetric water contents between 20 to 40 % (Chanzy and Bruckler, 1993; Arya et al., 1999). In our field study gravimetric soil water contents varied between 15 and 25 %. Plant water uptake at the site ‘North’ appeared to be facilitated resulting in a small decrease of midday leaf water potential compared to the other sites.

In contrast, the high response of the site ‘West’ represented low water availability which might be attributed to the combined effect of landscape position and other pedogenic factors. One of the factors might be the high soil bulk density, as also shown by Greminger et al. (1985), Tardieu et al. (1992) and Tolk et al. (1998). Tolk et al. (1998) reported that plant water use was limited due to high soil bulk densities even with full irrigation on an Amarillo sandy loam. The lower water availability at the site “West” compared to the other sites could be further explained by the higher proportions of sand in the soil, which were shown to reduce distinctly hydraulic conductivity of the soil compared to other soils despite similar soil matric potentials (Auerswald et al. 1997; Kumke et al., 1999).

On the basis of the response, two contrasting sites regarding water availability, ‘North’ and ‘West’, could be identified in the studied field. Water availability at the sites ‘West Hill’, ‘East Hill’ and ‘Valley (South)’ may be considered as intermediate, varying mainly with actual weather conditions during growing season, as the ranking of these sites was not consistent in both years either for the response or for the above-ground fresh biomass. Similar results were reported within one field by Lark (2001) and Timlin et al (2001). A clear classification of the sites in our study may still be difficult, since spatial yield variation was smaller compared to other findings reported by Funk and Maidl (1997), Lapen et al. (2001), and Wenderoth et al. (2001). In our study distinct water limitation only occurred after the start of anthesis of maize and winter wheat in 1999 and in 2000, respectively. Consequently, it mainly affected biomass accumulation by a reduction of the level of assimilate production and the duration of assimilation period (Ludlow and Muchow, 1990). This may further be supported by our finding that site-specific variation in net photosynthetic rate and transpiration rate only occurred after anthesis during growing season 2000 (data not shown).

Despite the rather low yield variation, the site-specific differences in water availability were evident in both years. This finding may further emphasise that the response is a sensitive indicator of site-specific water availability. However, the response is not a fixed, absolute value for one site. The crop had a crucial influence on the range of response found for the various sites. This might be predominantly explained by the range of midday leaf water potential which was distinctly smaller in maize than wheat. Similar ranges were reported by numerous authors for maize (e.g. Turner, 1974; Fiscus et al., 1991; Tardieu and Davies, 1992) and for wheat (e.g. Henson et al., 1989; Turner and Henson, 1989). Therefore it can be concluded that the response can be determined in both, wheat and maize, but represents a crop specific value for a site. Nevertheless, it is a suitable and sensitive criterion for characterising water availability at one site relative to others, integrating the effect of soil texture, elevation and soil bulk density on soil water availability into one term.

2.6 Conclusions

The response was shown to be a semi-quantitative criterion for characterising water availability during growing season. As it refers to a point in the field, the measurements necessary to determine the site-specific response could be used as a tool to be combined with data obtained by a sensor approach because the latter refers to greater spatial dimensions. A sensor can mainly collect data about the current crop status. For fertiliser application, however, information about the current crop status as well as about the future development is needed. E.g. on sandy soils plants may grow more vigorously in the beginning of growing season. In this case it is not reasonable to further stimulate growth through fertiliser, since water availability will be limited during growing season on this soil. In contrast, the response refers to the relative crop performance at a site during growing season. Therefore the response is suggested as a weighting factor in the algorithms calculating the amount of applied fertiliser from sensor values.

3 Silicon accumulation, a tracer of crop transpiration in wheat ?

3.1 Abstract

Spatial crop yield variability was shown to be related to site-specific water availability. The aim of this study was to investigate Si as a tracer of crop transpiration in wheat in order to separate management units differing in water availability.

At five selected sites differing in water availability transpiration rate was measured on the youngest fully developed leaf. At four times during growing season plant samples, separated into young and old leaves, stems and ears (from anthesis), were taken to determine Si accumulation in plant dry matter. Silicon concentration in the soil solution was determined in 25-cm increments down to a soil depth of 100 cm.

The total amount of Si taken up was shown to result mainly from a biomass-dependent accumulation in the stem representing 76 to 43 % of total Si uptake. In contrast, the proportion of Si accumulated in leaves decreased from 50 % at tillering to less than 20 % of total Si uptake at dough development. The biomass-dependent effect on Si accumulation might be excluded by deriving crop transpiration from the Si content changes in leaves (overall changes of old and young leaves). Site-specific differences occurred in Si content of young and old leaves. However, the absolute differences in Si content changes could not be interpreted as differences in crop transpiration, since the Si concentration in the soil solution decreased with depth in the root zone. The variation of Si concentration in soil solution with depth may make it necessary to quantify the contribution of the various soil layers to plant water uptake. Since the absolute difference in concentration amounted to 3 ppm, further investigation is needed to estimate if this difference could be detected in Si accumulation in leaf dry matter.

3.2 Introduction

Water availability was shown to determine the spatial pattern of crop yield distribution within one field (Ide et al., 1987; Shaffer et al., 1993; Moore and Tyndale-Biscoe, 1999). In precision agriculture the variation in water availability should be considered in crop management (Tolk et al., 1998; Geesing et al., 2001; Timlin et al., 2001). Therefore a characteristic is needed for site-specific water availability. An exclusively soil-oriented approach was shown not to be suitable by Duda et al. (2001a). They found that site-specific water availability could be characterised by the response of midday leaf water potential to soil drying, thus combining water status of soil and plants. But it could only characterise site-specific water availability in a semi-quantitative way. In this study a quantitative approach was used by deriving water availability from plant water use.

The Penman-Monteith equation, as recommended by Allen et al. (1989), might be less suitable, since the soil water status is not considered. In addition, errors in the determination of input data may cause substantial variation in evapotranspiration calculated from the Penman-Monteith equation (Winterhalter und Fabian, 2000). The Penman-Monteith equation may thus offer only poor prospects of success for separating areas within one field, differing rather gradually in crop transpiration.

As Si was shown to be closely related to transpiration (Handreck and Jones, 1968; Paltridge and De Vries, 1973; Adatia and Besford, 1986; Reay, 1987), its potential as a tracer of crop transpiration was investigated in this study. Jones and Handreck (1965) showed for oat that crop transpiration could be quantified from the total Si uptake in plant dry matter and the Si concentration in the soil solution. Other authors, however, could not confirm this simple relationship (Mayland et al., 1991; Masle et al., 1992; Mayland et al., 1993). This could be explained by the fact that Si accumulation may also be influenced by other factors independent of transpiration. Duda et al. (2001b) found that both transpiration and growth, the latter expressed as change in dry matter, influenced independently the Si accumulation in plant dry matter of wheat. The growth effect might be attributed to a biomass-dependent Si accumulation. Its contribution to total Si accumulation might be greater at low than at high transpiration. The findings of Walker and Lance (1991) support this idea. They reported that plants accumulated relatively more Si than could be explained by mass flow when grown under conditions of low light and high humidity in the greenhouse, while total Si uptake was approximately proportional to mass flow under field conditions. Duda et al. (2001b) suggested to minimise the growth effect on Si accumulation by deriving crop transpiration from Si-content changes in leaves.

In this field study additional focus was put on the Si concentration in soil solution, since it may vary between the sites and with soil depth. McKeague and Cline (1963) and Walker and Lance (1991) showed that the Si concentration in soil solution varied considerably with depth. The majority of the former studies on Si uptake and transpiration did not take this aspect into account. Experiments were either conducted in pots filled with one type of soil (Jones and Handreck, 1963, 1969; Mayland et al., 1993) or on soils with only one horizon where plant roots could penetrate (Walker and Lance, 1991). In the field at the Experimental Farm of Scheyern, Germany, where this investigation was realised, plant roots can penetrate into several horizons. However, no information is yet available about the variability of Si concentration in the soil profile.

The present experiment was conducted in a field with spatial variability in water availability. At five selected sites the Si accumulation in different above-ground plant parts and the Si concentration of the soil solution in 25-cm soil increments were determined.

3.3 Material and Methods

3.3.1 Location, weather conditions, experimental design, and site characteristics

The field trial was conducted at the Scheyern Experimental Farm located in the tertiary hills of southern Germany. In 2000 the annual precipitation was 919 mm. During the growing season of winter wheat (March to July) there were 462 mm of rainfall compared to the six-year average of 402 mm. One field was chosen on the farm, spatially varying in water availability. The experimental design was created in order to test uniform crop management versus two approaches of site-specific crop management. The various management strategies were realised in 7.5-m large strips. The experiment was arranged in a randomised block design with seven replicates. The intensive measurements for determining water availability were done at five selected sites, subjected to uniform crop management. The sites differed in soil texture, soil bulk density, elevation and relative yield. Site characteristics are described in detail in 2.3.1.

3.3.2 Crop management

Winter wheat, cv. Petrus, was sown on October 22 in 1999 at a seeding rate of 320 seeds*m^{-2}. Mineral N fertiliser was split into three portions: 50 kg N*ha^{-1} at the start of growing season in March, 60 kg N*ha^{-1} at the second node stage, and 40 kg N*ha^{-1} at the end of booting. During tillering slurry was applied corresponding to 20 kg N*ha^{-1}. Plants were harvested on July 21 in 2000 (273 days after sowing, DAS).

3.3.3 Measurement of transpiration rate

Transpiration rate was determined with a portable, open gas exchange system (Model LCA4, ADC, Hoddesdon, UK) on the youngest fully developed leaf. Measurements were made on four different plants per plot and per date of measurement. Since the area of wheat leaves was smaller than the one of the chamber, transpiration rate had to be recalculated to actual leaf area. Therefore after the measurements of gas exchange, the width of ten leaves was determined within the area used for porometric measurements twice, once towards the tip and once towards the basis of the leaf. Mean leaf area of the plot was then calculated and used for the recalculation of transpiration rate.

3.3.4 Silicon determination

For determining Si accumulation in plant dry matter samples were taken at each site with one to three replicates four times during growing season: at the end of tillering (200 days after sowing, DAS), at late-boot stage (230 DAS), at anthesis (242 DAS), and at dough development (seed ripening) (258 DAS). Plants were cut above the ground from a surface of 0.16 m^2. They were separated into young and old leaves, and stems until late-boot stage. With anthesis the dry mass of ears was also determined separately. Young leaves were considered as those which were directly exposed to light, while old leaves were at least partially shaded. For the first harvest at the end of tillering, the three upper expanded leaves were considered as young leaves, while at late-boot stage only the flag leaf was collected as young leaf. Leaves still curled up were added to the stem fraction. The samples were oven-dried to constant weight at 60°C and taken for Si analysis. Silicon content in dry mass was determined according to the method described by Camp (1996) with an ICP (Liberty, Varian, Mulgrave, Vic., Australia). Total Si uptake was calculated for each plant part from the Si content and the dry matter per m^2.

Silicon concentration in soil solution was determined with four replicates in 25-cm soil increments down to a depth of 100 cm. Soil solution was extracted from the soil at field capacity with a rhizon soil moisture sampler (UMS, München, Germany) and then filtrated. Silicon concentration of the soil solution was determined with an ICP (Liberty, Varian, Mulgrave, Vic., Australia).

3.3.5 Statistical analysis

Statistical analyses were performed with SAS (SAS Institute Inc., Cary, NC, USA), version 6.2. Differences among class variables were tested by using ANOVA (SAS general linear model procedure). Significant differences between class variables were identified with LSMEANS multiple comparison for $P \leq 0.05$. Correlations and linear regressions were calculated with SAS REG procedure.

3.4 Results

Transpiration rate of the youngest fully developed leaf varied spatially in the field (Fig. 7). Site-specific differences were consistent after 235 DAS (=days after sowing). The transpiration rate was generally highest at the sites ‘North’ and ‘West Hill’, intermediate at the sites ‘East Hill’ and ‘Valley South’, and lowest at the site ‘West’.

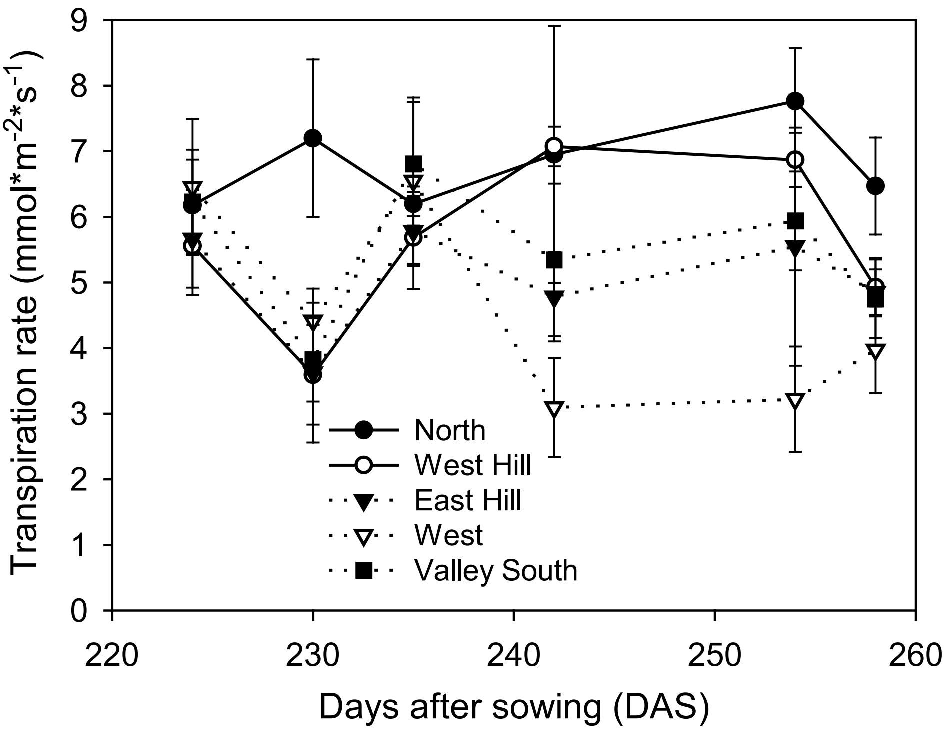

Fig. 7: Transpiration rate of the youngest fully developed leaf at the five selected sites during growing season of winter wheat. Mean values of four replicates are given. Vertical bars indicate the standard deviation.

The total Si uptake in above-ground dry matter increased continuously during growing season, but distinctly less from late-boot stage (230 DAS) to anthesis (242 DAS) compared to the other periods (Fig. 8). Site-specific differences in the total Si uptake were significant at 242 and 258 DAS. Silicon uptake was significantly higher at the sites ‘North’ and ‘West Hill’ at 242 DAS and at the site ‘North’ at 258 DAS compared to the other sites.

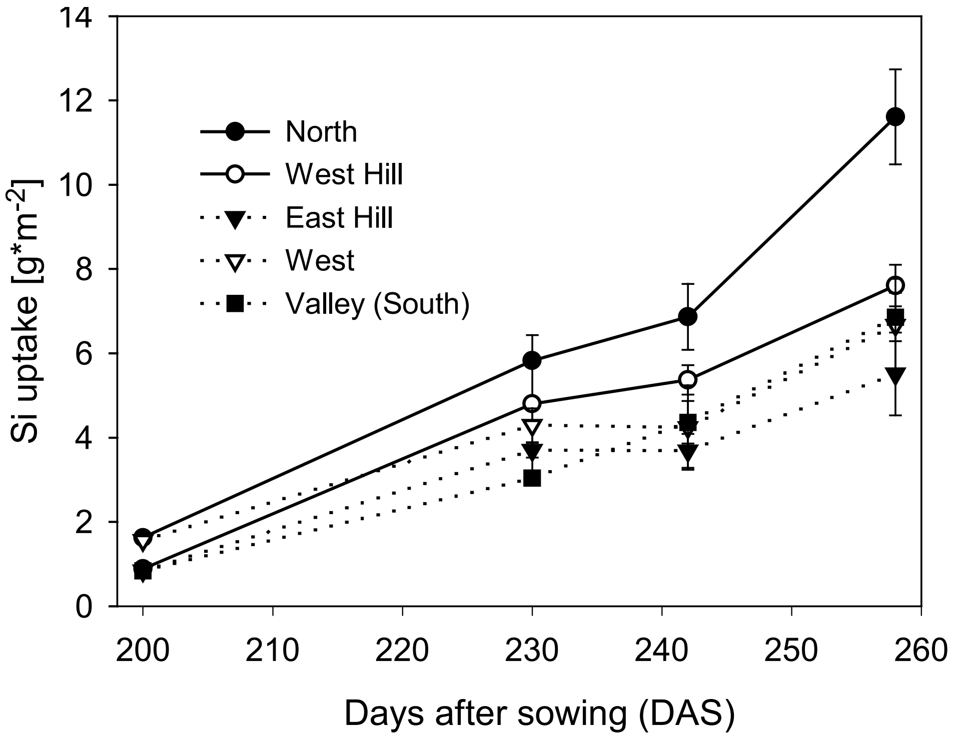

Fig. 8: Total Si uptake in above-ground dry matter at the five selected sites during growing season of winter wheat. Values of the first two sampling times (200 and 230 DAS) and at the last two sampling times (246 and 258 DAS) represent average values of two and three replicates, respectively. Vertical bars represent the standard deviation.

The total Si uptake reflected the accumulation of Si in non-transpiring organ to a large extent, as shown for the site 'North' in Table 4. The proportion of Si distributed to leaves decreased from nearly 50 % at late-tillering stage to less than 20 % during dough development (seed ripening). An important proportion of Si was accumulated in stems during growing season. It was highest at late-boot stage (76 %) and decreased to 43 % during seed ripening. After anthesis a considerable proportion was accumulated in the ears.

Table 4: Proportion of total Si uptake (%) in various above-ground plant parts at different times during growing season. Data is only shown for the site ‘North’.

	Days after sowing (DAS)			
Plant Part	200 DAS	230 DAS	242 DAS	258 DAS
young leaves	21	5	4	6
old leaves	25	19	15	11
stems	54	76	55	43
ears	-	-	26	40

Despite the varying contribution of stems and ears to total Si uptake, the Si content remained relatively constant in these organs (Fig. 9). Silicon accumulation could only be derived from the Si contents of young and old leaves (Fig. 9). While there was an overall increase in the Si content of young leaves during growing season, the Si content of old leaves only increased from anthesis to seed ripening. In young leaves the Si content was significantly lowest from 230 to 258 DAS at the site ‘East Hill’ and significantly highest at 230 and 242 DAS at the site ‘North’.

Site-specific differences were also found in the Si content of old leaves at 230 and 242 DAS. It was significantly highest at the site ‘North’. At 230 DAS the Si content in old leaves was significantly higher at the site ‘West Hill’ than at the other sites, and at 242 DAS it was significantly lower at the site ‘East Hill’ compared to the others.

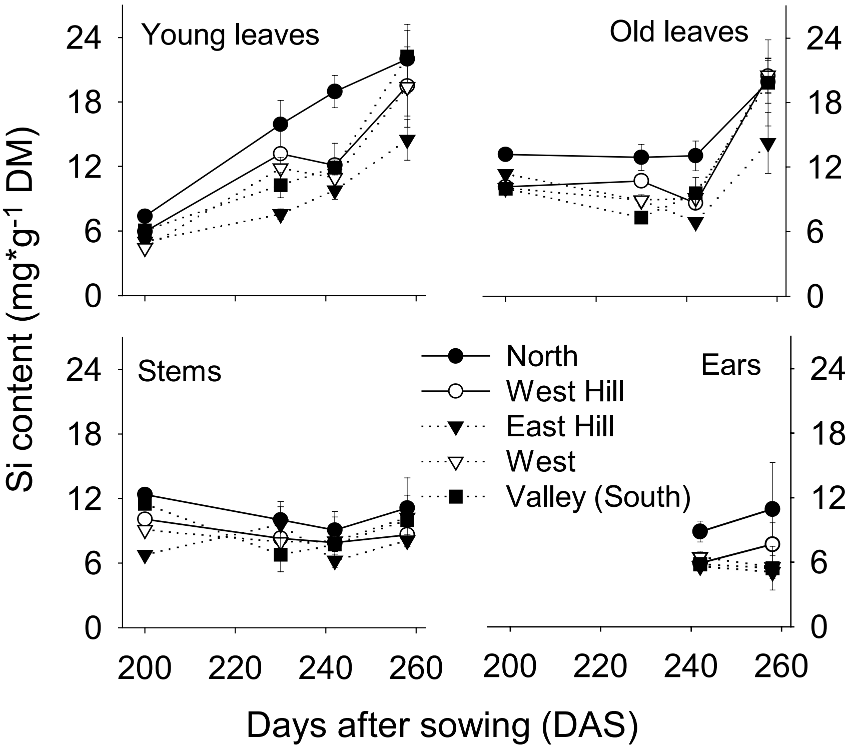

Fig. 9: Silicon content in various plant parts at the five selected sites during growing season of winter wheat. Values at 200 days after sowing (DAS), 230 DAS and at the last two sampling times (246 and 258 DAS) represent average values of one, two and three replicates, respectively. Vertical bars indicate the standard deviation.

The Si concentration in the soil solution generally decreased with depth in the soil profile at the various sites (Fig. 10). In the upper 25 cm the concentration ranged between 3 and 4.5 ppm Si, while it varied between 1 and 2 ppm Si below. At the site ‘North’, however, the Si concentration decreased less with depth compared to the other sites. At the site ‘Valley South’ the Si concentration in the soil solution was at 75-100 cm as high as in the upper 25 cm.

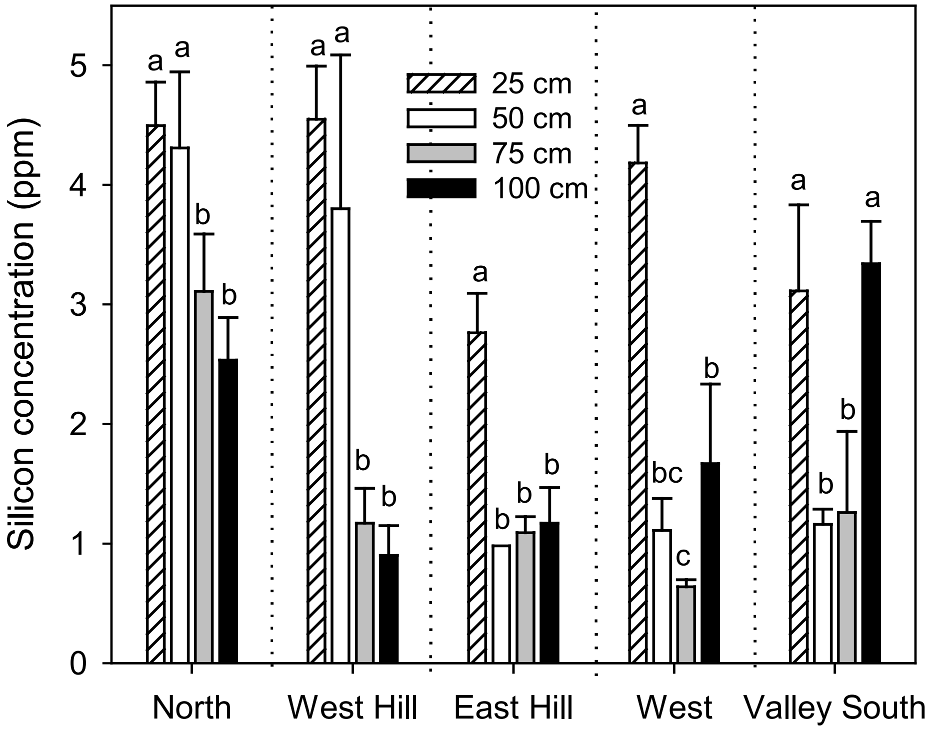

Fig. 10: Silicon concentration in the soil solution of 25-cm increments down to a depth of 100 cm at the five selected sites. Mean values of four replicates are given. Vertical bars indicate the standard deviation. Within the sites values with similar letters are not significantly different at $P \leq 0.05$ according to Tuckey-test.

3.5 Discussion

Total Si uptake was shown to be less suitable for quantifying crop transpiration, which is in agreement with the results of Hutton and Norrish (1974). According to our data this might be explained by the large amount of silicon allocated to the stem, which can be considered as a low-transpiring organ. In stems Si accumulation was reported to be concentrated in the walls of xylem vessels (Aston and Jones, 1976). Its extent may be independent of transpiration but rather dependent on dry matter already present, giving further evidence to the growth effect on Si accumulation, independent of transpiration, which was reported by Duda et al. (2001b) in wheat. Due to the dominant influence of stem Si accumulation, total Si uptake could not be used for detecting site-specific differences in crop transpiration.

Apart from the stem, the ear accumulated an important proportion of Si (40 %), which is in agreement with the results reported by Handreck and Jones (1968) for oat, but slightly higher than the proportion found by Hutton and Norrish (1974) in wheat. This finding may point to the relative importance of ears for crop transpiration at later growth stages, as also reported by Dubach (1990). A large part of Si accumulation in ears might be attributed to transpiration, since Si can be considered as phloem immobile (Reay, 1987; Samuels et al., 1991). Furthermore, Handreck and Jones (1968) and Hutton and Norrish (1974) reported that Si contents were distinctly higher in the husks than in the grains. In this study husks and grains were not separated, as this would have required too much time. The constancy of the Si contents of the whole ear can be explained by the extent of grain growth compensating for Si accumulation in the husks (Handreck and Jones, 1968).

Transpiration – at least in part - could be derived from the changes in the Si content of leaves. The presented data indicate that young leaves may be more suitable than old leaves for quantifying transpiration. The constancy in Si content of old leaves until anthesis can be attributed to the fact that they represented a mixture of leaves differing in duration and intensity of transpiration and hence in Si content according to their age, as also reported by Jones et al. (1963) and Fox et al. (1969).

The duration and intensity of transpiration generally had the predominant influence on the extent of Si content changes. The period from late-boot stage to anthesis might have been too short for determining the cumulative effect of transpiration in Si content of young leaves at all sites except ‘North’. The distinct increase at this site might be related to the fact that the transpiration rate was consistently higher relative to the other sites during the whole period before. These findings emphasised the characteristic of Si as a cumulative parameter for quantifying crop transpiration, with the duration and intensity of transpiration mainly determining Si accumulation.

The site-specific differences in Si content still did not indicate absolute differences in the extent of transpiration, since the Si concentrations in soil solution varied between the sites and with depth in the root zone. The major source of Si for the soil solution is amorphous opal A in the soil (Jones and Handreck, 1967; Hallmark et al., 1982). This fraction may be higher in the upper 25 cm, as amorphous opal A, the predominant form of Si in the plant (Parry and Smithson, 1964; Jones et al., 1966; Handreck and Jones, 1968; Bartoli and Wilding, 1980; Bartoli, 1985; Epstein, 1994) and the most important source of Si for soil solution (Jones and Handreck, 1965), was regularly added to the soil through plant residues. At the site ‘North’ the soil is of colluvic origin which might thus explain the lesser decrease in Si concentration with soil depth. At the site ‘Valley South’ the higher Si concentrations at 75-100 cm depth might also be attributed to colluvic soil material extending from neighbouring areas outside the field. At both sites the higher Si concentration in soil solution compared to the other sites could also indicate a greater degree of soil weathering (Jones and Handreck, 1965; Hallmark et al., 1982; Dahlgren, 1993; Hodson and Evans, 1995; Stonestrom et al., 1998), since the whole profile at the site ‘North’ and the depth of 80 and 100 cm at the site ‘Valley South’ were characterised by dynamic water movements (see chapter 2).

The variability in Si concentration in the soil solution between the sites and depths may confirm the need to consider it when site-specific crop transpiration should be derived from Si accumulation in leaf dry matter. However, absolute differences in concentration were relatively small with 1 to 3 ppm Si. As far as to the authors’ knowledge, there is no information available about the selectivity of Si accumulation in the plant with respect to the quantification of crop transpiration. This should therefore be determined in future experiments. If the variation in Si concentration can be detected in Si accumulation in leaves, the quantification of the relative contribution of each soil depth to total plant uptake during different periods will be necessary.

4 Evaluating Silicon as a Tracer of Crop Transpiration in Wheat

4.1 Abstract

Silicon accumulation was identified as a potential tracer of crop transpiration. In a previous study Si concentration in the soil solution was shown to vary with depth in the root zone in the field. For quantifying crop transpiration at different sites within one field differing in water availability the contribution of each soil depth to plant water uptake could therefore be necessary to be determined. Since the absolute difference in Si concentration in soil solution was only 3 ppm, the question arose if it can be detected in Si accumulation in plant dry matter. This study aimed at determining the feasibility of Si accumulation as a tracer of crop transpiration with respect to different Si concentrations in soil solution. The results are further discussed with respect to the differentiation between areas of varying water availability in the field.

Under controlled conditions in the glasshouse the relation between Si accumulation and crop transpiration was investigated as a function of water regime and three types of soils differing in Si concentration in soil solution and soil texture.

Silicon content changes in leaves could be used to quantify crop transpiration on the silt and on the clay loam. On the sandy loam Si uptake was inhibited by pedogenic factors. On the other two soils the cumulative effect of a 3-ppm difference in Si concentration in soil solution could not be clearly detected in Si accumulation in the range of 100 to 200 mm crop transpiration. When crop transpiration calculated from Si accumulation was related to measured crop transpiration, the measured crop transpiration was slightly overestimated. The variation of the data was high allowing an estimation of actual crop transpiration with a precision of 50 to 100 mm. As total plant water use during growing season may be expected to range between 150 and

250 mm under temperate climatic conditions, Si accumulation may give only a rough estimate of crop transpiration allowing to reveal tendencies in site-specific water availability within one field.

4.2 Introduction

The spatial variability in crop yield was shown to be related to differences in water availability in the field (Ide et al., 1987; Shaffer et al., 1993; Moore and Tyndale-Biscoe, 1999). As water availability is a crucial factor for nutrient availability, management practices, such as N fertilisation, should be varied according to the water regime in precision agriculture (Tolk et al., 1998; Geesing et al., 2001; Timlin et al., 2001). However, a parameter is still needed to quantify site-specific water availability (Mulla, 1991; Sadler et al., 2000b).

Silicon accumulation in the plant was shown to be closely related to crop transpiration (Jones and Handreck, 1965; Paltridge and De Vries, 1973; Adatia and Besford, 1986; Reay, 1987). Duda et al. (2001b) showed that crop transpiration could be derived from the changes in Si content of leaves. In a field study the Si content of leaves was found to differ among sites of varying water availability during growing season (see chapter 3). The observed spatial variability in Si contents of leaves resulted from a combined effect of different extents of transpiration, on the one hand, and the variation in Si concentration in soil solution, on the other hand. But the latter did not only vary between sites but also with soil depth, as also reported by McKeague and Cline (1963) and Walker and Lance (1991). The absolute variation in Si concentration in soil solution ranged only between 1 and 3 ppm. To our knowledge, there is no information available in literature if this small absolute variation in Si concentration can be detected in Si accumulation in plant dry matter.

This study aimed at determining the feasibility of Si accumulation as a tracer of crop transpiration with respect to differences in Si concentration in the soil solution. Therefore it was important to measure directly the crop transpiration. Wheat was grown in containers, filled with three soils of varying soil texture and Si concentration in soil solution, under controlled conditions in a glasshouse. In order to vary cumulative transpiration rates, plants were subjected to two different water regimes. The chances and limits of using Si accumulation in the field are discussed with respect to the differentiation between areas of varying water availability.

4.3 Material and Methods

4.3.1 Plant Material

Wheat (*Triticum aestivum* L., cv. Thassos) was sown in containers (0.7 m^2 x 0.6 m) on February 14, 2001. Seeding rate gave a final plant population of 255 ± 6 plants $*m^{-2}$. The experiment started at the end of tillering (March 21, 2001 = 1 day of experiment, DE) and ended during dough development (June 11, 2001 = 81 DE). Plants were kept in the glasshouse with temperature-based ventilation. Until the end of tillering (during preculture) target temperatures were 8°C/4°C, during the experiment they were 16°C/12°C day and night. In addition to natural light entering the glasshouse, light was supplied by high pressure sodium lamps (SON-T Agro 400 W, Phillips), ensuring a light intensity of 200 – 300 $\mu mol*m^{-2}*s^{-1}$ at the crop surface level from 6 a.m. to 6 p.m. Nitrogen fertiliser was applied as ammonium nitrate three times at a rate of 30 kg $N*ha^{-1}$, at the two-leaf stage (February 28, 2001), at the end of tillering (March 21, 2001), and at late-boot stage (May 3, 2001).

4.3.2 Irrigation and cumulative crop transpiration

During preculture the containers were similarly watered regularly with distilled water to ≈ 70 % soil water capacity. Water loss and the amount of irrigation water were determined by weighing the containers.

With the start of the experiment, corresponding to 1 day of experiment (DE), plants were irrigated daily after 6 p.m., unless they were subjected to drought. The amount of water irrigated was proportionate to water loss from the containers during the day and to soil matric potential. The latter was kept above –300 hPa in the control treatment. Drought was induced three times by omitting irrigation from 4 to 19 DE, from 27 to 38 DE, and from 48 to 58 DE.

Daily crop water consumption was calculated from the difference in containers' weight after irrigation and the following day before irrigation. Evaporation from bare soil could be neglected because the soil was covered by a 2-cm layer of coarse quartz (0.4 - 0.5 cm). Cumulative crop transpiration for a period was derived from the sum of daily crop water consumption.

4.3.3 Soil characteristics

Three types of soil were used in this experiment. They were topsoils from different sites at the Scheyern Experimental Farm, Germany. Water holding capacity as well as soil texture are given in Table 5.

Table 5: Water holding capacity and soil texture of the three topsoils of the Scheyern Experimental Farm, Germany.

Soil	Water holding capacity (g H_2O*1 kg^{-1} soil)	Si conc. in soil solution (ppm)	Soil texture		
			sand (%)	silt (%)	clay (%)
sandy loam	267	7	63	22	15
silt loam	412	7	19	58	23
clay loam	431	4	29	45	26

4.3.4 Measurements

For determining Si accumulation in plant dry matter eight plants in each container were cut above the ground (excluding plants from the edge of the container) at four growth stages: at the end of tillering (3 days of experiment, DE), at late-boot stage (48 DE), at anthesis (62 DE), and during dough development (83 DE). They were separated into young and old leaves, and stems until late-boot stage. With anthesis the dry mass of ears was also determined separately. Young leaves were considered as those which were directly exposed to light, while old leaves were at least partially shaded. For the first harvest at the end of tillering, the three upper expanded leaves were considered as young leaves, while at late-boot stage only the flag leaf was collected as young leaf. Leaves still curled up were added to the stem fraction. The samples were dried to constant weight at 60°C. Dry weight was determined. The samples were taken for Si analysis. Silicon content in dry mass was determined according to the method described by Camp (1996) with an ICP (Liberty, Varian, Mulgrave, Vic., Australia).

Silicon concentration in soil solution was determined in each soil with ten replicates. Soil solution was extracted from the samples at water capacity with a rhizon soil moisture sampler (UMS, München, Germany) and then filtrated. Silicon concentration of the soil solution was determined with an ICP (Liberty, Varian, Mulgrave, Vic., Australia).

4.3.5 Experimental design and statistical analysis

The experimental design was a randomised block design. In order to avoid edge effects the containers' position was daily changed in the glasshouse with the order of the containers (blocks) being maintained. Statistical analyses were performed with SAS (SAS Institute Inc., Cary, NC, USA), version 6.2. Differences among soils and treatments were tested by using ANOVA (SAS general linear model procedure). Significant differences between class variables were identified with LSMEANS multiple comparison for $P \leq 0.005$. Correlations and linear regressions were calculated with SAS REG procedure.

4.4 Results and discussion

4.4.1 Suitability of Si accumulation as tracer of crop transpiration with respect to differences in Si concentration in soil solution

The drought treatment resulted in a significantly lower cumulative crop transpiration compared to the control after the first drought period (Fig. 11). Differences between the soils occurred in both treatments. The lower cumulative crop transpiration on the sandy loam in the drought treatment could be ascribed to the lower water holding capacity of this soil. The higher cumulative crop transpiration on the clay loam, which was found in both treatments after late-boot stage (50 days of experiment, DE) compared to the silt loam, might be explained by the higher fresh biomass of the plants (data not shown).

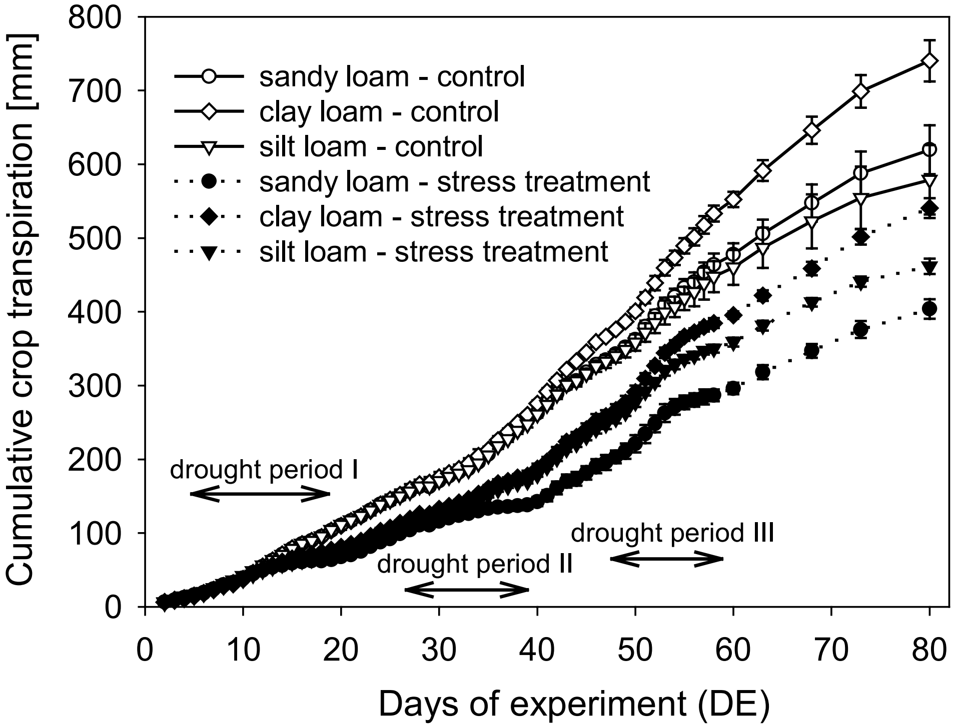

Fig. 11: Cumulative crop transpiration of wheat in the control and the drought treatment on the three types of soil from late tillering (3 days of experiment, DE) to dough development (83 DE). Mean values of three replicates are given. Vertical bars indicate the standard deviation.

Despite the distinctly higher cumulative crop transpiration, Si contents of the various plant parts varied in a smaller range on the clay loam compared to the silt loam (Fig. 12A and B) because Si concentrations were lower in the clay loam (4 ppm vs. 7 ppm). The distinctly smaller variation of Si contents on the sandy loam (Fig. 2C), however, could neither be attributed to differences in cumulative crop transpiration nor Si concentrations in the soil solution. At least in the control cumulative crop transpiration on the sandy loam was similar to the one on the silt loam. In addition, Si concentration in soil solution in the sandy loam was as high as in the silt loam (7 ppm). Variations in Si concentration, owing to soil drying and rewatering with distilled water, could neither explain the finding. In a former experiment with these three soils

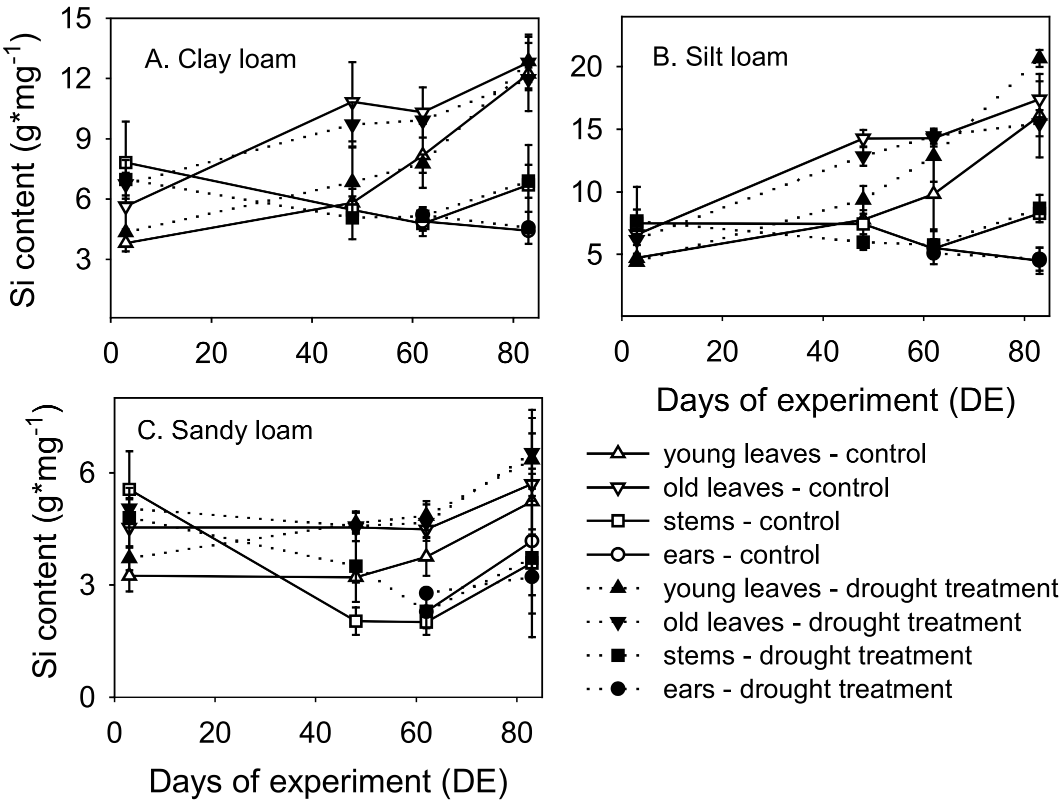

Fig. 12: Silicon content in various plant parts of wheat, subjected to the control and the drought treatment, on the three types of soil from late tillering (3 days of experiment, DE) to dough development (83 DE). Mean values of three replicates are given. Vertical bars indicate the standard deviation.

(data not shown), Si concentrations in all soils were found to remain constant with soil drying and to equilibrate within less than one day after watering with distilled water. Similar results were reported by Jones and Handreck (1965) for different soils. Therefore the small variation in Si contents on the sandy loam might rather point to a pedogenic factor inhibiting Si uptake by plant roots. Consequently, cumulative crop transpiration was not significantly correlated to the change in Si content of leaves, representing the overall change in young and old leaves (Fig. 13). In contrast, a significant correlation was found for the clay and the silt loam, as also reported by Duda et al. (2001b) for a different soil. According to the different Si concentrations in soil solution, the slope of the regression for the silt loam was higher than for the clay loam. Based on the total range of cumulative crop transpiration, the cumulative overall effect of a 3-ppm difference in Si concentration could be clearly shown (Fig. 13). In the lower range of crop transpiration (< 150 mm), however, a clear differentiation may be rather difficult due to the high variation of the data.

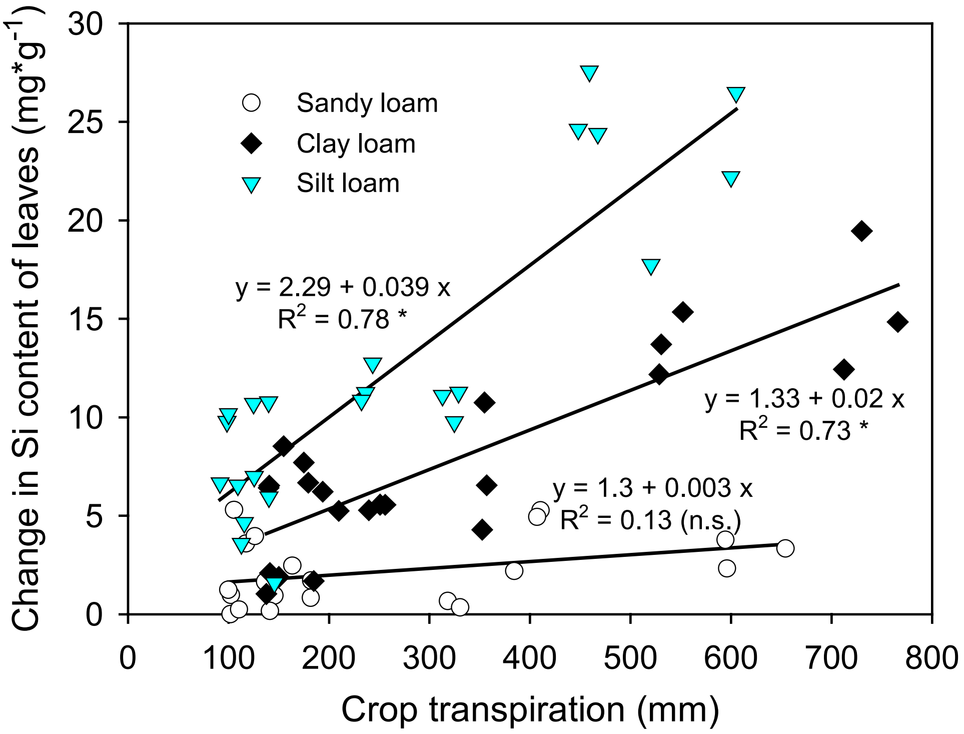

Fig. 13: Change in Si content of leaves (overall effect of young and old leaves) as a function of crop transpiration of wheat, grown on three types of soil. Single values are included from the control and the drought treatment. The equation of regression and the coefficient of determination are given. * indicates significance of the regression at $P \leq 0.05$; n.s. means non-significant.

4.4.2 Chances and limits for using Si for differentiating crop transpiration within one field, spatially varying in water availability

For evaluating Si as a tracer of crop transpiration, crop transpiration was calculated from Si content changes in leaves ($\Delta\ \mathrm{Cont}_{Si}$), representing the overall change in young and old leaves and the Si concentration in soil solution (Conc_{Si}) according to equation (1):

$$T = \Delta\ \mathrm{Cont}_{Si} / (\mathrm{Conc}_{Si} \cdot 0.005) \qquad (1)$$

The constant factor of 0.005 $m^2 \cdot g^{-1}$ was empirically derived from the regression equation (Fig. 13) for both soils. It might represent the average change in leaf dry matter thus reflecting growth conditions. If water availability is the major constraint to plant growth, the empirical factor determined might also be applied to field data. Poorter and Nagel (2000) showed with an allometric analysis of above-ground dry matter data from literature that changes in biomass allocation to leaves do not play a large role in the adaptation of plants to a low water supply. Nevertheless, the constant factor still needs further investigation.

The relation between the measured and the calculated crop transpiration (Fig. 14) was close to the 1:1-line for both soils, although actual (measured) crop transpiration was slightly overestimated when derived from Si accumulation. Since the Si content change of leaves included the change in young and old leaves, this finding may be attributed to dry matter retranslocation from old leaves occurring with anthesis. This may result in concentrating Si in the leaf, as Si is phloem immobile and not retranslocated (Jarvis, 1987; Reay, 1987).

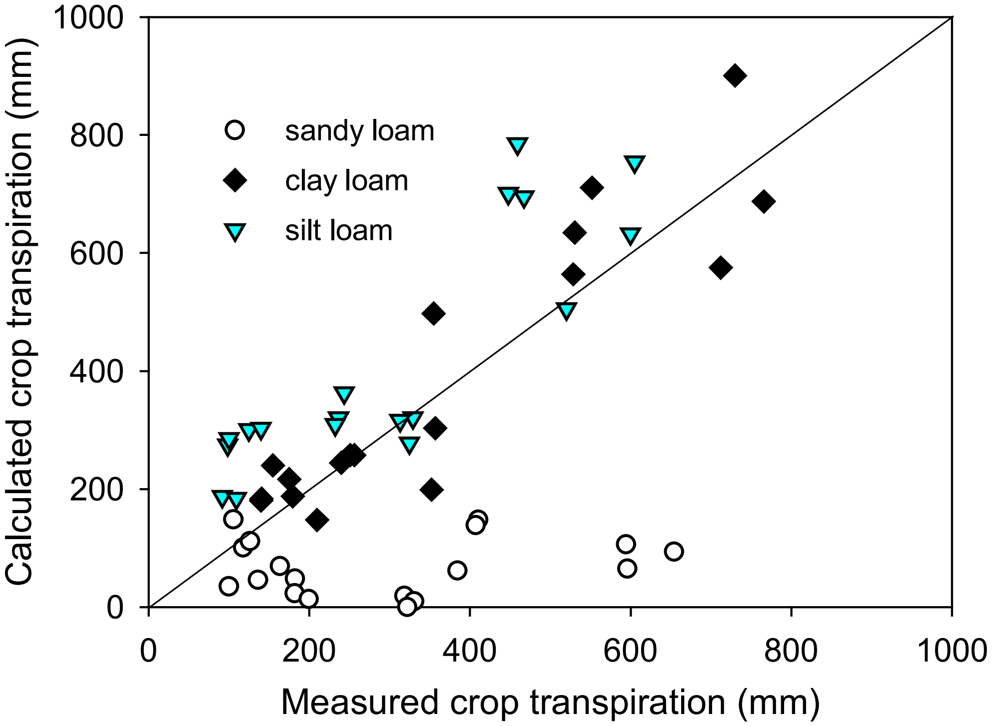

Fig. 14: Crop transpiration calculated from Si content changes in leaves as a function of measured crop transpiration. Single values are included from each soil and from both treatments. The 1:1-line is given.

The slight overestimation found and the high variation of the data might further be explained by the fact that the relation between Si and crop transpiration is based on the simple model that Si is taken up passively and transported with the transpiration stream at constant concentration into the shoot, as Hodson and Evans (1995) outlined in their review. The uptake of Si by the roots can be considered passive according to the results of Nable et al. (1990). But the transport at constant concentrations within the transpiration stream may rather represent conditions of high evaporative demand, as discussed by Steudle and Peterson (1998). They outlined that under low evaporative demand, like on cloudy days or during the night, water transport may be mainly symplastic or occur through special channels, with the path being different for water and solutes (Steudle and Henzler, 1995). Accumulation of Si in leaves may then occur at higher rates than due to the concentration in the soil solution. This may be further supported by the results of Mayland et al. (1991). They reported that Si accumulation was closely related to transpiration under conditons of high evaporative demand, but was greater than could be explained by mass flow under low evaporative demand. Consequently, Si concentration in the xylem sap may not be constant during the day or during growing season, as also reported by Jones and Handreck (1965) for oat and by Gartner et al. (1984) for wheat. Our results might further indicate that the assumption of constant Si concentrations could therefore only be applied with care under the climatic conditions of Germany, even in a glasshouse. The good relation between crop transpiration and the Si content change in leaves might be even rather surprising, considering that ear transpiration was reported to become more important for total crop transpiration (Handreck and Jones, 1968; Dubach, 1990). Nevertheless the Si content of ears remained constant. The finding could be explained by grain growth, which was shown to depend on photosynthesis of the flag leaf (Blum et al., 1988; Chhabra and Sethi, 1989; Bort et al., 1994) and on retranslocation from stems and leaves (Yang et al., 2001), and which may have compensated for the Si accumulation in the husks, as reported by Jones and Handreck (1967). Therefore the present data may indicate that the retranslocation from leaves concealed the influence of transpiration on Si accumulation in the ear.

The relation between the measured and the calculated crop transpiration (Fig. 14) is characterised by high variation of the data, allowing an overall estimation of crop transpiration with a precision of 50 to 100 mm. Under temperate climatic conditions crop transpiration for wheat was reported to range between 150 and 250 mm (Beese et al., 1978; Abdel-Kader, 1996; Cabelguenne and Debaeke, 1998). Hence, for differentiating areas of varying water availability within one field the spatial variability should be relatively high. At Scheyern, where the field trials of this investigation were realised, relative grain yield (yield of one unit within one field as percentage of the average yield of the field) spatially varied by only 10 - 20 % within one field. Therefore it can be expected that only extreme differences in water availability could be detected when Si is used as a tracer of crop transpiration.

4.5 Conclusions

Based on the whole range of crop transpiration the 3-ppm difference in Si concentration in soil solution could be detected in Si accumulation in plant dry matter. At lower crop transpiration (< 200 mm) the difference between the Si concentrations in soil solution was less clear. As this finding was based on the cumulative character of Si accumulation, the need to quantify plant water uptake from different soil depths may depend on the relative contribution of each depth to plant water use. This, however, may remain difficult in a field where lateral fluxes distinctly influence water availability, as their quantification was not yet shown.

The precision of 50 to 100 mm for estimating crop transpiration on the basis of Si accumulation may limit the feasibility of Si as a tracer of crop transpiration when spatial variability in water availability within one field should be detected. As total crop water use during growing season may be expected to range between 150 and 250 mm in the field, Si accumulation may represent a rough estimate of crop transpiration. It could be rather used to reveal tendencies in the variabililty in water availability within one field.

5 General discussion

Site-specific water availability could only be characterised by combining soil and plant water status, which is in agreement with the results reported by Sadler et al. (2000a). Soil matric potential alone measured at one point in the soil, has a limited suitability, since soil texture, soil bulk density as well as root distribution were shown to vary considerably within the soil profile (Ritchie, 1981; Tardieu and Kraterij, 1991; Cabelguenne and Debaeke, 1998). Midday leaf water potential could neither be used as a single characteristic, which could be attributed to the fact that it is strongly influenced by climatic conditions which cannot be kept constant from one measurement time to the other in the field. But the midday leaf water potential was also shown to be closely linked to the soil matric potential in the main root zone (Tardieu and Kraterij, 1991). The site-specific response, representing the decrease in midday leaf water potential to a 100-hPa decline in soil matric potential at 40 cm depth, was a suitable characteristic to reveal site-specific differences in water availability.

However, it was not a fixed value when derived from leaf water potential in maize or wheat, since crop water status did not vary within the same range for these crops. Midday leaf water potential was reported to decrease down to -1.9 MPa in maize (e.g. Turner, 1974; Fiscus et al., 1991; Tardieu and Davies, 1992) and to -3.0 MPa in wheat (e.g. Henson et al., 1989; Turner and Henson, 1989).

For precision agriculture the response can be used as a semi-quantitative characteristic of water availability, giving information about the relative crop performance at one site compared to other sites within one field.

An estimate of the amount of available soil water can be achieved by crop transpiration derived from Si accumulation. Both crop transpiration and Si accumulation were shown to be closely correlated (Handreck and Jones, 1968; Paltridge and De Vries, 1973; Adatia and Besford, 1986; Reay, 1987). The lack of correlation, found in the glasshouse experiment on a sandy loam, represented a rather unique phenomenon compared to the literature. Other authors (Mayland et al., 1991; Walker and Lance, 1991; Masle et al., 1992; Mayland et al., 1993) who could not confirm the quantitative relation between crop transpiration and Si accumulation, found more Si accumulated than could be explained by mass flow. Our results found on the sandy loam therefore need further verification.

The feasibility of Si accumulation for differentiating areas of varying water availability may depend generally on two factors. Firstly, climatic conditions were shown to have a crucial influence on the relation between crop transpiration and Si accumulation (Mayland et al., 1991; Walker and Lance, 1991), since Si uptake in above-ground dry matter may be explained by a transpiration-related and a biomass-dependent accumulation (Duda et al., 2001b). This study further supported these findings. Hence Si accumulation may be a suitable tracer of crop transpiration under conditions of high evaporative demand with transpiration-driven transport and accumulation of Si being more important than biomass-dependent Si accumulation.
Secondly, the Si concentration in soil solution may also have an influence on the suitability of Si as a tracer of crop transpiration. In the present field study Si concentrations varying between 1 and 5 ppm were relatively low compared to 20 and 30 ppm reported in literature (Mayland et al., 1991; Schultz and French, 1976; Jones and Handreck, 1967). Owing to the cumulative character of Si as a tracer, the low Si concentration in soil solution may result in a longer period required for detecting site-

specific differences in crop transpiration. The variation of Si concentration in soil solution within the root zone may make it further necessary to quantify plant water uptake at various soil depths.

In this study Si accumulation was calculated from the change in Si content of leaves. In most of the former studies crop transpiration was derived from the change in total Si uptake (Jones and Handreck, 1965; Schultz and French, 1976; Mayland et al., 1991), implying transpiration of leaves and ears during later growth stages. Dubach (1990) showed that ear transpiration may be important. Silicon in the ear may be mainly attributed to transpiration, since Handreck and Jones (1968) and Hutton and Norrish (1974) showed that it was mainly accumulated in husks. Therefore it would have been expected that at later growth stages crop transpiration would be underestimated when derived from Si content changes in leaves. However, this could not be confirmed in the glasshouse experiment (chapter 4). The good relation between the changes in Si content of leaves and crop transpiration, even at later growth stages, might be explained by the concentration of Si in the leaves during assimilate retranslocation owing to the fact that Si is phloem immobile (Jarvis, 1987; Reay, 1987). Assimilate retranslocation appeared to be closely linked to grain growth (Kruk et al., 1997; Evans and Fischer, 1999), since Si contents in the ears remained constant until dough development, which is in agreement with the results of Handreck and Jones (1968). For using Si content of leaves as a tracer for crop transpiration this aspect should be further investigated. In addition, the constant factor which is needed to calculate crop transpiration from Si content changes in leaves (compare chapter 4) should be studied in more detail.

The major limit for using Si as a tracer of crop transpiration can be attributed to the high varation of the data. Silicon accumulation may be only a rough estimate of crop transpiration, since the latter may only be calculated with a precision of 50 to 100 mm. Crop transpiration of field-grown wheat, determined by Abdel-Kader (1996) at the Scheyern Experimental station, Germany, was less than 200 mm. Beese et al. (1978), Cabelguenne and Debaeke (1998) determined crop transpiration of wheat, grown in the field under temperate climatic conditions, ranging between 200 and 250 mm during growing season. Higher amounts of crop transpiration, reported by Roth and Günther (1987), Roth et al. (1988), and Boese (1992) for wheat under temperate climatic conditions, could not be compared to our field data, since they were obtained in irrigated wheat and on soils with higher water holding capacity.

With the precision determined in this study Si accumulation may therefore only be suitable to differentiate areas of varying water availability when site-specific differences are large. The use of crop transpiration calculated from Si accumulation for separating different areas of water availability in precision agriculture might be further restricted when the contribution of various soil depths to plant water uptake have to be considered due to variable Si concentration in soil solution within the root zone. This may require tremendous installations, hence conflicting the need of simple means in precision agriculture, or be even erroneous in areas where lateral fluxes influence water availability, since their quantification was not yet shown.

6 General conclusions

This investigation has increased knowledge for the understanding of site-specific water availability, but the search for a characteristic which could be used to separate areas of differing water availability in precision agriculture will continue in future.

Silicon accumulation could principally be used as a tracer of crop transpiration despite the high variation of the data. On the one hand, this variation may facilitate the use of Si in the field when Si concentration in the soil solution varies with depth in the root zone. The present data indicated that in the range of 100 and 200 mm of crop transpiration during growing season, which can be expected for wheat under temperate climatic conditions, a 3-ppm difference in Si concentration in soil solution could not be clearly differentiated in Si accumulation in leaf dry matter.

On the other hand, the high variation restrains the feasibility of Si accumulation to fields where differences in water availability are large. In fields with water availability varying rather gradually only extreme sites might be identified or tendencies in spatial variability of water availability might be detected.

The site-specific response may offer more prospects for use in precision agriculture. As semi-quantitative criterion it can characterise water availability of a site relative to others. Since it refers to one point in the field, it has to be combined with an area-based parameter, e.g. sensor value. The response implies the development of plant water status during a period of water shortage. It therefore might be used as a weighting factor for sensor values being more determined by the current water status.

7. Summary

Spatial yield variability was shown to be related to site specific water availability. In precision agriculture fertilisation should be varied according to site specific water availability during growing season. But a parameter characterising site specific water availability is still needed. This study aimed at finding a characteristic of site specific water availability using two approaches.

In the first approach the potential of soil matric potential and leaf water potential were investigated as characteristics of site specific water availability. Therefore a field trial was conducted in the tertiary hills of southern Germany with heterogeneous soils and undulating relief. Based on information about variation in soil texture, soil bulk density,elevation and potential yield, five sites were selected within one field. Soil and plant water status and above-ground biomass were determined regularly during growing season of maize in 1999 and winter wheat in 2000.

Neither soil matric potential nor leaf water potential alone were suitable to characterise site specific water availability. Differences between the sites became evident when the soil matric potential at 40 cm depth was correlated with the midday leaf water potential. Its decrease to a 100-hPa decline in soil matric potential at 40 cm depth is called the ‘response’ of a site. The response was significantly, negatively correlated with the above-ground fresh biomass in maize (R2=0.72 at P<0.05) and in wheat (R2=0.48 at P<0.05). On the basis of these results the response was suggested as a semi-quantitativ characteristic of site specific water availability.

In the second approach water availability was derived from crop transpiration. Since silicon was shown to be closely correlated with crop transpiration, its potential as a tracer of crop transpiration to differentiate areas differing in water availability was

studied. During the field trial in 2000 Si content was determined in various plant parts of winter wheat, and Si concentration in soil solution was measured in 25-cm increments down to 100 cm depth.

The findings supported previous results that total Si uptake may not be suitable for quantifying crop transpiration, since it was shown to be predominantly determined by the transpiration-independent Si accumulation in the stem. This biomass-dependent accumulation in the stem might be excluded by deriving transpiration from Si content changes in leaves. However, the absolute differences in Si content changes between the sites could not be interpreted as differences in cumulative crop transpiration, as the Si concentration in soil solution varied by 1 to 3 ppm with depth in the rooting zone. This finding may make it necessary to quantify the contribution of each soil layer to plant water uptake.

In order to determine if the absolute difference in Si concentration in soil solution found could be differentiated in Si accumulation in leaf dry matter, this aspect was further studied in wheat, grown on three different soils of varying soil texture and Si concentration in soil solution under controlled conditions in the glasshouse. Silicon content changes in leaves could be used to quantify crop transpiration on the silt and on the clay loam. On the sandy loam Si uptake was presumably inhibited by pedogenic factors. In the two other soils the cumulative effect of a 3-ppm difference in Si concentration in soil solution could be shown for the total range of crop transpiration studied, but could not be clearly differentiated in the range of 100 to 200 mm owing to the relatively high variation of the data. This may have consequences for the feasibility of Si accumulation with respect to differentiating areas of differing water availability in the field. On the basis of the present results actual crop transpiration may be estmated from Si accumulation with a precision of 50 to 100 mm. With total plant water use during growing season ranging between 150 and 250 mm under temperate climatic conditions differences in site specific water availability would have to be large to be detected.

Concluding from the two approaches the response was found to be a sensitive criterion characterising water availability at one site relative to others. With Si accumulation crop transpiration, hence water availability could only be roughly estimated allowing to reveal tendencies in site specific water availability within one field.

8. Zusammenfassung

Die räumliche Ertragsvariabilität wird durch die standortspezifische Wasserverfügbarkeit bedingt. In der Präzisionslandwirtschaft soll die Düngung je nach standortspezifischer Wasserverfügbarkeit während der Vegetationsperiode variiert werden. Jedoch fehlt bisher ein Parameter, der die standortspezifische Wasserverfügbarkeit charakterisiert. Das Ziel dieser Arbeit bestand darin, mit Hilfe von zwei Ansätzen einen solchen Parameter zu finden.

Im ersten Ansatz wurde das Potential vom Bodenmatrixpotential und vom Blattwasserpotential als Parameter für die standortspezifische Wasserverfügbarkeit untersucht. Es wurde dazu ein Feldversuch im Gebiet des Tertiärhügellandes in Süddeutschland mit seinen heterogenen Böden und seiner hügeligen Landschaft durchgeführt. Auf der Grundlage der Kenntnisse über die Textur und die Dichte des Bodens, das Relief sowie den potentiellen Ertrag, wurden fünf Standorte in einem Feld ausgewählt. Boden- und Pflanzenwasserstatus sowie die oberirdische Pflanzenmasse wurden regelmäßig während der Vegetationsperiode 1999 in Silomais und 2000 in Winterweizen bestimmt.

Weder das Bodenmatrixpotential noch das Blattwasserpotential waren für sich allein geeignet, die standortspezifische Wasserverfügbarkeit zu charakterisieren. Unterschiede zwischen den Standorten wurden hingegen deutlich, wenn das Bodenmatrixpotential in 40 cm Tiefe mit dem Mittagsblattwasserpotential in Beziehung gesetzt wurde. Das Absinken des Blattwasserpotentials als Folge des Abfalls des Bodenmatrixpotentials um 100 hPa wird die „response“ eines Standortes genannt. Die „response“ war signifikant negativ zur oberirdischen Frischmasse in Mais ($R^2 = 0.72$ bei $P \leq 0.05$) und in Weizen ($R^2 = 0.48$ bei $P \leq 0.05$) korreliert. Auf

der Grundlage dieser Ergebnisse wird die „response“ als semi-quantitativer Parameter für die standortspezifische Wasserverfügbarkeit vorgeschlagen.

Im zweiten Ansatz wurde die Wasserverfügbarkeit von der Bestandestranspiration abgeleitet. Da die Siliciumakkumulation in der Pflanzensubstanz mit der Bestandestranspiration eng verbunden ist, wurde das Potential von Si als Tracer für Bestandestranspiration im Hinblick auf seine Eignung, Bereiche unterschiedlicher Wasserverfügbarkeit voneinander zu unterscheiden, untersucht. Während des Feldversuches im Jahr 2000 wurde der Si-Gehalt in verschiedenen Pflanzenteilen von Winterweizen an den fünf verschiedenen Standorten gemessen. Weiterhin wurde die Si-Konzentration in der Bodenlösung in 25 cm Abschnitten bis zu einer Bodentiefe von 1 m bestimmt.

Die Ergebnisse zeigten, dass die Aufnahme von Si in die gesamte oberirdische Pflanzensubstanz nicht geeignet war, um die Bestandestranspiration zu quantifizieren, weil die Aufnahme überwiegend durch die transpirationsunabhängige Si-Akkumulation im Stängel bestimmt wurde. Diese biomassenabhängige Akkumulation von Si im Stängel hatte keinen Einfluss, wenn die Bestandestranspiration von den Veränderungen im Si-Gehalt in den Blättern abgeleitet wurde. Jedoch konnte von den absoluten Unterschieden im Si-Gehalt in den Blättern zwischen den Standorten nicht auf Unterschiede in der Transpiration geschlossen werden, weil die Si-Konzentration in der Bodenlösung zwischen 1 und 3 ppm innerhalb des Wurzelraums variierte. Aufgrund dieses Ergebnisses könnte es notwendig sein, den Beitrag der verschiedenen Bodensschichten zur Pflanzenwasseraufnahme zu quantifizieren.

Um zu bestimmen, ob der absolute Unterschied in der Bodenlösungskonzentration von 3 ppm in der Si-Akkumulation in der Blatttrockenmasse messbar ist, wurde dieser Aspekt unter kontrollierten Bedingungen im Gewächshaus untersucht. Dazu wurde Weizen auf drei Böden, die sich in der Bodentextur und in der Si-Konzentration in der Bodenlösung unterschieden, angebaut.

Aus den Veränderungen im Si-Gehalt von Blättern konnte auf dem schluffigen und auf dem tonigen Lehmboden die Bestandestranspiration quantifiziert werden. Auf dem sandigen Lehm war die Si-Aufnahme wahrscheinlich durch pedogene Faktoren behindert. Auf den anderen zwei Böden konnte der kumulative Effekt des Unterschieds in der Bodenlösung von 3 ppm bezogen auf die gesamte Spanne der Bestandestranspiration gezeigt werden, aber aufgrund der großen Streuung der Daten nicht bei Bestandestranspirationen um 100 und 200 mm. Dies hatte Folgen für die Beurteilung der Differenzierbarkeit von Bereichen unterschiedlicher Wasserverfügbarkeit auf der Basis der Si-Akkumulation im Feld. Auf der Grundlage der vorliegenden Ergebnisse kann die Bestandestranspiration mit einer Genauigkeit von 50 bis 100 mm aus den Si-Gehaltsveränderungen in den Blättern geschätzt werden. Da der gesamte Pflanzenwasserverbrauch während der Vegetationsperiode im gemäßigten Klimas 150 bis 250 mm beträgt, müssten standortspezifische Unterschiede in der Wasserverfügbarkeit groß sein.

Die vorliegende Untersuchung ergab, dass die standortspezifische „response“ ein sensitiver Parameter ist, um die Wasserverfügbarkeit eines Standorts im Vergleich zu anderen im Feld zu charakterisieren. Über die Si-Akkumulation kann die Bestandestranspiration, und damit die Wasserverfügbarkeit, nur grob geschätzt werden, so dass darüber eher Tendenzen in der Wasserverfügbarkeit innerhalb eines Feldes aufgedeckt werden können.

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