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An analysis of factors determining spatial variable grain yield of winter wheat

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ABSTRACT

We analyzed under the temperate weather conditions of northwest Germany the relationships between soil water supply, crop canopy dynamics, radiation interception, components of the soil water balance and grain yield of winter wheat using data obtained from field experiments during three years. A dynamic model of the soil water budget in combination with frequent measurements of canopy parameters thereby was used to estimate the components of the water balance and radiation interception site specifically. Differences in soil texture and soil water supply characteristics in combination with variable canopy dynamics lead to substantial differences in radiation interception, components of the soil water budget and yield. The sum of intercepted photosynthetic active radiation corrected for drought stress by the ratio of actual to potential transpiration showed a unique positive correlation to grain yield over the three experimental years. Positive correlations between grain yield and actual transpiration normalized by saturation deficit were also found, however, the slopes differed between years. The best predictor of grain yield was the ratio of the sum actual transpiration to the sum of potential evapotranspiration. We could also show that drought stress corrected radiation interception and the ratio $\Sigma T_a/\Sigma ET_p$ evaluated at end of May already correlated significantly with final grain yield. This may offer options for improved site specific crop management.

1. Introduction

Spatial differences in the water holding capacity of agricultural fields is in many environments the main reason of differences in yield potential. Most often this is caused by direct drought stress (Howell, 1990; Musick and Porter, 1990; Graham, 1999; Moore and Tyndale-Biscoe, 1999; Sadler et al., 2000a,b; Duda, 2002; Wong and Asseng, 2006; Lawes et al., 2009) but also indirect effects due to an altered nutrient availability and soil mineralization may be involved (Müller et al., 2008). Due to the foreseeable impacts of climate change, a higher water demand of high yielding crops and cropping systems, drought stress may become more important in the near future even in temperate climates (Porter and Semenov, 2005; Moriondo et al., 2011), thereby also increasing within field variability of yield potentials at heterogeneous sites. Under conditions of intensive farming, even mild drought stress may become the main cause for spatial variability of grain yield in the field because other yield limiting factors are suspended (Wong and Asseng, 2006; Basso et al., 2011). Under low to moderate drought stress conditions in high yielding rainfed environments, however, the importance of drought stress may vary between years and therefore the stability of yield ore management zones may be low (Gebbers, 2004; Moore and Tyndale-Biscoe, 1999; Taylor et al., 2003). More elaborated methods may be needed which take into account annual weather conditions in order to estimate annual site specific yield potentials as a perquisite for an improved crop management than management zones derived from multi-year yield maps or maps of plant available soil water. Measures derived from the year and site specific water deficit alone or in combination with the amount of intercepted radiation seem promising candidates for such an approach.

Positive linear correlations between cumulative evapotranspiration and biomass or yield of winter wheat has been shown by several studies (Aggarwal et al., 1986; Nielsen and Halvorson, 1991; Mandal et al., 2005). Few studies, however, are available for the high yielding environments of central and northern Europe (Hakojärvi et al., 2013). Furthermore, published studies seldom differentiate between actual transpiration (T_a) and soil evaporation (E_a) because the T_a is difficult to determine and detailed experimental data on site specific variability of soil water characteristics and yield are scarce.

The aim of this work therefore is to analyze causes for spatial and season to season yield variability in a high yielding environment. A focus thereby is on the site specific estimation of key parameters of the soil water budget and the establishment of quantitative relationships between spatial different soil water supply, seasonal

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Table 1
Precipitation and air temperature at the Hohenschulen experimental station during the experimental periods and for the long term average.

Month	Experimental period							
	2003/2004		2004/2005		2005/2006		Long term	
	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)
September	14.6	41	14.3	88	15.3	20	14.2	61
October	8.4	73	10.1	38	11.8	67	9.8	75
November	6.5	58	5.2	42	5.8	44	4.9	58
December	3.3	53	3.2	60	2.8	46	1.6	62
January	0.1	82	3.6	55	-0.6	14	1.2	48
February	2.8	70	0.4	27	1.6	22	2.0	50
March	4.5	41	2.7	50	0.8	47	3.4	44
April	8.9	31	8.5	22	6.7	50	8.0	44
May	11.4	28	11.8	102	11.8	81	11.9	62
June	13.9	93	15.0	44	15.7	31	14.8	69
July	15.7	98	18.0	92	20.8	53	16.9	100
August	18.4	34	15.8	49	16.5	143	17.9	59
Average	9.0		9.1		9.1		8.9	
Sum		702		669		616		732

transpiration and the yield variation. Such an understanding may help to improve site specific fertilization strategies and increase N use efficiency.

2. Materials and methods

2.1. Site and weather conditions

The climate at the Hohenschulen experimental station of the University of Kiel located in NW Germany 15 km west from Kiel is relatively humid. The long term average rainfall is 730 mm per year. From March to August the precipitations amounts to 380 mm and from September to February 350 mm (Table 1). The soil types vary typically for the young moraine zone from cambisols to luvisols, gleyic luvisols, and kolluvisols. The main textures are loamy sand and sandy loam as well as in some parts loam and clay belts (Table 2).

Field data were collected during three vegetation periods of winter wheat (2004/05, 2005/06, 2006/07) on two different production fields of the experimental station (54°18′54 N 9°59′46 E and 54°18′44 N, 10°00′10 E). Average pH of the fields was about 6.5, and the nutrient status for P and K, about 22 mg P_2O_5/100 g dry soil and about 25 g K_2O/100 g dry soil (double lactate extraction method, VDLUFA, 1991). Two transects each with four to five observation points selected at characteristic topographic positions were used for measurements of soil and plant parameters (Fig. 1) each year. The management of these strips was according to the usual farm strategy (Table 3).

Time domain reflectometry (TDR) wave guides of 0.2 m length (soil moisture equipment Inc., Santa Barbara, CA, USA) were

Table 2
Maximum rooting depth (RD_{max}) soil water to root depth (SW_{root}), plant available soil water ($PASW_{root}$) to root depth, soil water at wilting point (WP_{root}) to root depth and for all experimental plots.

Year	Plot	RD_{max} [cm]	SW_{root} [mm]	$PASW_{root}$ [mm]	WP_{root} [mm]
2004	1	120	328	213	115
	5	120	332	238	94
	12	120	338	224	114
	15	80	219	140	79
	20	120	345	225	120
	21	80	266	150	116
	28	80	218	147	70
	32	80	230	126	103
	av.	100	285	183	101
	cv.	21%	20%	25%	18%
2005	6	110	317	157	160
	7	120	346	238	109
	8	120	351	243	108
	9	120	329	227	101
	10	140	374	238	135
	21	120	329	218	111
	22	120	372	211	161
	23	120	346	170	176
	24	120	524	231	293
	25	120	352	185	167
	av.	121	364	211.8	152.1
	cv.	6%	16%	14%	37%
2006	5	120	325	221	104
	6	120	341	245	97
	7	130	407	288	119
	8	120	381	214	167
	13	120	340	228	112
	14	120	306	219	87
	15	120	369	227	142
	16	120	461	204	257
	av.	121.25	366.25	230.75	135.625
	cv.	3%	14%	11%	41%