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Interaction of potassium and drought in barley - Yield, water-use efficiency and growth

Andersen, M.N.[1], *Jensen, C.R. and Lösch, R.*

Address for correspondence:
[1] Dept. of Soil Science, Research Centre Foulum, The Danish Institute of Plant and Soil Science, P.O. Box 23, DK-8830 Tjele, Denmark

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Summary

A factorial experiment on a coarse textured sand low in K and water holding capacity (WHC) investigated how K fertilizer at rates above the normal for barley (ca. 50 kg ha^{-1} K) might affect the crop's reaction to natural or artificially imposed drought during grain filling. Extra K increased the rate of vegetative growth. High K increased leaf area by up to 26% at anthesis and top dry matter by up to 15% between anthesis and milk ripe stages with 10% increase in straw yield at harvest. K increased ear number but reduced grain weight. Grain yield was not affected by K on irrigated plots. Drought during grain filling reduced yield (grain weight and number/ear) but K tended to reduce this effect at a medium level of drought. Water use efficiency (WUE) for total dry matter was increased by up to 12% by high K but grain yield was not affected. K improved subsoil root density in a wet year but not in a dry. Despite the lack of influence of K on grain yield, its effect on total dry matter is important when barley is grown for fodder.

Introduction

Many drought prone sandy soils low in K in W. Europe are used for arable cropping. Jensen (1982) in pot experiments found that KCl increased DM yield and reduced transpiration under medium drought stress, turgor potential in relation to water content was increased. Similar results were reported by Lindhauer (1985) with sunflower and by Studer and Blanchet (1963) in the field with ryegrass. Leigh and Johnston (1983b) found grain yield in barley to be correlated with K content of young plants. Van der Paauw's (1958) survey demonstrated correlation of response to K with length of dry period in potato, wheat and grass.

Our field experiment with spring barley on a coarse textured sandy soil aimed to further investigate the interaction of applied K with drought on growth, nutrient uptake (Andersen *et al.*, 1992), plant water relations (Jensen *et al.*, 1992) and stomatal resistance (Lösch *et al.*, 1992).

Experimental

Site

The soil of the Government Research Station, Jyndevad, S. Jutland is an Orthic Haplohumod (Nielsen and Møberg, 1985) with plant available water capacity ca 67 mm to 60 cm. Chemical soil properties in Table 1 were determined by standard methods (Landbrugsministeriet, 1972).

Table 1. Chemical properties of the unfertilized soil. pH was determined in 0.01 M $CaCl_2$, CEC was determined at pH 8.1, Ca^{2+} and Mg^{2+} were extracted with 1 M NH_4Cl, K^+ and Na^+ with 0.5 M $NH_4OOC_2H_3$ and P with 0.5 M $NaHCO_3$.

Horizon	pH	CEC (m.e./100 g)	Ca^{2+}	Mg^{2+}	K^+	Na^+	P
Plough layer (0-30 cm)	6	7-9	4.0	0.20	0.10	0.03	0.2
Subsoil (30-60 cm)	5-6	7-8	2.0	0.06	0.08	0.03	0.1

Treatments

The experiment was planted with spring barley (cv. Gunnar) for 3 years (1985-'87); K extracted by 0.5 M NH_4OAc from the plough layer was 0.17 m.e./100 g in 1986 and 0.13 in 1987. 110-120 kg ha^{-1} N as calcium ammonium nitrate was applied at emergence with 30 kg ha^{-1} P and 30 kg ha^{-1} Mg.

There were three replicates of factorial combinations of 50, 125 and 200 kg ha^{-1} K, given as muriate of potash (49%) at emergence with the following irrigation treatments: (a) irrigated at 30 mm water deficit (fully irrigated); (b) a 50 mm water deficit imposed by polythene shelters during early grain-filling; (c) irrigation at 50 mm deficit if reached naturally.

The polythene roofs at 1.2 m above ground used in (b) covered the plots from heading to early grain filling just before re-irrigation. They reduced light intensity (PAR) by 20 to 30% but only slightly affected temperature (Jensen, 1987). Soil moisture was measured at 10, 30, 50 and 70 cm depth. Irrigated plots were re-watered to field capacity when the calculated deficit reached 30 or 50 mm respectively. Soil water content was measured by the neutron moderation method at 10, 30, 50 and 70 cm depth. When the calculated deficit reached 30 or 50 mm the plots were rewatered to field capacity. Field capacity was assessed by measuring the water content of the soil with a neutron probe two days after the soil profile had been thoroughly wetted by rain, and tensiometers placed at 10 cm intervals from 0.10 to 1.00 m soil depth showed readings of about 0.01 MPa.

Water balance

Actual evapotranspiration (ET_a) from drought-stressed plots and maximum evapotranspiration from fully irrigated plots (ET_m) were calculated from the change in water content to 0.7 m depth and precipitation (McGowan and Williams, 1980). Soil moisture was measured weekly (twice per week during drought). Precipitation and pan (HL 315) evaporation were measured daily at a weather station within 1 km of the experiment. To estimate potential evapotranspiration (ET_o), the pan evaporation was multiplied by the factors given by Aslyng and Stendal (1965). When precipitation exceeded the water-holding capacity of the soil, ET_a was assumed to equal the maximum evapotranspiration (ET_m) and was estimated from the equation:

$$ET_m = k_c \times ET_o \qquad (1)$$

where k_c is a crop coefficient which varies with developmental stage and to some extent with climatological factors (Doorenbos and Kassam, 1979). Values of k_c for the different developmental stages were obtained from estimates of ET_m/ET_o derived from neutron measurements in the fully irrigated treatment during periods without deep percolation (soil water deficit 5 to 30 mm).

Drought sensitivity and WUE

Two models were used to relate yield to evapotranspiration in the treatments. The first model (Doorenbos and Kassam, 1979):

$$1 - Y_a/Y_m = k_y(\mathrm{P}) \times (1 - \mathrm{ET}_a/\mathrm{ET}_m) \qquad (2)$$

relates relative yield decrease ($1 - Y_a/Y_m$) to relative evapotranspiration deficit ($1.- \mathrm{ET}_a/\mathrm{ET}_m$) in the growth phase (P) by the drought sensitivity factor k_y. Y_a is the actual yield of an individual plot of a drought stress treatment, Y_m is the maximum yield of the fully irrigated treatment, ET_a is the actual evapotranspiration from the drought stressed plot and ET_m is the maximum evapotranspiration from the fully irrigated treatment. k_y (P) was estimated by linear regression analysis. The second model:

$$1 - Y_a/Y_m = k_y(\mathrm{S}) \times \mathrm{SD} \qquad (3)$$

is modified after Hiler and Clark (1971) and Mogensen (1980). SD is the number of stress days in the stage (S) and was calculated as:

$$\mathrm{SD} = \sum_{j=1}^{n} (1 - \mathrm{ET}_a / \mathrm{ET}_m)_j \times N_j \qquad (4)$$

where j is the interval between two determinations of soil water content, N_j is the number of days in that interval and n is the number of intervals in the drought stressed stage (S). k_y (S) was estimated by linear regression analysis.

Dry-matter yields of grain and straw of the individual plots were determined by harvesting an area of 8.40 m^2 at maturity. Water-use efficiency (WUE in kg ha^{-1} mm^{-1}) was calculated as the ratio between yield and evapotranspiration.

Shoot and root growth and yield components

Areas of 0.54 m^2 were sampled 6-8 times during each season in all plots to obtain a growth analysis of root and shoot production, green leaf area index, nutrient uptake and shoot and ear number. The leaf area was determined by an optical planimeter (LiCor model 3050A Li-Cor Inc., NE, USA). Four root samples per plot were taken to a depth of 50-80 cm with a 6.5 cm diameter auger. The root samples were sectioned in 10 cm layers, dried and washed free of soil on a 0.2 mm mesh: Root length was determined by the line intersect method (Newman, 1966), modified to obtain at least 100 intersects per sample, thereby reducing error caused by the counting procedure. For the yield component analysis the number of ears per m^2 was determined from the last sampling. Grain number per ear was calculated as: grain yield per m^2 (g m^{-2})/[mean grain weight (g) x number of ears per m^2 (m^{-2})].

Results

Water balance

The water balances for the three seasons were very different (Fig. 1). In 1985 irrigation was needed only once and was soon followed by rain. In 1986 the fully irrigated treatment (a) was irrigated four times in June and July, during which period high evapotranspiration and low precipitation prevailed. 1987 was very damp and cool with low evapotranspiration and abundant precipitation. As in 1985 irrigation was needed only once and was likewise followed by rain.

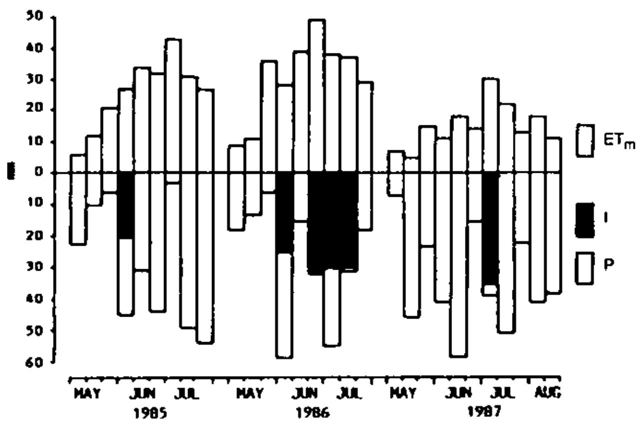

Fig. 1. Maximum evapotranspiration (ET_m), irrigation (I) and precipitation (P) in the fully irrigated treatment (a) during 10-11 day intervals for the three seasons.

The crop coefficients (k_c), obtained from eqn. (1), were averaged over the three seasons, as significant differences between seasons or treatments could not be detected from the soil water balance measurements. The k_c values, given in Table 2 and measured during periods without percolation, were finally used to calculate ET_m from eqn. (1) throughout the seasons.

Table 2. Crop coefficients (k_c) in relation to LAI for the three seasons.

LAI	k_c
0 - 1	0.40
1 - 2	0.40
2 - 3	0.66
> 3	1.25
3 - 2	1.17
2 - 1	0.93
1 - 0	1.00

ET_a in the sheltered and unirrigated treatments, expressed as a fraction of ET_m, decreased (Fig. 2) when soil water deficit (SWD) exceeded about 30 mm in 1985 and 1986 and about 40 mm in 1987, where ET_m was low. Despite a large scatter due to short measuring intervals, it is clear that the ET_a/ET_m ratio decreased towards an extrapolated intercept of about 45-50 mm in 1985 and 1986 and 55-60 mm in 1987. The higher capacity found in 1987 may be due to a slightly deeper plough layer and better exploitation of the soil water at a low evaporative demand which prevailed in 1987.

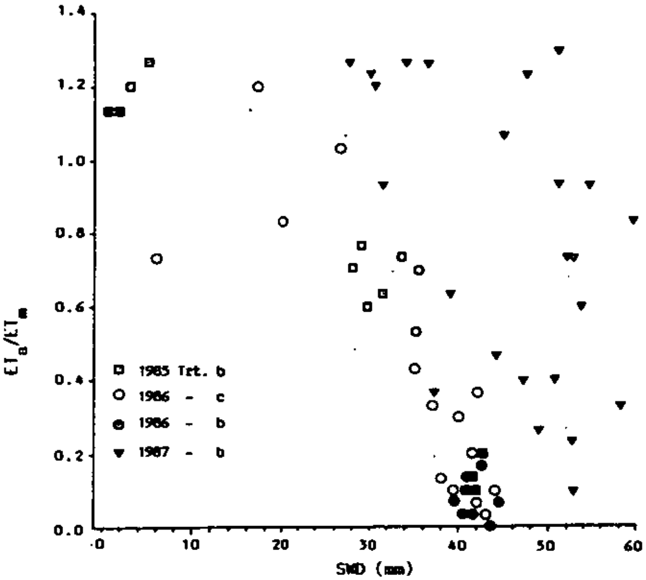

Fig. 2. Actual evapotranspiration (ET_a)/maximum evapotranspiration (ET_m) as a function of soil water deficit (SWD) for the drought stress treatments.

The ET_a/ET_m ratio as a function of ET_m showed that the ratio decreased more at high ET_m values, in 1986, than at low ET_m values, typical of 1987. This probably means that leaf water potentials decreased more under high evaporative demands, when soil water was restricted, causing a higher leaf resistance to water vapour flow and thus decreasing ET_a (e.g. Denmead and Shaw, 1962; Slatyer, 1967). There was no discernible difference in the rate of stress day accumulation between potassium rates. In 1986 the drought stress in treatment b developed earlier in the grain-filling stage than in the other two years.

Final yield

K did not influence grain yield (Table 3) despite low extractable K in the soil though in 1986 it tended to increase it at irrigation level b and to decrease it at level c. K at levels 2 and 3 increased straw yield by about 10% in all three years (Table 3). Drought imposed during the early part of the grain filling period (irrigation level b) decreased grain yield by about 5% in 1985 and about 35% in 1986. Straw yield was only slightly affected. In 1986 drought during the flowering period (irrigation level c) decreased grain yield by about 35% and straw yield by about 25%. The short drought period, which arose during the jointing-shooting stage (irrigation level c) in 1985 (Table 3), reduced straw yield by about 10%, while grain yield was unaffected. Thus the harvest index declined the more the later drought stress occurred (Table 3). In 1987 sheltering gave a higher yield, probably because leaching of nitrogen was prevented.

High K application tended to increase the number of ears per m^2 and decrease the grain weight (significantly in 1986) (Table 4). Drought during the grain-filling stage reduced grain weight, and in 1986 the grain number per ear was also reduced by drought. In 1986 drought developed during the flowering stage in irrigation level c and reduced the size of all three yield components, i.e. grain weight, number of grains per ear and number of ears per m^2. These results may be interpreted as an increased drought sensitivity of a particular yield component during its ontogenetic growth.

Table 3. Final yield of grain and straw and harvest index.

	1985 K-level (kg ha^{-1})					1986 K-level (kg ha^{-1})					1987 K-level (kg ha^{-1})				
Irrigation	50	125	200	Mean	LSD_{95}	50	125	200	Mean	LSD_{95}	50	125	200	Mean	LSD_{95}
Yield of grain (hkg dry matter/ha)															
a	43.5	44.3	43.2	43.7		55.4	55.5	55.3	55.4		49.2	47.3	47.4	48.0	
b	41.9	38.4	43.0	41.1	2.0	35.5	37.9	37.8	37.0	2.8	50.1	51.8	50.1	50.7	1.5
c	41.7	43.6	43.7	43.0		38.2	36.4	34.9	36.5		-	-	-		
Mean	42.4	42.1	43.3			43.0	43.3	42.7			49.7	49.6	48.8		
LSD_{95}		n.s.					n.s.					n.s.			
Yield of straw (hkg dry matter/ha)															
a	44.7	49.1	45.7	46.5		39.8	41.8	44.9	42.2		48.7	53.0	51.6	51.1	
b	43.6	43.2	45.8	44.2	1.9	37.8	42.1	43.9	41.3	2.5	46.8	51.5	51.1	49.8	n.s.
c	39.2	43.9	43.5	42.2		31.6	31.3	32.1	31.7		-	-	-		
Mean	42.5	45.4	45.0			36.4	38.4	40.3			47.8	52.3	51.4		
LSD_{95}		1.9					2.5					2.6			
Harvest index (% grain of total dry matter)															
a	49.3	47.5	48.6	48.5		58.3	57.0	55.2	56.8		50.3	47.2	47.9	48.5	
b	49.0	47.0	48.4	48.1	1.1	48.4	47.3	46.2	47.3	1.4	51.7	50.2	49.5	50.5	1.4
c	51.6	49.8	50.1	50.5		54.8	53.7	52.1	53.5		-	-	-		
Mean	50.0	48.1	49.1			53.8	52.7	51.2			51.0	48.7	48.7		
LSD_{95}		1.1					1.4					1.4			

Table 4. Ears per unit area, grain number per ear and grain weight.

Irrigation	1986 K-level (kg ha^{-1}) 50	125	200	Mean LSD_{95}
Ears per unit area (m^{-2})				
a	667	666	710	681
b	650	757	702	703
c	564	515	630	570
Mean LSD_{95}	627	645	681	
Grain number per ear				
a	18.5	18.6	18.0	18.4
b	16.6	15.6	16.9	16.4
c	16.6	18.0	14.2	16.3
Mean LSD_{95}	17.2	17.4	16.4	
Grain weight (mg)				
a	45.1	44.8	43.5	44.5
b	33.0	32.0	31.9	32.3
c	41.0	40.1	39.8	40.3
Mean LSD_{95}	39.7	39.0	38.4	

Drought sensitivity and WUE

The drought sensitivity factors relating grain and total dry matter yield to ET_a were calculated from equations (2) and (3) and mean values for the drought treatments only are given in Table 5 as there were no differences between K levels. There was no yield depression by drought in 1987.

Both models indicated that the drought sensitivity factors for irrigation level b were roughly trebled in 1986 as compared with 1985. A difference between the two models was noted, as eqn. (2) showed a lower drought sensitivity factor [k_y(P)] for grain yield at irrigation level c than at level b in 1986; while eqn. (3) [k_y(S)] gave a similar value for both levels.

In Table 6 the water-use efficiencies (WUE) for grain and dry-matter yield for the three seasons are given. WUE for grain yield (WUE_G) was not influenced by level of K application, but increasing rates of K increased WUE for total dry matter yield (WUE_{DM}) by up to 12% at irrigation level b in 1986. WUE was highest in 1987 in damper conditions.

Table 5. Drought sensitivity factors of grain and dry matter yield according to eqn. (2) for individual growth phases [k_y(P)]; the total growth period [$k_y(P_T)$]; and eqn. (3) for individual growth stages [k_y(S)]; ± standard error of the estimate.

Year	Irrigation	Grain			Dry matter		
		k_y (P)	k_y (P_T)	k_y (S)	k_y (P)	k_y (P_T)	k_y (S)
1985	b	0.16±0.06	0.38±0.15	0.005±0.002	0.14±0.06	0.34±0.14	0.005±0.002
1986	b	0.61±0.03	1.48±0.07	0.022±0.001	0.36±0.03	0.88±0.07	0.013±0.001
1986	c	0.42±0.02	1.50±0.06	0.023±0.001	0.37±0.02	1.33±0.07	0.020±0.001

Table 6. Water-use efficiency for grain production (WUE_G); for dry matter production (WUE_{DM}); and actual evapotranspiration (ET_a) during the three seasons.

Year	K-level (kg ha^{-1})	Irrigation level	WUE_G (kg/ha mm)	WUE_{DM} (kg/ha mm)	ET_a (mm)
1985	50	a	18.6	37.6	235
	125	a	18.6	39.8	235
	200	a	18.6	37.9	235
	50	b	21.8	44.5	192
	125	b	20.1	42.8	191
	200	b	21.9	45.2	196
1986	50	a	19.9	34.2	278
	125	a	19.9	35.0	278
	200	a	19.9	36.0	278
	50	b	16.3	33.7	217
	125	b	17.7	37.4	214
	200	b	17.5	37.8	216
	50	c	17.9	32.7	213
	125	c	16.9	31.4	216
	200	c	16.1	31.0	216
1987	50	a	30.7	60.9	161
	125	a	30.7	62.5	161
	200	a	30.7	61.7	161

Shoot and root growth

Total and ear dry matter accumulation during the three seasons are shown in Fig. 3. No sampling at K-level 1 was undertaken in 1985.

In 1985 and 1986 K increased vegetative growth by 10% at the early grain filling stage and both total and ear dry matter by 15% in 1986. In 1986 drought caused the difference in ear dry matter to be maintained for a prolonged period during the grain-filling stage, and in all three years K application had the greatest effect on dry matter accumulation during periods of drought.

The green leaf area index (LAI) is shown in Fig. 4. LAI was not determined at irrigation level c, or at K-level 1 in 1985. In 1985 LAI increased at K-level 3 as compared with K-level 2. In 1986 LAI increased up to 26% at K-level 3 as compared with K-level 1 ($P < 0.0001$). In 1987 there was no effect of increased K application on LAI.

Leaf area duration (LAD), which is an expression of the crop's total photosynthetic potential during the season, was calculated as a time-integrated leaf area (Hunt, 1982) of the data given in Fig. 4. Increased application of potassium caused a marked increase in LAD ($P < 0.0008$), and was visible very early in the seasons of 1985 and 1986, while a similar effect did not appear in 1987 (Fig. 4).

In the rooting zone, the root density at different depths in 10 cm soil layers was followed throughout the three seasons by sampling in the fully irrigated treatments (level a). In 1985 roots were sampled in plots at K-level 2, and in 1986 and 1987 roots were sampled in plots at K-levels 1 and 3.

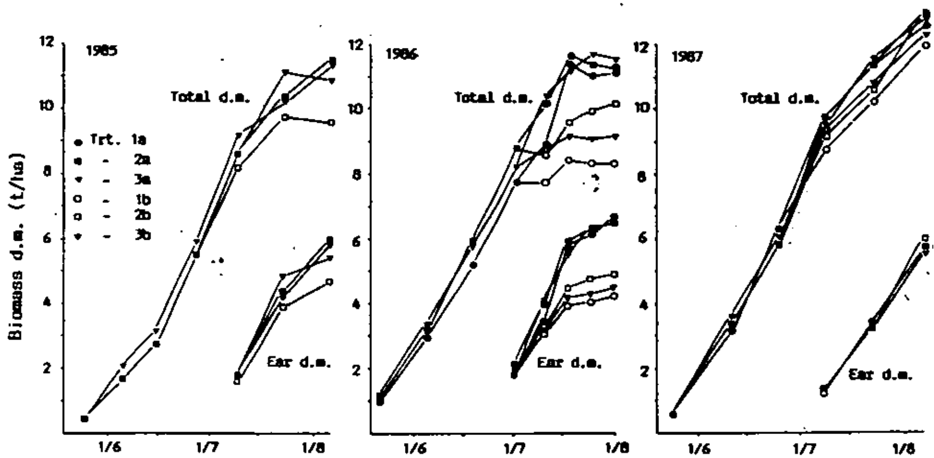

Fig. 3. Total above-ground dry matter and ear dry matter accumulation for the different treatments as a function of time.

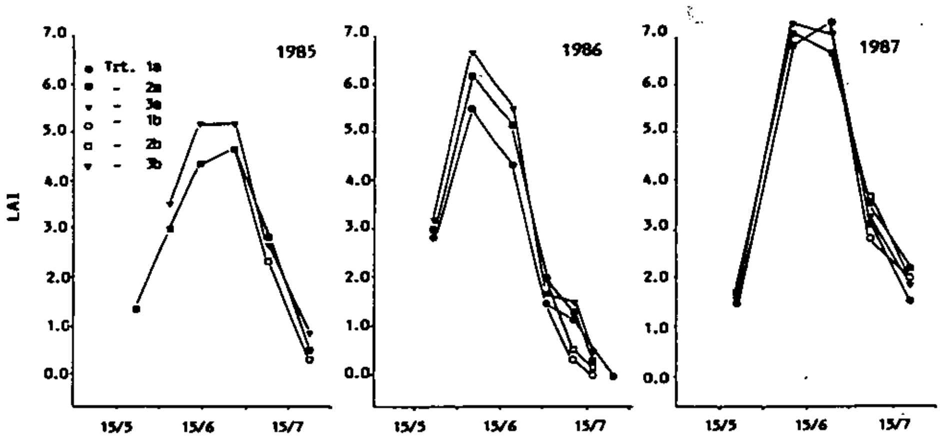

Fig. 4. Leaf area index as m^2 green leaf area per m^2 ground area (LAI) for the different treatments as a function of time.

As seen in Fig. 5, the pattern of root development was the same for the three seasons. The root density generally reached a maximum about two weeks after heading. The root density was high in the plough layer especially at 0-10 cm depth, while the root density in the subsoil was much lower. In 1986 root densities were similar at both K-levels, while in 1987 the root density in the subsoil layers was significantly ($P < 0.04$) increased by application of 200 kg K ha^{-1} (K-level 3).

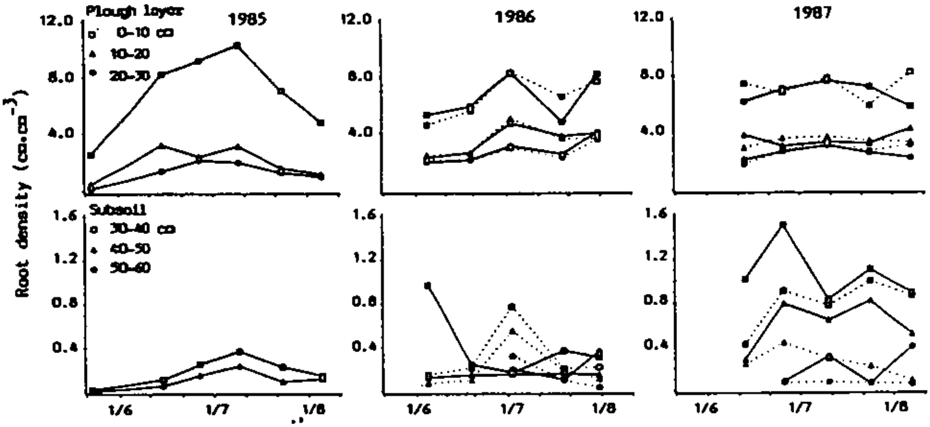

Fig. 5. Root density in 10 cm soil layers in the plough layer and in the subsoil of the fully irrigated treatments as a function of time. Data for 1985 are from K-level 2; data for 1986 and 1987 are from K-level 1 (······) and K-level 3 (——).

Discussion

High K stimulated leaf area expansion (Fig. 4), resulting in an increase in dry-matter accumulation during the vegetative growth phase (Fig. 3) by 0-15% (by generating osmotic potential and leaf turgor), and in final straw yield by about 10% (Table 4), confirming similar findings in barley in both pot (Jensen and Tophøj, 1985) and field experiments (Leigh and Johnston, 1983a, b). Leaf area was especially increased by high K supply (Fig. 4), and was up to 26% higher at K-level 3 as compared with K-level 1.

As much as 90-95% of the carbohydrate in the grain is usually derived from CO_2 fixation after anthesis (Evans *et al.*, 1975). In barley about 45% of the assimilates for final grain yield may originate from photosynthetic activity of the ear and the remaining 55% from photosynthesis of the upper two leaves and stem (Thorne, 1965). Thus, for the final grain yield, formation the leaf area duration (LAD) during the grain filling period is an important yield determinant (Yap and Harvey, 1972; Thorne, 1974).

Increased vegetative growth induced by high K application, causing a greater leaf area at anthesis and during the grain filling period and a slightly higher number of ears per m^2, did not generally result in higher grain yield irrespective of irrigation level (Table 3). This consistent pattern over three years indicates that a low rate of K suffices for optimum LAI for production of assimilates for grain production. LAI at anthesis at low K application was about 5.5 and 6.5 for 1986 and 1987, respectively (Fig. 4) (LAI for 1985 was not measured at K-level 1). These LAI values are comparable with similar optimum values reported by Thorne (1974) and obtained from nitrogen response curves for grain yield. The results also suggest that the sink capacity (number of grains per unit land area) was optimum at K-level 1, a lower number of ears per m^2 being compensated by a higher grain weight, resulting in similar grain yields at all K levels.

During the early grain filling period grains grow rapidly, and severe water stress imposed at this stage reduces grain size (Aspinall *et al.*, 1964; Mogensen, 1980). Our study confirms this as grain weight was reduced when water stress was imposed during early grain filling in 1986 (irrigation level b). Increased K application slightly increased grain yield in this treatment. However, severe water stress imposed in the middle of the flowering period in 1986 (irrigation level c) had the opposite effect, as grain yield was highest at low K. No clear conclusion can yet be drawn about the possibility of stabilizing grain yield under drought conditions by increasing K application.

No differences in drought sensitivity were found between K-levels, an even higher vegetative yield was obtained in high K treatments, and ET_a was of similar magnitude in all K treatments (Tables 5 and 6).

In the present study high K application increased WUE for total dry matter production (WUE_{DM}) by about 1-12%, except when the plants were severely drought stressed, as in treatment c of 1986 (Table 6). The increase in WUE_{DM} was an effect of both K-stimulated increased vegetative growth (including leaf area), and of a slight reduction of water use per unit leaf area, since we found the total water use to be unaffected by K application (Table 6). Lösch *et al.* (1992) have further investigated the reason for the increase of WUE on a single-leaf basis, and found that a change of stomatal dimensions and density in plants grown at high K-levels probably caused the increase of WUE in these plants. Our results thus agree with those of Jensen and Tophøj ,(1985) on barley in pot experiments. Similar findings have also been reported for linseed (Linser and Herwig, 1968) and sugar beet (Mengel and Forster, 1972). However, with respect to grain production, there was no increase in WUE for high K applications.

Increasing K application to fully watered plots did not improve root growth in 1986 but improved it at 30-60 cm in the wet year 1987 (Fig. 5). But this increase might have only a marginal effect on the availability of soil water (Fig. 2) because the sandy subsoil had a low water holding capacity. The lack of stimulation of root growth in the dry year might have been caused by mechanical resistance to root penetration (Wiersum, 1957; Taylor and Radcliffe, 1969; Warnaars and Eavis, 1972). Any improvement in root growth by K could secure a better water supply to the plant during intermittent drought.

That applying K in excess of rates normal for the area did not increase final grain yield indicates that in the Atlantic climate of Western Europe high grain yields are possible with limited rates of K fertilizer in agreement with results of long-term trials with cereals in Sweden (Mattson, 1987) and Germany (Schön *et al.*, 1976). However, the fact that total above-ground biomass was increased by 10-15% by higher rates of K in the period up to the milk-ripe stage is of practical importance; 50 000 ha of barley in Denmark alone is harvested as green fodder for cattle. Furthermore, farmyard manure, rich in K, is most often cheaply available in the same farms and can be used to fertilize the barley crop.

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