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Effects of waterlogging and drought on winter wheat and winter barley grown on a clay and sandy loam soil

II. Soil and plant water relationships

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Summary The effects were investigated of waterlogging and drought on winter wheat and winter barley growing in a clay soil, and winter wheat growing in a sandy loam. The crops were grown in lysimeters that were waterlogged or freely-drained between December and March, and then irrigated or subjected to drought from April to harvest.

On the clay soil drought restricted water use and dry matter production by wheat and by barley. The effect on water use was proportionately greater than on dry matter production. On the sandy loam drought decreased water use by wheat, but had only a small, non-significant, effect on dry matter production. Measurements made with a neutron probe in lysimeters that had been subjected to drought showed that the maximum amount of water that winter wheat could extract from the clay soil was 150 mm, and from the sandy loam was 170 mm. Winter barley could extract 114 mm from the clay soil. On both soils transpiration by wheat and barley was restricted when about three quarters of the available soil water had been extracted. Drought decreased leaf water potential and stomatal conductance.

Waterlogging in the winter decreased dry matter production and water use in the summer, but not by causing plant water stress in the summer. Plants that had been waterlogged had higher leaf water potentials and stomatal conductances in the summer, and dry matter production was decreased more than water use.

There was no evidence that waterlogging in the winter made the crop more vulnerable to drought in the summer.

Introduction

Water shortage may limit the yields of cereals in the United Kingdom, though not in all years or on all soils. Whether the yield of a particular crop is limited by water shortage depends mainly on: the amount of rain and its seasonal distribution, the water holding capacity of the soil, the fraction of the soil water that the roots can extract, and the depth from which they can extract it. Few measurements have been made in the field of the amount of water that crops can extract from different types of soil.

We examined the effects of waterlogging and drought on winter wheat and winter barley growing in a clay, and winter wheat growing in a sandy loam. The crops were subjected to waterlogging in the winter, and drought in the summer, as single treatments and in combination. The direct effects of the treatments on water extraction were measured, and the hypothesis tested that exposure to winter waterlogging would predispose the crop to damage by drought, possibly through restricting the depth of the root system. The effects on crop growth and yield have already been described[4]. In this paper we describe evaporation, the pattern of soil water extraction, the ratio of dry matter production to water use, and effects of the treatments on plant water potential and stomatal conductance.

Materials and methods

The method of growing the crops in undisturbed soil monoliths in lysimeters, and experimental details have been fully described previously[3,4].

Soil water contents were measured at approximately weekly intervals with a neutron probe (Didcot Instrument Co., type IH2). Readings were made at 5 cm intervals to 30 cm depth, then at 10 cm intervals to 110 cm; measurements below this depth in the 135 cm deep lysimeter were not possible because of the geometry of the neutron probe. Water deficits in both soils were calculated with respect to 2 April 1982, when the lysimeters contained water in excess of field capacity and were still draining. The volume of water that drained was measured weekly, and the calculated deficits were corrected for drainage. Because of the volume of water draining from the sandy loam after 2 April, profiles of water extraction for this soil were calculated with respect to 4 May. Details of the irrigation schedule are given in Table 1.

Stomatal conductances, of the wheat only, were measured at approximately weekly intervals with a continuous flow diffusion porometer[5,19]. Measurements were made on one of the uppermost leaves from each lysimeter between 13.00 h and 16.00 h GMT. The adaxial and abaxial conductances were measured separately, then added. After a leaf was measured it was cut from the plant, sealed immediately in a polyethylene bag and stored in the dark. Later its water potential was measured with a pressure chamber.

Results

Evaporation

The total evaporation from the beginning of April to harvest was about 330 mm for wheat, and 268 mm for barley (Table 2). On the sandy loam, evaporation was decreased by drought and by waterlogging, but the effect of waterlogging just failed to be statistically significant, and there was no interaction between the two treatments. On the clay, drought and waterlogging decreased evaporation and there was a significant interaction: the effect of drought was less when the crop had been waterlogged.

From the end of March to early June, evaporation was similar for all treatments, but thereafter was slower from lysimeters that were subjected to drought (Fig. 1). The date on which evaporation from lysimeters subjected to drought started to lag cannot be defined accurately but was between 2 and 14 June for both soils, both species,

Table 1. Irrigation schedule

	Water applied (mm)	
	Subjected to drought	Irrigated
16 April	9.7	17.7
22 April	3.9	11.9
28 April	9.0	25.0
7 May	10.3	10.3
13 May		8.0
14 May	9.1	17.0
18 May	4.5	4.5
19 May	4.5	4.5
20 May	8.7	8.7
21 May		4.0
28 May	8.1	16.1
4 June		16.0
9 June		32.0
16 June		16.0
24 June		8.0
30 June	4.9	4.9
6 July		16.0
7 July	5.0	5.0
9 July		16.0
15 July	7.3	7.3
Total	85.0	249.0

and irrespective of whether they had been waterlogged in the winter.

Soil water deficits

The soil water deficits for all crops that were subjected to drought increased steadily until mid-June, then increased more slowly towards a maximum value as the crops matured (Fig. 2). The maximum deficit reached in freely-drained lysimeters that were subjected to drought were larger in the sandy loam than the clay, and for wheat than for barley, and were also affected by winter waterlogging, though not in a systematic way (Table 2). The deficits in freely-drained irrigated wheat rose to about 85 mm in July, but were less in waterlogged irrigated wheat and in irrigated barley.

From Figs. 1 and 2 the soil water deficits have been estimated at the time when evaporation began to slow down, and are referred to as limiting soil moisture deficits for transpiration (Table 2). These values are also presented in Table 2 as fractions of the maximum deficit, and lie between 0.66 and 0.82.

Pattern of soil water extraction

Waterlogging in the winter affected the pattern of water extraction in the summer. During April and May wheat that had been waterlogged

Table 2. Evaporation, maximum soil moisture deficits, limiting soil moisture deficit for transpiration, and transpiration ratio of winter wheat and barley growing on sandy loam and clay soils

			Freely-drained		Waterlogged		
			Irrigated	Subjected to drought	Irrigated	Subjected to drought	SE
Evaporation (mm)	Sandy loam	Wheat	331	244	319	217	8.2
	Clay	Wheat	333	224	294	235	6.9
		Barley	268	192	243	200	4.9
Maximum soil moisture deficit (mm)	Sandy loam	Wheat	82	159	70	132	8.2
	Clay	Wheat	84	139	45	150	7.0
		Barley	26	114	6	123	4.3
Limiting soil moisture deficit for transpiration (mm)	Sandy loam	Wheat	–	109 (0.69)	–	93 (0.70)	
	Clay	Wheat	–	104 (0.75)	–	99 (0.66)	
		Barley	–	93 (0.82)	–	93 (0.76)	
Transpiration ratio (mm/t/ha)	Sandy loam	Wheat	20.2	15.0	22.0	16.7	0.9
	Clay	Wheat	17.2	14.0	20.8	15.9	0.7
		Barley	17.1	13.8	21.0	18.8	0.8

Figures in brackets are the limiting soil moisture deficit for transpiration as a fraction of maximum soil moisture deficit

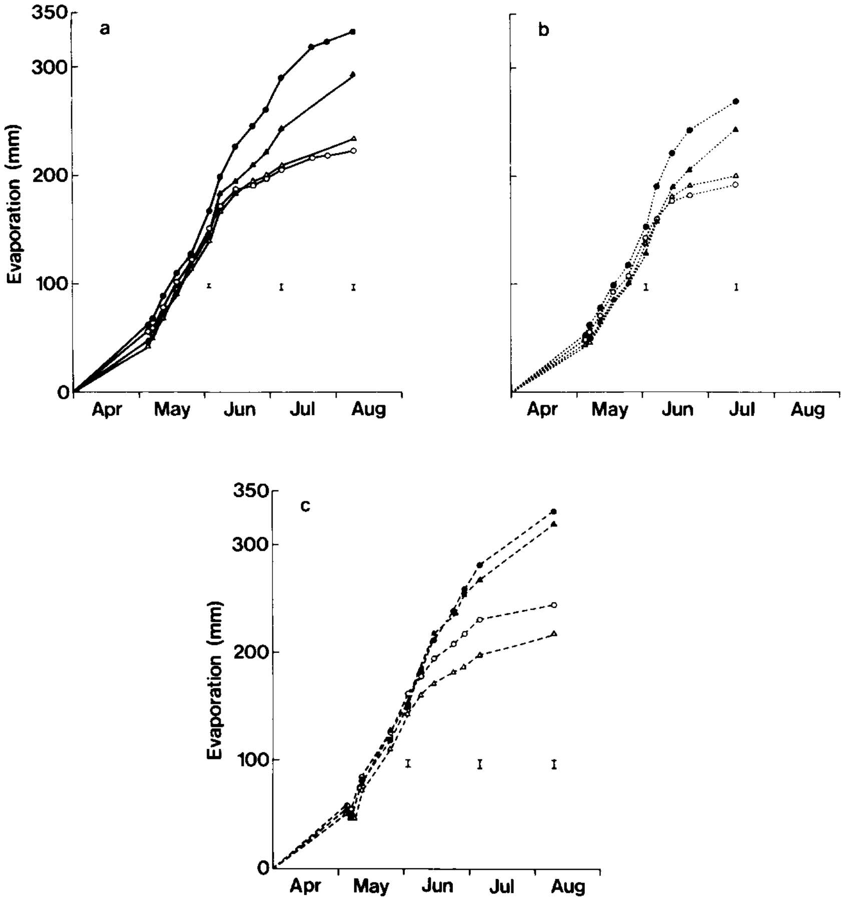

Fig. 1. Evaporation from winter wheat and winter barley crops. a. Winter wheat on clay soil: b. Winter barley on clay soil; c. Winter wheat on sandy loam. ●, ○ freely-drained; ▲, △ waterlogged in winter; *closed* symbols, irrigated; *open* symbols, subjected to drought. I, S.E.

extracted more water from the clay above 20 cm depth (Fig. 3a, 7/6/82) and from the sandy loam above 40 cm (Fig. 3c, 2/6/82), and less from below these depths, than wheat that had been freely-drained. The differences were small, and only just significant. Such an effect was not detectable for winter barley growing on the clay (Fig. 3b, 7/6/82).

The profiles of water extraction by wheat and barley differed slightly, though the differences could not be tested statistically (Fig. 3). On 7 June, before water extraction by barley slowed down as the crop approached maturity the wheat had extracted 87 mm from above 60 cm depth, and the barley 85 mm; from below 60 cm wheat extracted 25 mm, and the barley 15 mm.

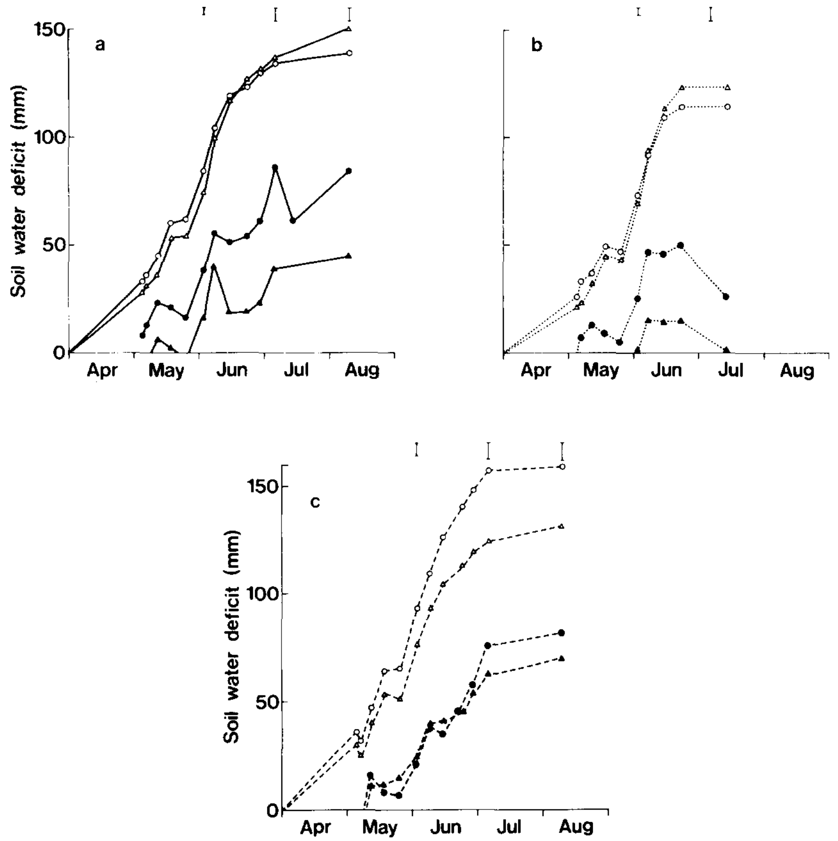

Fig. 2. Soil water deficits under winter wheat and winter barley crops. a. Winter wheat on clay soil; b. Winter barley on clay soil; c. Winter wheat on sandy loam. ●, ○ freely-drained; ▲, △ waterlogged in winter; *closed* symbols, irrigated; *open* symbols, subjected to drought. I, S.E.

Plant-water relationships

On the clay, waterlogging and drought affected leaf water potential and stomatal conductance of wheat but they did not interact; therefore the mean effects only are shown in Table 3. Waterlogging increased leaf water potential and stomatal conductance slightly: drought decreased them. The effects of drought became significant at the beginning of June and increased towards harvest.

On the sandy loam the effect of drought on leaf water potential and stomatal conductance was significant, but not the effect of waterlogging (Table 3).

Dry matter production in relation to water use

Drought decreased water use proportionately more than dry matter production, while waterlogging had the opposite effect. This was

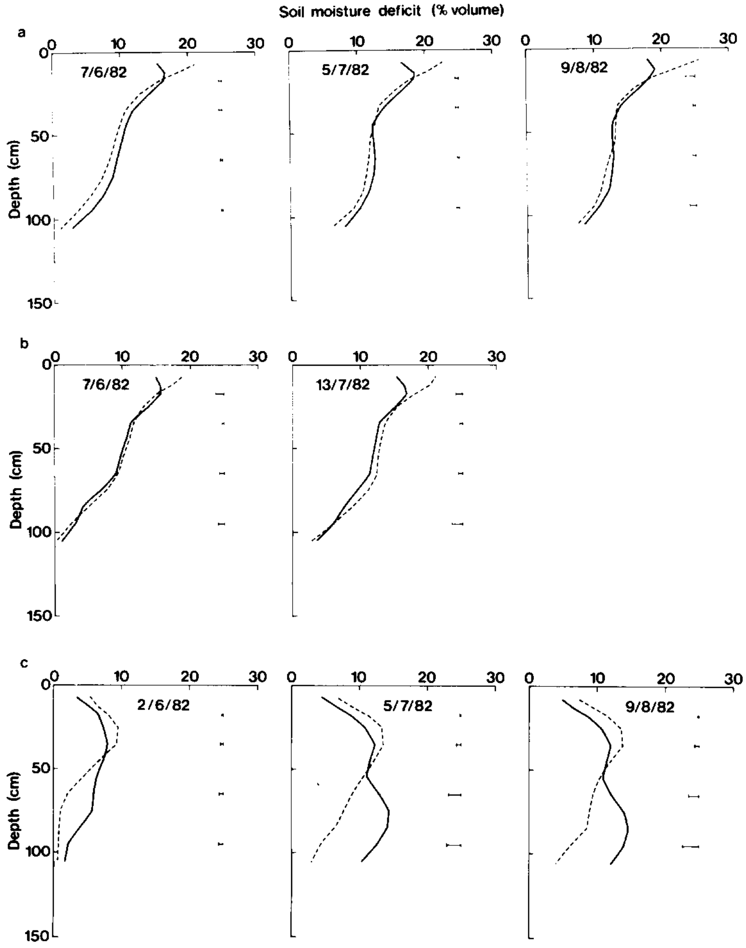

Fig. 3. Profiles of soil water extraction for the crops subjected to drought. a. Winter wheat on clay soil; b. Winter barley on clay soil; c. Winter wheat on sandy loam. —— freely-drained; ---- waterlogged in winter. For the clay soil the deficits are calculated with respect to 2 April 1982, and for the sandy loam with respect to 4 May 1982. ├──┤, S.E.

shown by calculating the amount of water evaporated per unit increase in crop dry weight per unit ground area. This is referred to as the transpiration ratio (Table 2), and is the inverse of what is often referred to as the water use efficiency[8]. It was calculated for the period 1 April – harvest using total shoot weight[4], and as no destructive samples were taken before harvest includes the weight of the shoot at 1 April, and excludes root weight.

Table 3. Leaf water potentials and stomatal conductance of winter wheat plants subjected to waterlogging in the winter or drought in the summer

Soil type	Date	Freely-drained	Waterlogged	Irrigated	Subjected to drought	SE
Leaf water potential (MPa)						
Clay	13 May	– 1.30	– 1.24	– 1.26	– 1.29	0.02
	8 June	– 1.69	– 1.56	– 1.53	– 1.72	0.03
	7 July	– 1.63	– 1.49	– 1.34	– 1.79	0.05
Stomatal conductance (cm s^{-1})						
	13 May	0.29	0.39	0.35	0.33	0.01
	88 June	0.24	0.31	0.33	0.23	0.02
	7 July	0.17	0.22	0.27	0.11	0.03
Leaf water potential (MPa)						
Sand	13 May	– 1.26	– 1.25	– 1.22	– 1.29	0.02
	8 June	– 1.64	– 1.52	– 1.54	– 1.62	0.10
	7 July	– 1.46	– 1.45	– 1.34	– 1.58	0.06
Stomatal conductance (cm s^{-1})						
	13 May	0.21	0.23	0.21	0.23	0.035
	8 June	0.27	0.23	0.32	0.19	0.025
	7 July	0.22	0.23	0.33	0.11	0.033

Discussion

Drought restricted water use and dry matter production by wheat and barley on the clay, although the effect on barley dry matter was not quite significant[4]. The effect on water use was proportionately greater than on dry matter production. On the sandy loam, drought decreased water use by wheat but had only a small, non-significant, effect on dry matter production.

Penman[20] and French and Legg[11] suggested that when water was freely available the rate of increase of total dry weight would be proportional to the transpiration rate, and that when the soil water deficit exceeded a limiting value, D_1, transpiration and growth would stop or slow down. If more water became available growth and transpiration would resume. These hypotheses imply that loss of yield due to a large soil water deficit would be proportional to the decrease in transpiration. In other work, total dry matter and grain yield were linearly related to water use in spring barley[6] and spring wheat[15], consistent with Penman's hypotheses. Our results do not support the hypotheses, but suggest that there might be two values of D_1, one at which transpiration is restricted and another, higher value, at which growth is restricted. In our experiment, D_1 for transpiration was reached on both soils (Table 2), but D_1 for growth was reached only on the clay, with

Table 4. Measured values of plant available water (PAW) for several soils, and calculated values of profile available water and maximum extractable water XWC_{max} for two soils

Soil series	Textural class	PAW (mm)	Profile available water (mm)	XWC_{max} (mm)	Reference
Lakenheath	Sandy loam	170	160	154	This paper
Evesham	Clay	150	144*	169*	This paper
Denchworth	Clay	186	–	–	M J Goss and K R Howse**
Astley Hall	Sandy loam	150	–	–	10
Downholland	Silty clay	150	–	–	10
Hamble	Silt loam	180	–	–	12

* These values were calculated for a typical clay soil, not necessarily Evesham series.

** Agricultural Research Council Letcombe Laboratory, Private Communication.

both wheat and barley.

The maximum deficit reached in a lysimeter subjected to drought is a measure of the maximum amount of water that the crop can extract from the soil. This is equivalent to the term 'plant available water' (PAW) used by Meyer and Green[18], and is a combined property of the soil type and the crop.

In our experiments the maximum measured deficits in lysimeters that were subjected to drought and had been freely-drained, were 139 mm for wheat on the clay, 159 mm for wheat on the sandy loam, and 114 mm for barley on the clay (Table 2). Measurements were made to 110 cm, but extrapolation downwards of the profiles of extraction suggests that wheat extracted water from below that depth. In both soils the wheat might have extracted water to 1.4 m depth (had the lysimeters been that deep), and another 10–15 mm could be added to the maximum deficits. The maximum depth of extraction by barley from clay was about 1.2 m so the measured maximum deficit need not be increased.

In the absence of any restriction to rooting, such as a lysimeter base, the PAW for winter wheat on Evesham series clay and Lakenheath series sandy loam are therefore at least 150 and 170 mm, respectively, and the PAW for winter barley on the clay is 112 mm. The difference in PAW between wheat and barley on the clay cannot be tested statistically, but if it were significant would suggest that winter barley is more vulnerable to drought than winter wheat. However, winter barley is likely to avoid the most serious drought because it matures a few weeks earlier.

The values of PAW for wheat can be compared with published values of maximum recorded extraction of water from other soil types (Table 4).

Values of PAW obtained by measuring water extraction by crops can be compared with the amount accessible to crops as calculated by two methods from laboratory determinations of water holding capacity. Hall *et al.*[13] defined available water as that held between 0.005 and 1.5 MPa, and easily available water as that between 0.005 and 0.2 MPa; they suggested that the water accessible to a cereal crop from a soil profile would be the sum of the available water from 0 to 50 cm depth and the easily available water from 50 to 120 cm depth. They refer to this as the profile available water. The method of calculating the available water does not assume that the crops actually extract water from the soil profile in the pattern suggested by the calculations. The method is simply a convenient way of estimating the total from laboratory measurements.

An alternative method of calculating the amount of water accessible to crops was suggested by Francis and Pidgeon[9]. They defined extractable water capacity (XWC) as the water held in the soil between field capacity and permanent wilting point which is accessible to the root system of the crop. XWC is not constant for a given soil, but increases with the size of the root system to a maximum value, XWC_{max}. They calculate XWC_{max} as the sum of the available water (0.005 to 1.5 MPa) down to 80 cm depth and a linearly decreasing portion of the available water in each 10 cm layer from 80 to 140 cm depth.

From our own laboratory measurements we calculated profile available water and XWC_{max} for the Lakenheath series sandy loam (Table 4), though few measurements were made and errors cannot be attached to the values. We have no laboratory measurements for the Evesham series clay, but calculations were done using published measurements for typical clay soils[13]. The calculated values of profile available water and XWC_{max} came close to the measured PAW for the Lakenheath series soil, but the method of Hall *et al.*[13] was better.

The measured values of maximum deficit vary widely between replicate profiles within one soil series. For example the average maximum deficit for wheat on the Evesham series clay was 140 mm, but the individual values for the four replicate profiles were 126, 128, 143, and 158 mm. Errors of measurement in these values arise from three main sources: random errors associated with counting, location errors of the neutron probe in the access tube, and calibration errors. Using methods outlined by Bell[1,2] we calculated the random counting error, then by assuming that errors from all three sources were equal we estimated that the 95% confidence limit on a measured deficit is ± 4 mm. Similar estimates of error when using the neutron probe have been made previously[16]. Thus the range of values for the Evesham series clay mainly represents real variation between four profiles that were originally collected from a small area.

On both soils transpiration was restricted when the soil water deficit reached about 0.75 of PAW. Similar results were reported by Meyer and Green[17,18] for wheat growing in clay lysimeters and for various other species and soils as reviewed by Ritchie[21]. It has been shown for maize, however, that the ratio of soil water deficit to PAW at which transpiration begins to slow down is less at greater rates of potential evaporation[7]. In our experiment if the rate of water use by the irrigated crop represents the potential evaporation then it was 4–5 mm/day when the critical ratio of about 0.75 was reached in early June.

Waterlogging in the winter decreased dry matter production[4], but not by causing plant water stress in the spring and summer. Plants that had been waterlogged had higher leaf water potentials and stomatal conductances (Table 3), and dry matter production was decreased more than water use.

There was no evidence that waterlogging in the winter made the crop more vulnerable to drought in the summer. This is in spite of possible restriction to rooting by waterlogging as indicated by slightly greater extraction of water from above 20–30 cm, and less from below, than by wheat that had been freely-drained (Fig. 3), an effect also found in the field in undrained and drained clay land[14]. Waterlogging might have mitigated the effect of the subsequent drought, by decreasing the crop's demand for water. This could explain why, on the clay soil, the effect of drought on total water use was significantly less when it followed waterlogging (Table 2).

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