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Bioclimatology

Water deficits during reproductive growth of soybeans. II. Water use and water deficiency indicators

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Summary — An experiment was carried out over 2 years with soybeans to study water use and performance of different indicators of water status under field controlled conditions, comparing an irrigated check with treatments with imposed water deficiencies. Statistically significant differences were found between treatments in predawn water potential *(PWP)*, noon water potential *(NWP)* and leaf resistance *(LR)*. PWP best reflects soil water availability or percentage of available water *(PAW)*. The determination coefficient (R^2) between *PWP:PAW* for both years was 0.77**. Water use was reduced when water deficiency was applied, and actual water use: potential evapotranspiration *(WU:PET)* relationship was drastically reduced for the dry treatments. (0I, I0, 00) compared with the control (II), but it recovered almost completely when the deficiency was removed. Total water used efficiency *(TWUE)*, as dry matter: water use *(DM:WU)* and water use efficiency *(WUE)*; as seed yield: water use *(SY:WU)*, were significantly higher for the second year. A time-integrated deficiency index *(DI)* was calculated as:

$$DI = 1 - \int_{tb}^{te} (PAW/AWT)\, dt,$$

for all *PAW* < *AWT*, where *tb* and *te* are the beginning and the end of the period, and *AWT* is the *PAW* threshold (62%). Below that value, *WU* and *DM* are reduced. Dry matter production and seed yield were related to *DI* as:

$$DM = 5.216 - 1.353 \ln (DI);\ R^2 = 0.75^{**}\ n = 32$$
$$GY = 3.187 - 0.349 \ln (DI);\ R^2 = 0.61^{**}\ n = 32.$$

***Glycine max* = soybean / water use / water stress / water use efficiency / indicator parameter**

Résumé — Déficit hydrique durant la phase reproductive du soja. II. Utilisation de l'eau et indicateurs de déficience en eau. *On a effectué durant 2 ans le suivi de l'utilisation de l'eau et de différents indicateurs de l'état hydrique d'une culture de soja dans une expérience en conditions contrôlées en plein champ comportant un contrôle irrigué et 3 traitements d'imposition de sécheresse.*

On a constaté des différences significatives entre traitements pour le potentiel hydrique avant l'aurore (PWP), *le potentiel hydrique à midi* (NWP) *et la résistance des feuilles* (LR). PWP *cependant reflète beaucoup mieux la disponibilité en eau du sol ou le pourcentage d'eau utile* (PAW). *Le coefficient de détermination* (R^2) (PWP/PAW) *a été de 0,77** pour les 2 ans.*

L'utilisation de l'eau est réduite lors de l'imposition de la sécheresse et la relation entre l'utilisation réelle de l'eau et l'évapotranspiration potentielle (WU:PET) *pour les traitements de sécheresse (OI, IO, OO) baisse drastiquement, en comparaison avec le traitement contrôle (II), mais elle se rétablit presque complètement quand le déficit est levé.*

L'efficience totale d'utilisation de l'eau (TWUE) *calculée comme la matière sèche produite divisée par l'eau utilisée* (DM WU) *et l'efficience d'utilisation de l'eau calculée comme le rendement en grains divisé par l'eau utilisée* (SY:WU), *ont été significativement plus élevées pour la seconde année.*

On a calculé un indice de déficit intégré dans le temps à partir de la formule:

$$DI = 1 - \int_{tb}^{te} (PAW/AWT)\, dt,$$

* Correspondence and reprints

pour toutes les situations PAW< SWT *où* tb *et* te *sont l'initiation et la fin de la période considérée, et* AWT *est le seuil de* PAW = *62%. En-dessous de ce seuil,* WU *et* DM *sont réduits. La production de matière sèche et le rendement sont en relation avec* DI *selon les relations suivantes :*

$$DM = 5{,}216 - 1{,}353 \ln (DI);\ R^2 = 0{,}74^{**}\ n = 32$$
$$SY = 3{,}187 - 0{,}349 \ln (DI);\ R^2 = 0{,}61^{**}\ n = 32$$

Glycine max = *soja / consommation d'eau / déficience en eau / efficience d'utilisation de l'eau / paramètre indicateur*

INTRODUCTION

The effect of drought during different subperiods in soybean crops has been established under controlled conditions (Mingeau, 1974; Sionit and Kramer, 1977), and also in field experiments with plastic covers to exclude rainfall (Doss *et al*, 1974; Brown *et al*, 1985), and without protection (Ashley and Ethridge, 1978; Korte *et al*, 1983; Kadhem *et al*, 1985; Puech and Bouniols, 1986).

In Balcarce, the R_1–R_7 period occurs during January and February, when the mean difference between potential evapotranspiration and rainfall is 167 mm (50-year record), which must be supplied by the soil water. Then the possibility that a crop uses as much water as needed depends on the soil water at the depth at which the roots are actively growing. A more intense soil exploration can be expected under conditions of water deficiency (Maertens, 1986), but no agreement exists on the soil depth explored by soybean roots. Mayaki *et al* (1976), Kaspar *et al*, (1978, 1984); Willat and Taylor (1978); Reicosky and Deaton (1979); Hoogenboom *et al* (1987), found soybean roots at 1–2 m, and Maertens (1986) at 2–3 meters; but Cox and Jolliff (1987) reported little soil water absortion below 90 cm.

Total dry matter production for several crops is linearly related to water use (Hanks, 1983). Mingeau (1974), Puech *et al* (1978) and Scott *et al* (1987) verified the relation for soybean under different environmental conditions.

Correlations between seed yield and water use may be improved by measuring the effect of deficiencies during critical growth stages (Kanemasu, 1983) since the part of the plant most affected is that which actively grows at the time the deficiency occurs (Donald and Hanblin, 1976).

Several indicators of plant water status have been recommended by Begg and Turner (1976), Kramer (1983), and Cox and Jolliff (1987). Predawn water potential *(PWP)* and leaf resistance *(LR)* have been suggested by Hiler and Howell (1983). Cox and Jolliff (1987) used leaf temperature (LT) measured with a porometer to compare soybean under well watered and dry treatments. Plant and soil deficiency indicators were used by Hiler (1973) to develop a stress day index.

Changes in deficiency indicators must be associated with changes in physiological processes responsible for crop yields. One of the processes most affected by water stress is transpiration. It has been demonstrated for several crops (Ritchie *et al*, 1972; Shouse *et al*, 1982) that when percentage of available water *(PAW)* is above a given value, transpiration depends on the climatic demand, and below this value the ratio actual: maximum evapotranspiration drops dramatically. In cowpea actual transpiration: maximum transpiration also showed a clear response to a threshold value of predrawn water potential (Shouse *et al*, 1982). Reduction in soybean transpiration and photosynthesis has been reported in response to a similar water deficiency (Boyer, 1970; Huang *et al*, 1975). A reduction in dry matter can be expected as a consequence of lower transpiration.

The objective of this study was to examine the performance of some indicators and their threshold values, and to study how water deficiencies that normally occur in the area during soybean reproductive period modify soil water extraction pattern and affect both water consumption and production and their relationship.

MATERIALS AND METHODS

The experiment was a complete randomized block design, with 4 treatments: a control (II), kept over 50 percentage available water *(PAW)*, and 3 dry treatments imposed during the following periods (adapted from Fehr and Caviness, 1977): R_1–R_4 (0I); R_4–$R_{6.3}$ (I0) and both R_1–R_4 and R_4–$R_{6.3}$ (00).

Daily climatic values were obtained from the meteorological station located 1 000 m from the experimental site. In table I some averaged data have been presented. Rainfall was measured with a rain gauge in

Table I. Soil properties: typic argiudol, Balcarce, Bs As, Argentina.

	Depth (cm)	Soil particles (%)				OM	BD	UL	LL	ASW
		Cl	FS	CS	S					
Ap	0– 11	26.1	22.7	18.0	33.2	5.5	1.17	41	23	18
A12	11– 25	25.8	22.7	16.7	34.8	5.2	1.20	53	30	23
B1	25– 37	26.5	16.1	18.1	39.3	2.1	1.28	43	24	19
B21	37– 51	35.4	11.6	17.1	35.9	1.3	1.33	52	26	26
B22t	51– 85	35.8	10.7	15.8	37.7	0.6	1.40	124	63	81
B3	85–100	24.0	13.6	17.0	45.4	0.3	1.32	48	21	27
C	100–200	19.0	13.6	17.4	50.0	0.4	1.24	239	113	126
Sum for the whole profile								600	300	300

Cl: Clay, 0–2 microns; FS : fine silt, 2–6 microns; CS: coarse silt, 6–200 microns; S: sand, 200–2 000 microns; OM: organic matter, %; BD: bulk density, $Mg.m^{-3}$; UL and LL: upper and lower limit of soil water, mm; ASW: available soil water, mm.

the center of the experimental site and irrigation applied with 5 rain gauges per plot.

The soil was a Typic Argiudol (fine, illitic clay, thermic), 2 m in depth. Table II presents some of the soil characteristics. Details of the field experiment have been described by Andriani *et al* (1991).

Soil water content was measured weekly using a neutron probe (Troxler 103 A and 2651). Access tubes were installed to a depth of 2 m (1 per plot in 1986 and 2 in 1987). The probe was calibrated with volumetric soil samples.

Total available water *(TAW)* for the entire profile is the sum of the available water (AW) on each soil layer, and:

$$AW\,(\text{mm}) = UL - LL$$

The upper limit *(UL)* in mm, is the constant soil water content in each soil layer after drainage of the excess applied water under non evaporative conditions. The lower limit *(LL)* was estimated as:

$$LL\,(\text{mm}) = UL \times A/B$$

A and *B* being the amount of water (mm) in disturbed soil samples at –1.5 and –0.033 MPa, respectively.

The maximum water holding capacity for the modal soil profile was 600 mm and the *TAW* 300 mm.

The percentage of available water *(PAW)* at a given time and at the root depth (*z* layers), was calculated as:

$$PAW = 100 \sum_{i=1}^{z} [(SWC - LL)/AW]$$

Table II. Meteorological parameters during soybean growing season in 1986/1987 and 1987/1988, Balcarce, Bs As, Argentina.

Solar radiation		Mean max temp		Mean VPD		PET		Mean RH		Rainfall		ST
1986	*1987*	*1986*	*1987*	*1986*	*1987*	*1986*	*1987*	*1986*	*1987*	*1986*	*1987*	
24.0	24.2	23.4	23.2	9.8	10.6	5.7	5.6	60	56	193	61	I
24.1	22.0	25.1	23.3	10.7	7.9	5.8	4.9	61	57	7	116	II
25.5	26.1	27.8	27.6	17.0	18.5	6.5	6.7	65	67	56	100	III
25.1	21.7	29.4	24.3	19.7	10.5	6.0	4.8	72	59	42	63	IV
13.7	15.0	24.5	24.6	10.6	8.7	3.4	3.3	40	46	108	22	V

Solar radiation, MJ.m–2.day–1; mean maximum temperature, °C; vapour pressure deficit (VPD), mb; potential evapotranspiration (PET), mm.day–1; Doorenbos and Pruitt, 1977; mean relative humidity (RH), %; rainfall, mm; stages (ST): I: S–V_3; II: V_3–R_1; III: R_3–R_1; IV:R_4–$R_{6.3}$; V: R_6–R_8. Fehr and Caviness, 1977.

where *SWC* is the soil water content at the time of measurement.

The crop actual water use *(WU)*, was calculated with a hydrological balance:

$$WU\,(\mathrm{mm}) = I + R - SV$$

where *I*: irrigation (mm); *R*: rainfall (mm); and *SW*: variation in soil water storage (mm), between 2 dates for all *SWC* lower than *UL*.

Leaf water potential was measured with a Scholander type chamber between 5.00 and 7.00 am for predawn water potential *(PWP)* and between 12.00 and 3.00 pm for noon water potential *(NWP)*. Leaf resistance *(LR)* and leaf temperature *(LT)* were measured with a steady state gas diffusion porometer (Licor 1600) of both faces of 3–5 leaves.

ANOVA and Duncan's tests were applied to find differences between treatments and for means comparisons respectively, at the 5% significance level. The least-squares method was used to find the best fit for the water stress indicators.

A *PAW* value that produced clear changes in *PWP* and in the water use: maximum evapotranspiration *(WU:MET)* ratio was identified using the analysis proposed by Cate and Nelson (1965, 1971) to separate 2 populations with different responses to a given factor.

The deficiency index *(DI)* was calculated as the time integral from *tb* (beginning time), to *te* (ending time) of the period with *PAW* below the available water threshold *(AWT)*:

$$DI = 1 - \int_{tb}^{te} (PAW/AWT)\,.\,dt$$

for all *PAW* lower than *AWT*.

RESULTS AND DISCUSSION

Water deficiency indicators

The evolution of water deficiency indicators is shown in figure 1. Percentage available water *(PAW)*; predawn water potential *(PWP)*, and noon water potential *(NWP)* in the leaves and leaf resistance *(LR)* showed significant differences ($P < 0.05$) between the dry treatments (0I, I0, 00) and the control (II). Significant differences were found between dry and wet treatments in *LR* (Heatherly *et al*, 1977; Neyshaboury and Hatfield, 1986; Cox and Jolliff, 1987; in *NWP* (Brady *et al*, 1974; Heatherly *et al*, 1977; Mason *et al*, 1982; Cortes and Sinclair, 1986; Neyshaboury and Hatfield, 1986; Cow and Jolliff, 1987), and in *PWP* (Brady *et al*, 1974; Heatherly *et al*, 1977; Turner *et al*, 1978; Cortes and Sinclair, 1986).

PAW was chosen as a standard to test the plant indicators, because it is unaffected by daily climatic changes. As no incidence of plant age was found (Sionit and Kramer, 1976; Turner *et al*, 1978), both early and late deficiency data were included in the relations presented in table III. Poor association between *PAW* and *LR* was found even though the *LR* values for the dry treatments were always higher than those reported by Neyshaboury and Hatfield (1986) as critical for indeterminate soybean net photosynthesis (250 $s.m^{-1}$).

Leaf temperature *(LT)* was a clear sign of water stress only with high climatic demand (air temperature > 30 °C) and low *PAW* (< 30%). This agrees with the findings of Cox and Jolliff (1987).

Great dispersion in *NWP* was found at high *PAW*. During the first year, when *PAW* was lower, a better *NWP:PAW* relationship was obtained. Heatherly *et al* (1977) found that *NWP* was less affected by climatic demand when the soil was dry. Brady *et al* (1974) reported that *PWP* was better related to soil water potential than *NWP* because it was less affected by climate. *NWP* during the dry periods was always < –1.1 MPa (fig 1). Soybean net photosynthesis has been reported as affected by NWP ranging

Table III. Relationship between percentage available water *(PAW)* and predawn leaf water potential *(PWP)*, noon leaf water potential *(NWP)* and leaf resistance *(LR)* for the 2 years of soybean experiments.

	R^2 (** $P < 0.01$) 1986/1987			1987/1988		
PAW:PWP	0.69**	(n = 160)	p = 1	0.81**	(n = 96)	p = 2
PAW : NWP	0.51**	(n = 160)	p = 1	0.42**	(n = 96)	p = 2
PAW : LR	0.25**	(n = 140)	p = 3	0.45**	(n = 96)	p = 6

n = samples; p = subsamples.

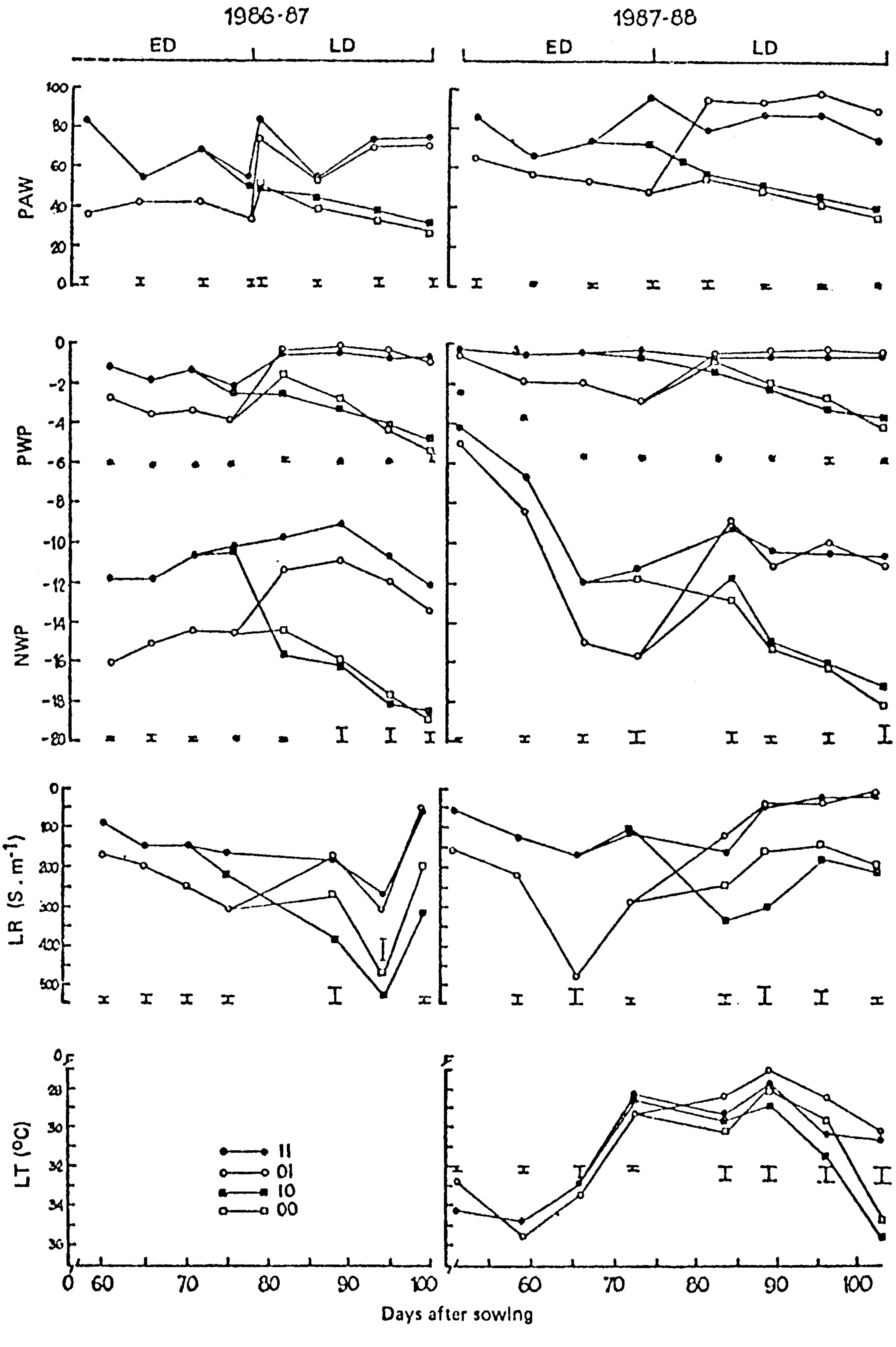

Fig 1. Percentage of available water, predawn water potential and noon water potential in the leaves (in MPa), leaf resistance and leaf temperature. *ED* and *LD* refer to early and late deficiencies. Vertical lines represent standard deviations, * indicating values smaller than the symbol used.

from −1.2 MPa (Boyer, 1970; Cox and Jolliff, 1986; Neyshabouri and Hatfield, 1986) to −1.5 MPa (Turner *et al,* 1978). *NWP* seems to be a good indicator of crop water deficiencies only under similar climatic demands.

The relations between all the parameters with *PAW* were in general better the second year (table III) because of a larger number of subsamples (doubled in 1987/1988). An exponential equation gave the best fit for the relationship between *PWP* and *PAW* (R^2 = 0.77**; *n* = 256). Brady *et al* (1974) reported similar R^2 for the relationship *PWP*: soil water potential.

The ratio actual water use to maximum crop evapotranspiration *(WU:MET)* was related to *PAW* (fig 2b). Paired *WU* and *MET* data were selected to fulfill the requirements of *MET* for the control treatment (high *PAW*) and 95% photosynthetic active radiation intercepted for dry treatments (to reduce the incidence of soil evaporation). Below a critical PAW of 62 the crop evapotranspiration was reduced (*WU:MET* = 0.75). Brun *et al* (1985) suggested that with *PAW* = 50 the soybean water use was 74% of the *MET*. Burch *et al* (1978) found that *PAW* = 50 was a threshold for the ratio *WU:MET*, and Constable and Hearn (1980), reported that for maximum yield, *PAW* > 60 was required during pod filling.

Below the critical *PAW* threshold of 62% *PAW* affected *WU*. This threshold was related to *PWP* = −0.14 MPa, using the method suggested by Cate and Nelson (1965, 1971) as shown in figure 2a. Consequently, *PWP* = −0.14 MPa can also be used as a threshold value associated with reduced water use.

CROP WATER USE

Figure 3a shows cumulative water use for the different treatments. The dry treatments (I0, 0I, 00) used less water in the second year because of the lower climatic demand (see table II). In both years, *WU* was reduced compared with the control immediately after starting the early and late deficiency periods *(ED, LD)*, recovering upon re-irrigation.

Figure 3b shows the time evolution of the ratio between water use *(WU)* and Penman potential evapotranspiration *(PET)* as calculated by Doorenbos and Pruitt (1977). The water used for the control (II) is considered the maximum crop evapotranspiration *(MET)* and the ratio *MET:PET* the crop coefficient (K_c). K_c values > 1.0 were obtained after 95% of *PAR* was intercepted, and the maximum value (K_c = 1.6) was achieved at the R_6–R_7 stage.

SOIL WATER EXTRACTION PATTERNS

Figure 4 shows that the depth of water extraction was strongly modified by the drought treatments. At the end of the early deficiency (R_4 stage), treatments 0I and 00 explored at least at 180 cm of soil profile compared with 140 cm of treatments I0, II. The maximum soil depth (190 cm) was explored at 85 days in treatments 0I, 00 and at 115-120 days in treatments II and I0.

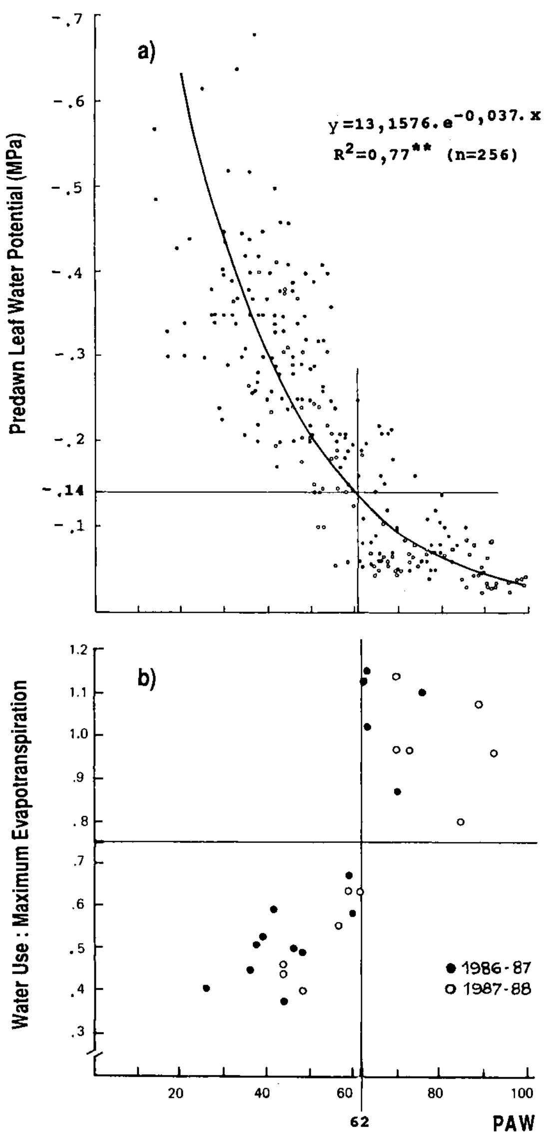

Fig 2. a) Relationship between predawn leaf water potential (in MPa), and percentage of available water. **b)** Relationship between water use in the treatment I0 : maximum evapotranspiration, and percentage of available water.

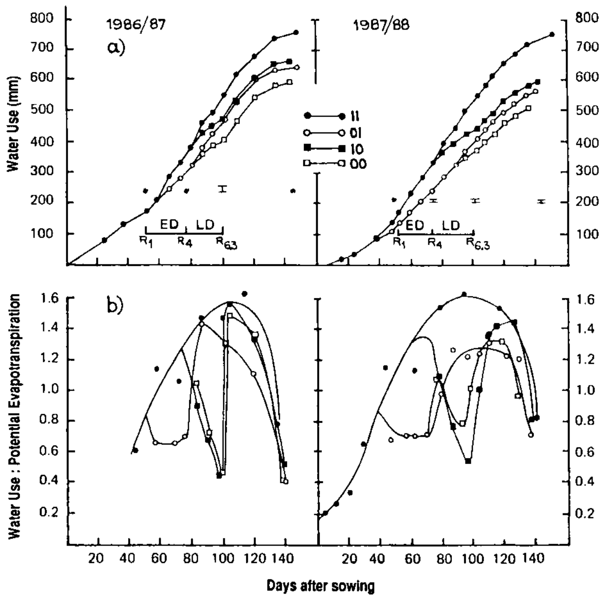

Fig 3. a) Soybean cumulative water use during 2 growing seasons (1986/1987 and 1987/1988). *ED* and *LD* refer to early and late deficiencies. **b)** Water use: potential evapotranspiration relationships for soybean crop.

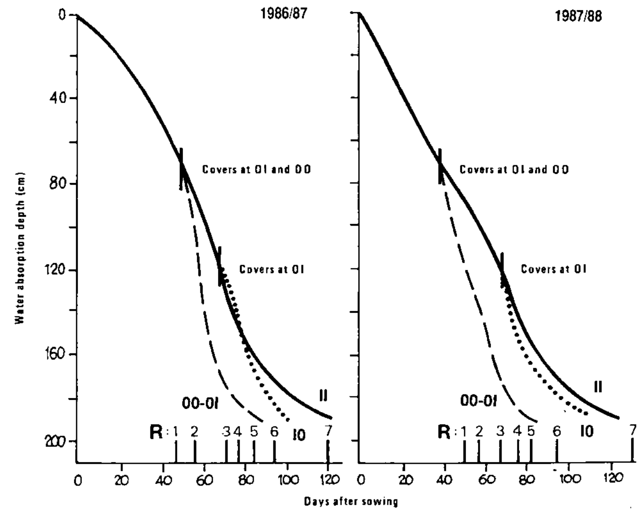

Fig 4. Water absorption depth evolution under soybean crop during 2 growing seasons (1986/1987 and 1987/1988), for different deficiency treatments (00, 0I, I0, II).

Upon re-irrigation, water extraction patterns became similar for all treatments. These observations are in agreement with Mason *et al* (1982), who found soybean water extraction during dry periods down to 260 cm. When the upper 70 cm of the soil was rewetted no water extraction occured below 90 cm.

Deep root water absorption patterns observed in this study are similar to those reported by Willat and Taylor (1978) and Mason *et al* (1982), but Cox and Jolliff (1987) under very intense and continuous drought reported only a low water extraction below 90 cm.

WATER USE EFFICIENCY

Above ground dry matter *(DM)*, seed yield *(SY)*, water use *(WU)*, total water use efficiency as *DM:WU (TWUE)* and water use efficiency as *SY:WU (WUE)* are presented in table IV. High influence of the soil evaporation on *WU* can be expected from sowing to V_3 period because of the scarce crop cover. Total rainfall and its frequency favored evaporation the first year producing a *WU* 50 mm higher than in the second year.

Differences in *DM* accumulation from R_1 were associated with water deficiency indicators (Andriani *et al,* 1991). *PAW* and *PWP* were more favorable in the second year (fig 1), giving higher *TWE* values the second year (table IV).

The quantitative relationship between *DM* and *WU* is strongly affected by environmental conditions *ie,* the water saturation deficit in the air. With low relative humidity and high temperature, the *WUE* is reduced. High values of water saturation deficit occurred during the late deficiency *(LD)* period the first year (table II), reducing *TWUE.* The *WU* adjusted by vapour pressure deficit gives a better relation with *DM* accumulation (Van Keulen and Van Laar, 1986).

Water deficiency during R_1–R_4 period reduced *DM* production without affecting *SY*; consequently, *WUE* was in general higher for the treatments 0I and 00 (table IV). Snyder *et al* (1982) found higher *WUE* when water shortage was imposed on an indeterminate soybean crop during R_2–R_4.

The linear relationship between *WU:MET* and seed yield proposed by Merrien (1987) for indeterminate soybean cultivars is only applicable in our experiment to the treatments with equal *WUE.*

DEFICIENCY INDEX

Since *PAW* = 62 has proved to give a good indication of water deficiencies during the reproductive period, this value was used as a threshold to calculate a deficiency index for each drought treatment.

DI during R_1–R_8 was related to dry matter *(DM)* and since no effect of water deficiency during flowering on seed production has been

Table IV. Soybean crop during 1986/1987 and 1987/1988. Total dry matter *(DM)*, seed yield at 13% humidity *(SY)*, water use *(WU)*, total water use efficiency *(TWUE)*, as *DM* : *DU*, and water use efficiency *(WUE)*, as *SY* : *WU*.

Year	*Treat*	*DM* $(kg.ha^{-1})$	*SY* $(kg.ha^{-1})$	*WU* *(mm)*	*TWUE* $(kg.mm^{-1})$	*WUE* $(kg.mm^{-1})$
1986/1987	II	11 150a	4 560a	751a	14.8a	6.1b
	0I	8 100b	4 431a	649b	12.5b	6.8a
	I0	7 897b	3 783b	665b	11.9b	5.7b
	00	6 862c	3 569b	593c	11.6b	6.0b
	SD	152	140	8	0.3	0.2
1987/1988	II	12 496a	5 507a	753a	16.6a	7.3b
	0I	9 589bc	4 891ab	566b	16.9a	8.6a
	I0	9 923b	4 422b	600b	16.5a	7.4b
	00	8 464c	4 437b	510c	16.6a	8.7a
	SD	332	191	11	0.4	0.2

found, only the *DI* during R_4–R_8 was related to seed field *(SY)* (fig 5). Better response was obtained for the relationship DM:DI (R^2 = 0.74** n = 32) than for *SY:DI* (R^2 = 0.61** n = 32). Shouse *et al* (1982) found a good relation (R^2 = 0.66) between cowpea seed yield and *PWP* integrated during the reproductive period.

CONCLUSIONS

Water deficits imposed on soybeans during reproductive stages (R_1–R_4). R_4–$R_{6.3}$ significantly reduced both water use and above ground dry matter accumulation, in spite of the depth of water extraction being strongly increased by dry treatments. Seed yield was only affected by deficiencies during the grain filling period (R_4–$R_{6.3}$).

The performance of soil (percentage of available water: *PAW*), and plant indicators (leaf water potential at predawn: *PWP*; noon leaf water potential; leaf resistance and leaf temperature: *LT*, showed that all excepting *LT* had a clear response to water deficiency.

PAW was used as a reference against which the other indicators were compared. *PWP* was the plant indicator which showed the best relationship (R^2 = 0.77**). The ratio of actual evapotranspiration over maximum evapotranspiration was drastically reduced when *PAW* fell below a threshold of 62% (*PWP* = –0.14 Mpa).

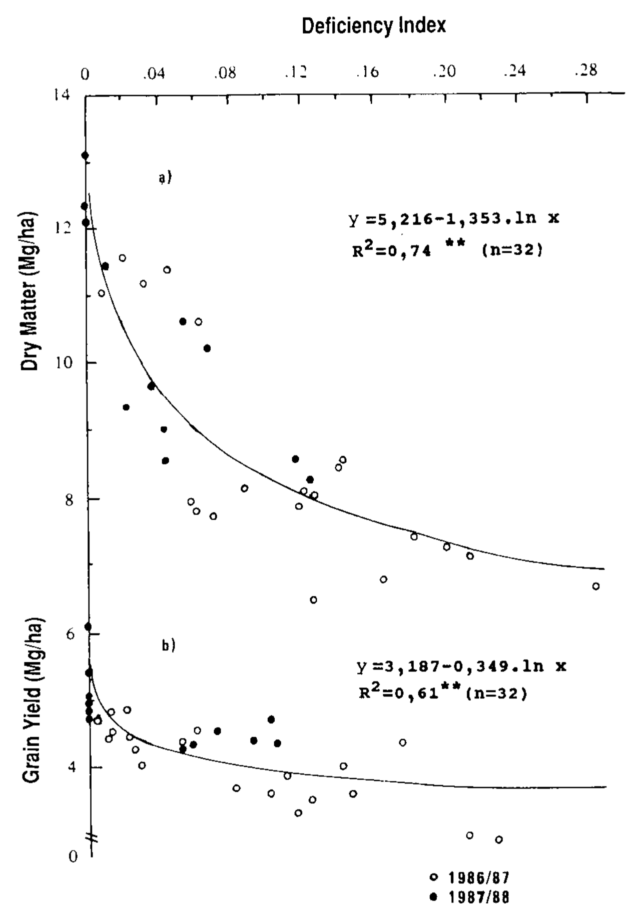

Fig 5. Soybean crop during 1986/1987 and 1987/1988. Relationship dry matter : water use. Bars represent standard deviation, when its magnitude exceeds symbol size used.

A deficiency index wich integrated reproductive periods during which the *PAW* was below the previously determined threshold showed significant relationships with both above-ground dry matter production (R^2 = 0.74**) and grain yield (R^2 = 0.61**).

As an overall conclusion, *PWP* and *PAW* are considered to be reliable water deficiency indicators, and may be used to quantify the water deficit and its effect on biomass and grain production.

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