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Agricultural Water Management 82 (2006) 223–236
Agricultural water management
www.elsevier.com/locate/agwat

The validity of predawn leaf water potential as an irrigation-timing indicator for field-grown wheat in northern Syria

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Accepted 25 July 2005
Available online 24 August 2005

Abstract

We evaluated the validity of predawn leaf water potential (ψ_{PL}) as an irrigation-timing indicator, using five field-grown wheat cultivars in three moisture regimes in northern Syria. The relationships between ψ_{PL} and amount of roots, soil water potential (ψ_{Soil}), and vapor pressure deficit (VPD) were examined. The effect of the amount of roots on ψ_{PL} was only observed before the onset of tillering. The effect of ψ_{Soil} was recognized for values below the primary wilting point, and a relationship between nighttime VPD and ψ_{PL} was observed above the primary wilting point in some cultivars. However, grain yield decline in the 50% irrigation treatment was not explained by the ψ_{PL} change; therefore, the use of ψ_{PL} alone is not recommended for determining irrigation timing in the study area.

Keywords: Predawn leaf water potential; Primary wilting point; Root length density; Soil water potential; Vapor pressure deficit

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doi:10.1016/j.agwat.2005.07.023

1. Introduction

The timing and quantity of irrigation are important factors for stabilizing and improving crop performance under conditions of water scarcity. The timing of irrigation should be determined based on plant water status. The water status of plant cells is most usefully characterized in terms of chemical potential or water potential (Kramer and Boyer, 1995), and the value of predawn leaf water potential (ψ_{PL}) has generally been considered to best represent crop level water status. Many researchers have pointed out the correlation of ψ_{PL} and plant-water relation parameters, such as soil available water (Stričević and Čaki, 1997), evapotranspiration (Meyer and Green, 1980), relative transpiration (Valancogne et al., 1997), daily minimum stomatal resistance (Dwyer and Stewart, 1984), and leaf expansion and photosynthesis (Turner et al., 1986). However, the validity of using ψ_{PL} as an irrigation indicator depends on the mechanisms influencing ψ_{PL} itself. Schmidhalter (1997) demonstrated the equilibration of ψ_{PL} with the wetter zone in bulk soil for maize, sunflower, barley, and wheat. Améglio et al. (1999) showed that ψ_{PL} in walnut trees did not change with heterogeneous distribution of soil water content in orchards and containers. In addition, Donovan et al. (2001) noted the disequilibrium of ψ_{PL} under well-watered conditions in many species and the contribution of nighttime transpiration to ψ_{PL}. If these correlations also apply to field-grown crops, the applicability of using ψ_{PL} as an indicator for irrigation scheduling would be doubtful. Field assessment of these factors is essential for establishing the validity of ψ_{PL} for irrigation scheduling.

The wheat cultivation environment in northern Syria is classified as a Mediterranean climate, characterized by winter rainfall (and a lesser amount during the warmer spring period) and hot, dry summers (Oweis et al., 2000). Soil-moisture stress usually starts in March, April, or May, depending on whether the total seasonal rainfall in the area is low, average, or high, respectively (Oweis, 1997). In Syria, wheat is normally sown in the middle of November, heads in April, and is harvested in June. Wheat response to water stress is more sensitive in the period from stem-elongation to grain-filling than in other stages (Zhang and Oweis, 1999); thus, the period of maximal water demand by wheat usually corresponds to the beginning of soil water storage decline. To avoid crop water shortages during this period, supplemental irrigation is widely practiced (Perrier and Salkini, 1991; Oweis et al., 1998). However, the excessive use of water in supplemental irrigation, because of its low cost and the increased yields, has resulted in the decline of aquifers in many areas of northern Syria (Ward and Smith, 1994). The use of an appropriate irrigation indicator would mitigate water scarcity in this area.

The primary purpose of this study was to assess the appropriateness of ψ_{PL} as an irrigation-timing indicator for wheat in the Mediterranean climate of northern Syria. Five spring bread wheat cultivars were grown under rainfed and irrigated conditions in northern Syria, and the correlations among ψ_{PL} and other factors related to wheat water relations, leaf area, amount of roots, and soil and air properties were examined during the 2001–2002 planting season.

2. Materials and methods

2.1. Site and crop management

The experiment was conducted at Tel Hadya, northern Syria (36°01′N, 36°56′E), at the main research station of the International Center for Agricultural Research in Dry Areas (ICARDA). The soil at Tel Hadya is classified as Calcixerollic Xerochrept (Ryan et al., 1997). Five cultivars (Cham4, Cham6, Bloyka1, Qafza8, and Qimma5) of spring bread wheat, *Triticum aestivum* L., were planted in plots measuring 8.0 m × 1.6 m. Cham4 and Cham6 are the most widely cultivated spring bread wheat varieties in Syria. Bloyka1, Qafza8, and Qimma5 are advanced lines from the CIMMYT/ICARDA Joint Dryland Wheat Program for West Asia and North Africa. Seeds were sown by hand in eight rows at a rate of 13.89 g m^{-2} on 23 December 2001, and 30 kg ha^{-1} of $CO(NH_2)_2$ were applied twice, once before sowing and once during tillering (12 March 2002). The plots were arranged in a randomized complete block design with three replications of three irrigation regimes (rainfed, 50% irrigation, and 100% irrigation).

2.2. Irrigation

A drip system was used for irrigation. The soil volumetric water content (θ) was monitored in the top 0.6 m of soil in the 100% irrigation regime to decide the timing and amount of irrigation. Based on the long-term measurement of θ at 0.15-m intervals from depths of 0.15–0.6 m, the minimum and maximum θ per soil layer were defined before the study, as shown in Fig. 1a (Oweis, 2000, personal communication). These values were used to represent permanent wilting point and field capacity, respectively. For the 100% irrigation treatment, water was applied to fill the soil profile to the field capacity when θ decreased to 50% of the available water. Half the amount of water applied in the 100% irrigation treatment was applied for the 50% irrigation treatment on the same day as the 100% irrigation treatment. The distance between emitters controlled the water treatment level. The emitters were placed 0.15 m apart for 100% irrigation and 0.3 m apart for 50% irrigation; no emitters were installed for the rainfed treatment (Oweis et al., 1998). The lines were laid in alternate spaces between rows, and the amount of water applied was measured using a flow meter. The supplied daily water amount in the 100% irrigation treatment was estimated to be 100 mm on 15 April and 90 mm on 5 May (113 and 133 days after sowing, respectively).

2.3. Measurements

2.3.1. Weather and crop agronomic data

Air temperature (T_{air}), relative humidity (RH), and daily rainfall data were collected at a standard weather station adjacent to the experimental field. The air vapor pressure deficit (VPD) was calculated using the following equation from Murray (1967):

$$\mathrm{VPD} = \left(1 - \frac{\mathrm{RH}}{100}\right)\left[6.1078 \times \exp\left\{\frac{(17.27 \times T_{air})}{(T_{air} + 273.15 - 35.86)}\right\}\right].$$

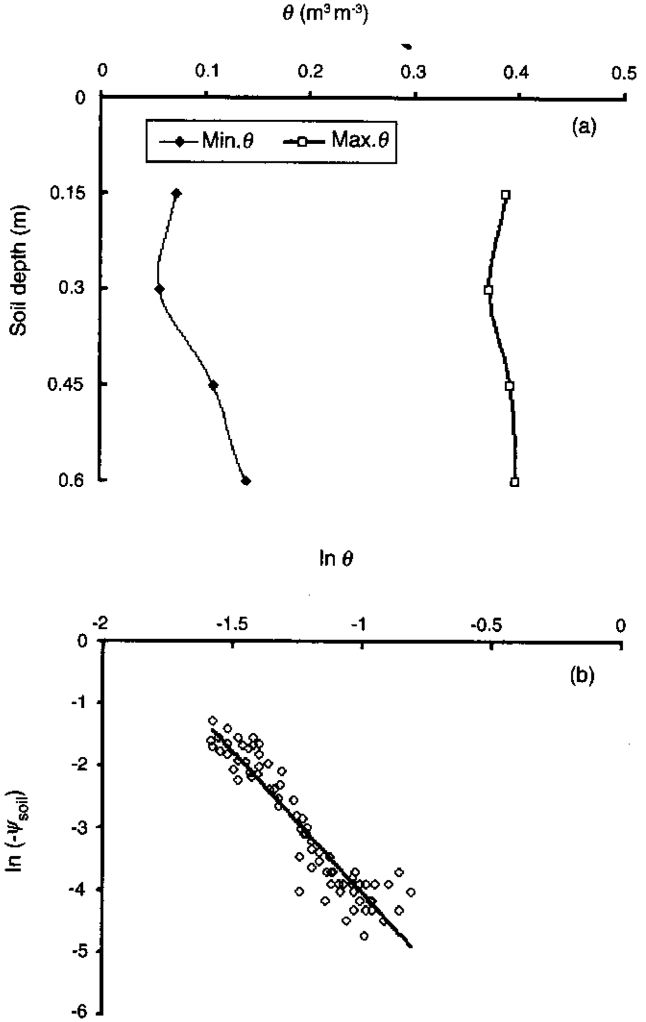

Fig. 1. Soil characteristics of the experimental field. (a) Maximum and minimum soil volumetric water content (θ) at soil depths from 0 to 0.6 m. (b) Moisture retention curve.

To examine plant growth, green leaf area was measured beginning 33 days after sowing (DAS). Five plants were randomly selected from each plot, and leaf area was measured using a leaf area meter (Li-3100, Li-Cor, Lincoln, NE, USA). The onset of tillering and heading date were recorded as the dates on which more than 66% of the plants per plot reached the respective stages. Plants were harvested on 27 June 2002.

Minirhizotrons (Böhm, 1979) were used to measure root length density in two dimensions. Glass tubes with cross sections of 0.2 m × 0.2 m to match the plant row spacing were installed in the edges of all plots 1 month prior to sowing. The bottoms of the minirhizotrons were at a depth between 60 and 95 cm. Here, we analyze the amount of roots in the upper 60 cm of soil. The parts of the glass tubes exposed above-ground were sealed with black tape that transmitted no light, and covered again with white tape to prevent increased temperatures inside the tubes. Digital cameras were mounted on the edge of a wooden bar, and root pictures were taken at every 15 cm of soil depth. The line intersection method (Newman, 1966) was applied to calculate root length in each picture using image analysis software (Adobe Photoshop 5.5). The worst contact between the minirhizotron and the surrounding soil was observed at 73 DAS because of soil volume shrinkage caused by dehydration. Therefore, we only present data until 66 DAS. Because no irrigation was applied during this period, the presented data were not divided into treatments.

2.3.2. *Soil matric potential and predawn leaf water potential*

We measured θ with a neutron moisture probe (MK II, Didcot Instrument, Wallingford, UK). Access tubes were installed in each plot after sowing. Counts were made at 0.15-m intervals starting at a depth of 0.225 m. The θ of the top 0.15 m was measured gravimetrically. Measurements were made at 7- to 17-day intervals from 8 to 146 DAS. The moisture retention curve, i.e., the relationship between θ and soil matric potential (ψ_{Soil}), is shown in Fig. 1b. It was examined using soil cores (50 mm in diameter × 50 mm in height) sampled from the experimental field. A gypsum block (5201, Soilmoisture, Santa Barbara, CA, USA) was inserted into the core samples with minimum disturbance of the soil structure. The ψ_{Soil} of the sampled cores was measured using the electrical resistance method (5910-A, Soilmoisture) at the same time as the measurement of θ, while drying each soil core. The values of θ averaged over four soil layers (0–0.15, 0.15–0.30, 0.30–0.45, and 0.45–0.60 m) were converted into ψ_{Soil} using the moisture retention curve.

Predawn leaf water potential (ψ_{PL}) was measured before sunrise between 0300 and 0500 using a pressure chamber (3005, Soilmoisture) on the same day as, or on the day following or previous to, the measurement of θ. When no rainfall was observed between the measurement of θ and ψ_{PL}, parameters are assumed to parallel each other. The youngest fully expanded leaf per plot was selected and placed in the chamber as quickly as possible (in less than 10 s).

2.3.3. *Statistical analysis*

The data were analyzed using computer software (Microsoft Excel 2000/Excel Toukei, Syakai Joho Service, Tokyo, Japan). Analyses were conducted using a combined analysis of variance (ANOVA) based on the individual ANOVA for each moisture regime (Gomez and Gomez, 1984). If the combined ANOVA was significant, differences among the means were compared using Tukey's test. Single and multiple regression analyses were performed using the least squares method.

3. Results

The grain yield response of five bread wheat cultivars under three irrigation regimes is presented in Table 1. Significant differences were seen among the three irrigation regimes, but no differences were observed among the cultivars. The seasonal changes in daily rainfall, average daily VPD, and green leaf area for the 2001–2002 planting season are

Table 1

Grain yield response of five bread wheat cultivars under rainfed, 50% irrigation and 100% irrigation regimes at Tel Hadya, Syria

Moisture regime	Mean grain yield[a] (g m^{-2})					
	Cham4	Cham6	Bloyka1	Qafza8	Qimma5	Av[b]
Rainfed	402	392	372	299	413	376 c
50% irrigation	496	501	484	456	478	483 b
100% irrigation	604	628	597	549	570	590 a
Av[b]	501 a	507 a	484 a	434 a	487 a	

[a] Average of three measurements.

[b] Within a row (or column), means followed by a common letter are not significantly different at $p = 0.05$.

shown in Fig. 2. The cumulative rainfall from 1 September 2001 to 27 July 2002 (harvest) was 404.7 mm, 18% higher than the 24-year average for 1977–2002. The rainfall amounts between 1 and 50 DAS, 51 and 100 DAS, and 101 and 150 DAS were 109.3, 94.1, and 38.7 mm, respectively. A rapid increase in VPD was observed after 100 DAS. Green leaf area increased gradually until 50 DAS. Sharp increases in green leaf area were observed after the onset of tillering (56 DAS), followed by a decline in green leaf area after 109 DAS in all treatments. A significant difference between the rainfed treatment and the two irrigated treatments was observed on 142 DAS, and comparatively high values of green leaf area were maintained in the irrigation treatments. The heading date for Bloyka1 and Qafza8 was 117 DAS, while the other cultivars headed on 123 DAS. None of the cultivars showed any effect of treatment on heading date.

The seasonal changes in average ψ_{Soil} and ψ_{PL} are shown in Fig. 3. The ψ_{Soil} values remained high until 102 DAS, after which a continuous decline in rainfed ψ_{Soil} was observed. Irrigation resulted in recovered ψ_{Soil} for the two irrigation regimes on 116 and 135 DAS. The changes in ψ_{PL} did not correspond to changes in ψ_{Soil}; the ψ_{PL} increased in early growth stages (from 25 to 39 DAS), and then remained comparatively stable until 81 DAS. Although the ψ_{Soil} decreased continuously from 109 DAS in the rainfed treatment, the rainfed ψ_{PL} recovered on 126 DAS from low values at 117 DAS. The daily rainfall amounts greater than 1 mm in this 10-day period were 4.8, 3.9, and 1.5 mm at 120, 121, and 122 DAS, respectively (Fig. 1). A sudden decrease in ψ_{PL} in the rainfed treatment was observed at 139 DAS. In the irrigation treatments, the first irrigation application seemed to contribute to ψ_{PL} recovery. However, no significant difference was observed between the two irrigation regimes throughout this period.

Fig. 4 shows the seasonal changes in root length density for each 15-cm soil layer. From 8 to 38 DAS, wheat roots only reached the 15–30-cm soil layer, with the amount of roots increasing per layer. Downward root growth was observed from 45 DAS and reached the 45–60-cm soil layer by 56 DAS. A horizontal increase in the amount of roots in the deeper soil layer was observed at 66 DAS, when sharp increases in leaf area were also observed (Fig. 2). The average root length density in the 0–60-cm soil depth was 0.10, 0.18, 0.24, 0.40, 0.58, and 0.71 cm cm^{-2} at 8, 25, 38, 45, 56, and 66 DAS, respectively.

The relationship between the average root length density in the 0–60-cm soil layer and ψ_{PL} in the period from 25 to 66 DAS is shown in Fig. 5. When root length density was less

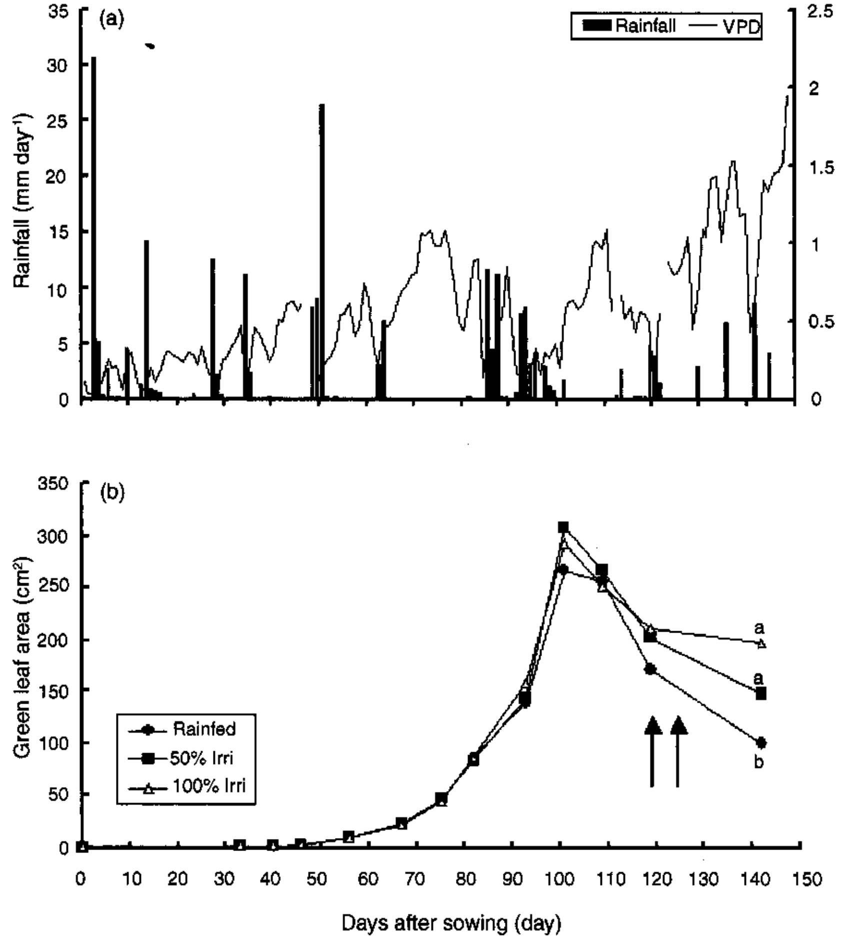

Fig. 2. Seasonal changes in (a) rainfall and vapor pressure deficit, and (b) green leaf area during the 2001–2002 wheat planting season. Data are not separated by cultivar. Arrows indicate the tillering and heading dates of Bloyka1/Qafza8 and the three other cultivars. Differences among treatment at each measurement date for points without letters are not significant (Tukey's test, $p = 0.05$).

than 0.3 cm cm^{-2}, ψ_{PL} increased sharply with increases in root length. When root length density was between 0.5 and 0.8 cm cm^{-2}, ψ_{PL} remained relatively stable, between −0.1 and −0.2 MPa. The relationship between root length density (X) and ψ_{PL} (Y) for all points in Fig. 5 was estimated as follows:

$$Y = 0.08 \times \ln(X) - 0.1 \quad (R^2 = 0.65^{**})$$

No apparent cultivar difference was observed among these regressions.

The relationship between averaged ψ_{Soil} and ψ_{PL} from 100 and 150 DAS are presented in Fig. 6. We found no apparent relationship between ψ_{PL} and ψ_{Soil} for ψ_{Soil} between 0 and

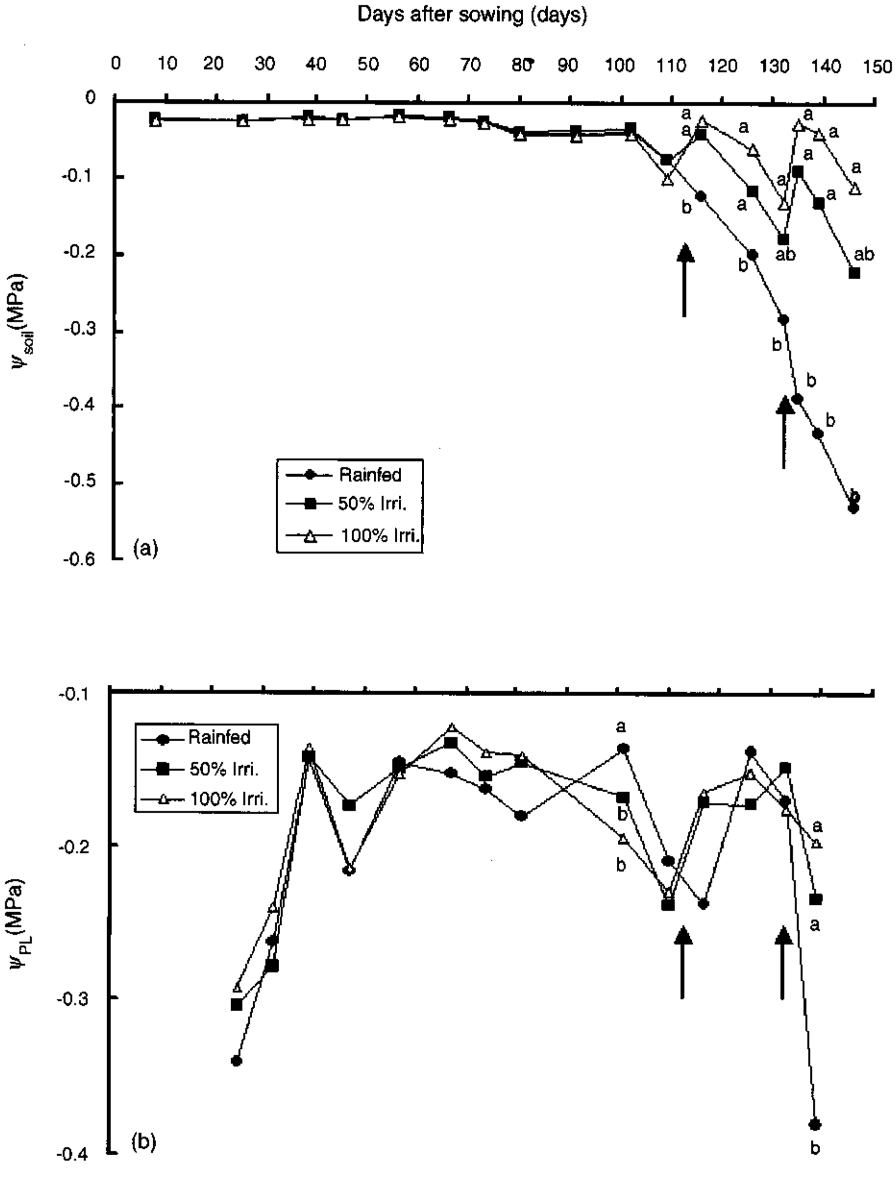

Fig. 3. Seasonal changes in (a) average soil water potential (ψ_{Soil}) in the 0–60-cm soil layers and (b) predawn leaf water potential (ψ_{PL}). Data are not separated by cultivar. Arrows indicate the date of irrigation. Differences among treatment at each measurement date for points without letters are not significant (Tukey's test, $p = 0.05$).

−0.4 MPa. In Bloyka1, Qafza8, and Qimma5, for ψ_{Soil} less than −0.4 MPa, ψ_{PL} was also substantially lower. Fig. 7 indicates the relationship between predawn VPD and ψ_{PL} for the five cultivars in the 100% irrigation treatment. The predawn VPD values were averaged for the period from 0300 to 0500 h, when ψ_{PL} was measured. The estimated relationships

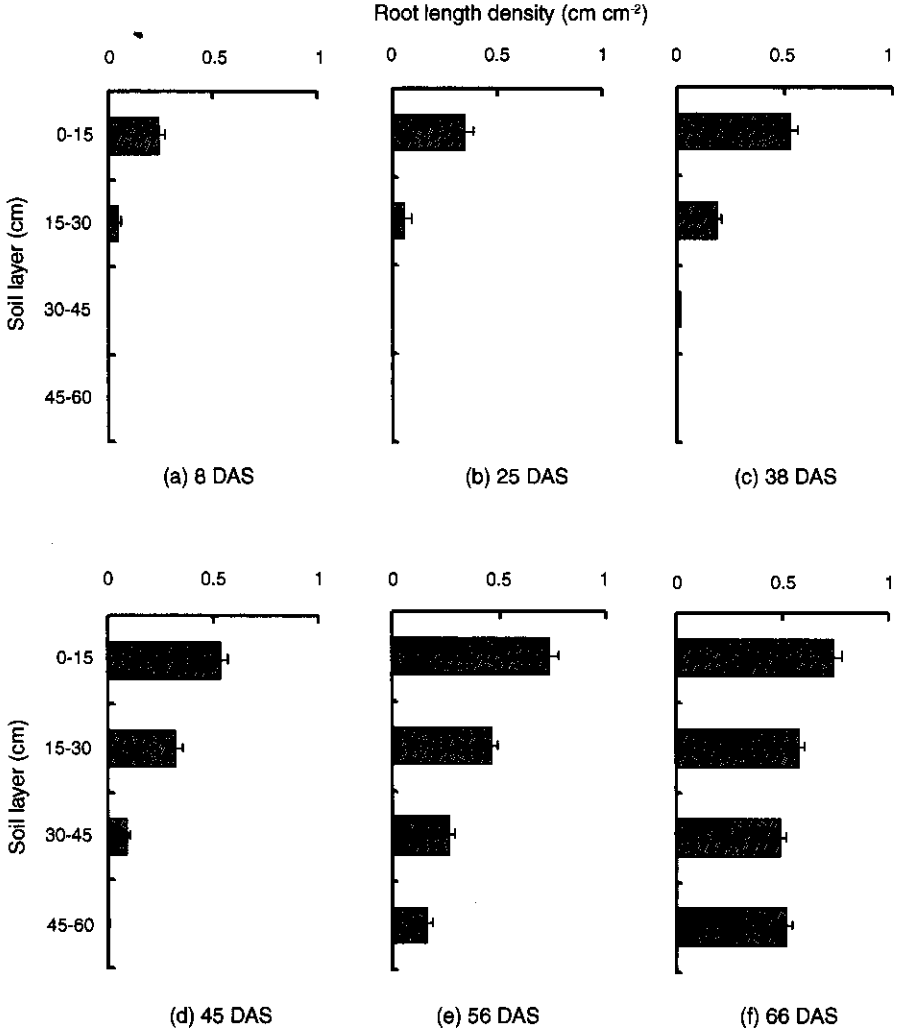

Fig. 4. Seasonal changes in root length density per 15-cm soil layer. Data are not separated by cultivar or treatment. Horizontal bars indicate standard error.

between predawn VPD (*X*) and ψ_{PL} (*Y*) per cultivar were as follows:

$$\begin{aligned}
&\text{Cham4}: && Y = -0.211X - 0.127 && (r = 0.49, \text{ns})\\
&\text{Cham6}: && Y = -0.061X - 0.153 && (r = 0.15, \text{ns})\\
&\text{Bloyka1}: && Y = -0.409X - 0.114 && (r = 0.62^{*})\\
&\text{Qafza8}: && Y = -0.084X - 0.152 && (r = 0.14, \text{ns})\\
&\text{Qimma5}: && Y = -0.499X - 0.107 && (r = 0.68^{*})
\end{aligned}$$

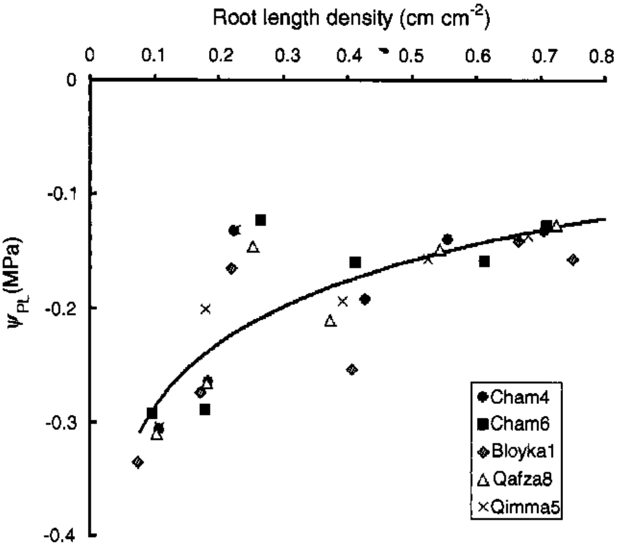

Fig. 5. Relationship between the average root length density in the 0–60-cm soil layer and predawn leaf water potential (ψ_{PL}). Values are averaged over treatments.

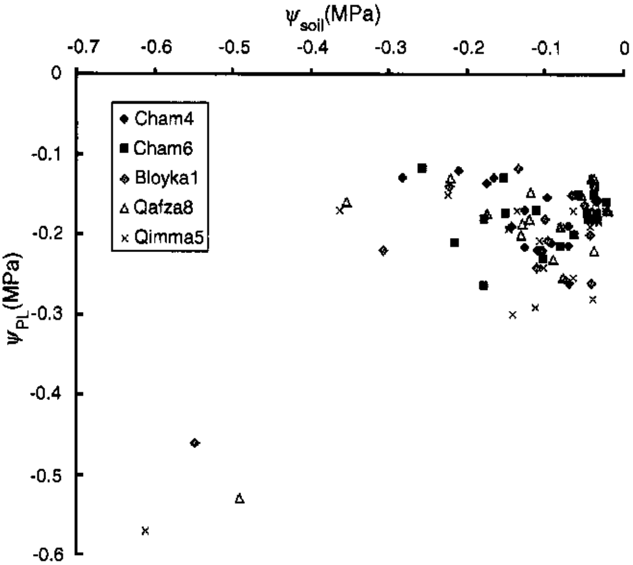

Fig. 6. Relationship between the average soil water potential (ψ_{Soil}) of the 0–60-cm soil layer and predawn leaf water potential (ψ_{PL}).

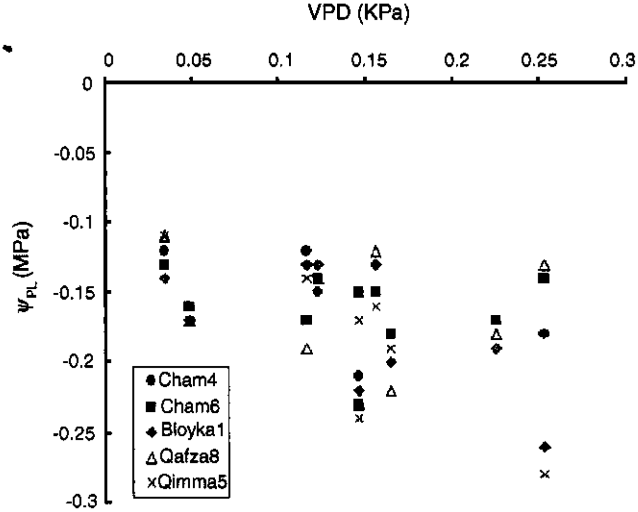

Fig. 7. Relationships between predawn vapor pressure deficit (VPD) of the air and predawn leaf water potential (ψ_{PL}) in the 100% irrigation treatment.

In Bloyka1 and Qimma5, linear relationships were observed between the two variables. The three other cultivars showed no relationship under nighttime air conditions.

4. Discussion

In contrast to the steady decline in soil water potential during the drying cycle, plants, and leaves in particular, exhibit diurnal fluctuations in water status as evaporative demand varies with day and night (Turner and Begg, 1981). Water status recovers during the night via root water absorption, and is at a maximum before sunrise. The ψ_{PL} reflects the maximum daily value of leaf water potential. Root water absorption from bulk soil occurs via two mechanisms: active and passive absorption (Kramer and Boyer, 1995). Because of the low nighttime evaporative demand, active absorption may contribute more to ψ_{PL}. Three factors may be considered to influence ψ_{PL}: soil water conditions, nighttime air conditions, and water absorption surface.

The emergence of wheat crown roots is highly organized in space and time, and is synchronized with shoot development (Wang and Smith, 2004). In cereal plants, leaf growth is related to root growth (Klepper et al., 1984; Li et al., 1993; Suga and Yamazaki, 1988). The cereal root system is composed of a seminal root and nodal roots, and both produce lateral roots. In contrast to the comparatively few changes in green leaf area before the tillering stage (Fig. 2), the root length density increased continuously with soil depth in our study (Fig. 4). Morita et al. (1993) reported that wheat nodal roots were mainly distributed in shallow soil layers, and that only the seminal root reached deeper soil layers. The increase in the amount of roots up to 66 DAS found in this study was likely caused mainly by seminal root growth. Although root data are not available after 66 DAS, an increased amount of roots could be surmised from the sharp increase in green leaf area. However, in contrast to the amount of roots, comparatively stable ψ_{PL} was observed even before the rapid increase in green leaf area (Figs. 2 and 4). Kramer (1983) related data on root water absorption rate to distance from the root cap in pumpkin and barley. An apparent decline in the absorption rate with distance was observed; however, endodermis suberization is not a complete barrier to water movement because water absorption was still observed in the suberized portion (Kramer, 1983). It is possible that root suberization prevents water movement by passive absorption caused by high transpiration demand in the daytime, but its influence may be negligible in the gradual water movement of active absorption. Thus, most wheat roots apparently influence ψ_{PL}. The effect of the amount of roots on ψ_{PL} decreased after the emergence of tillers, and the effect of the shoot/root balance on ψ_{PL} may have been established in early growth stages. Améglio et al. (1999) showed that ψ_{PL} in walnut can equilibrate with the wettest soil in split pot experiments, even when only 20% of the root volume is found in the wettest soil.

The rainfed ψ_{Soil} decreased continuously in response to rapid increases in VPD (Figs. 2a and 3a), but ψ_{PL} did not synchronize with the changes in ψ_{Soil} (Fig. 3b). Dwyer and Stewart (1984) reported different reactions of ψ_{PL} to changes in ψ_{Soil} during soil water drying and recovering cycles, and found quick recovery of ψ_{PL} with small changes of ψ_{Soil}. In our study, the rainfed ψ_{PL} recovery at 126 DAS could have been caused by the small amount of rainfall between 120 and 122 DAS, but recovery of ψ_{Soil} at 126 DAS may not have been expressed because of the dry spell and high VPD after the rainfall. When ψ_{Soil} decreased to less than −0.4 MPa in Bloyka1, Qafza8, and Qimma5, ψ_{PL} also decreased to less than −0.4 MPa (Fig. 6). A ψ_{PL} of −0.4 or −0.45 MPa has been designated by some as the beginning point of plant water stress (Stričević and Čaki, 1997; Dwyer and Stewart, 1984; Meyer and Green, 1980). However, the ψ_{Soil} corresponding to ψ_{PL} was not reported in these studies. The range of ψ_{Soil} that showed different ψ_{PL} responses in this study could reflect the primary wilting point, defined as the highest value of the wilting range (Furr and Reeve, 1945), for field-grown wheat at our experimental station. Kyuma (1984) described the primary wilting point (−0.62 MPa) as the point at which plant growth stops, but can recover if additional water is applied. These values may vary with species, growth stage, or environment. In combination with our results, it is inferred that ψ_{PL} could be directly influenced by other factors, at least below the primary wilting point.

In the rainfed treatment, a significantly lower green leaf area compared with the other treatments was observed just after the apparent decline in ψ_{PL} (Figs. 2b and 3b). The grain yield decline in the rainfed treatment (Table 1) may be caused by this rapid decline in the green leaf area. However, an apparent yield decline was also observed in the 50% irrigation treatment, even though there was no significant decline in green leaf area or ψ_{PL}. These results suggest the impossibility of detecting plant water stress before apparent morphological changes appear, when ψ_{PL} is used as the irrigation timing indicator. No relationships between ψ_{PL} and ψ_{Soil} could be recognized from Fig. 6 when the ψ_{Soil} was higher than that of the primary wilting point. Meanwhile, a linear relationship between ψ_{PL} and nighttime VPD was observed in three cultivars with 100% irrigation (Fig. 7). These correlations may be caused by nighttime transpiration, as described by Donovan et al. (2001), and this could be a factor in explaining why the ψ_{PL} under a mild soil water deficit does not reflect the soil water condition correctly. In conclusion, the use of ψ_{PL} alone as an irrigation-timing indicator in the study area is not recommended because it may result in a reduction in grain yield. Further studies concerning another characteristic of the climate in this area, the wide diurnal range in temperature and humidity, are needed to establish appropriate irrigation indicators.

Acknowledgments

We would like to thank Mr. Mohamed Hamady, Mr. Ali Haj-Dibo, and the other ICARDA staff members for their labor support and hospitality. This research was conducted while T. Sato was at ICARDA as a Japan Overseas Cooperation Volunteer (JOCV), arranged by the Japan International Cooperation Agency (JICA).

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