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Extinction coefficients and radiation use efficiency of barley under different irrigation regimes and sowing dates

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ABSTRACT

The aim of this experiment was to determine the hourly extinction coefficient and radiation use efficiency (RUE) of winter barley under various sowing date and irrigation regimes. Field experiments were performed at the Experimental Research Station at the College of Agriculture of Shiraz University in Iran over two consecutive years: 2012 and 2013. The study used an experimental design arranged in split plots based on a randomized complete block design with three replicates. There were four irrigation level treatments in the main plot, consisting of the full crop Irrigation requirement (W1), 75% and 50% of full irrigation (W2 and W3) and a dry land treatment (rain-fed, W4). The four sowing dates consisted of October 23rd (T1), November 6th and 22nd (T2 and T3) and December 6th (T4) which were considered the subplots. Two types of radiation adjustment were applied in order to evaluate the effect of air temperature changes on photosynthesis. The hourly extinction coefficient was 0.584 based on Photosynthetically Active Radiation (PAR), and the values of RUE ranged from 0.73 to 2.17 g MJ^{-1} and 0.85 to 1.94 g MJ^{-1} in 2012 and 2013, respectively. The variations in air temperature and environmental conditions caused a significant difference among the RUE values in 2012 and 2013. The maximum values of RUE were obtained in W1, which were significantly higher than other irrigation treatments. However, the RUE decreased significantly under irrigation level reductions. It is concluded that delaying in sowing date decreases the RUE values and the reduction in Growing Degree Day (GDD) before barley dormancy can effectively change the RUE. Therefore, to achieve a suitable value of RUE, the value of the GDD should be more than 120°-days before barley dormancy under any irrigation regime.

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1. Introduction

Crop biomass production depends on the ability of the canopy (i) to intercept incoming photo-synthetically active radiation (PAR, 400–700 nm), which is a function of the leaf area index (LAI) and canopy architecture, and (ii) to convert this radiation into new biomass (Sinclair and Muchow, 1999). Radiation use efficiency (RUE) is a parameter that relates dry matter (DM) production with intercepted solar radiation (Monteith and Moss, 1977). Several crop growth simulation models have used RUE to forecast crop growth and yield (Bonhomme, 2000; Muchow et al., 1993; Muchow and Sinclair, 1994; Rashid and UllahKhan, 2010; Robertson et al., 1996). In these models, the DM production is calculated as the product of the amount of intercepted solar radiation and RUE. Several factors can influence RUE (Sinclair and Muchow, 1999). Estimates of RUE depend on whether radiation is measured as the total solar radiation or as photo-synthetically active radiation (PAR). On the other hand, there are a number of important criteria for estimating the solar radiation received by the plant. These are the leaf area index and the extinction coefficient (K). The extinction coefficient is an important indicator the amount of light absorption by the canopy.

The value of RUE is affected by abiotic factors such as air temperature (Andrade et al., 1993; Ridao et al., 1996), vapor pressure deficit (Kemanian et al., 2004; Kiniry et al., 1989), soil water content (Wajid et al., 2007), toxicity (Alvarez and Steinbach, 2009), and nutrient levels (Muurinen et al., 2006; Sinclair and Horie, 1989). Based on PAR measurements in non-stress conditions, RUE values for wheat have been reported from 1.46 to 3.50 g MJ^{-1}, and values for barley in drought stress conditions have ranged from 1.3 to 2.52 g MJ^{-1} (Jamieson et al., 1995). Drought stress reduces RUE progressively by preventing effective photosynthesis for growth due to lower intercepted PAR as a result of reduced leaf area (Wilson and Jamieson, 1985). Drought stress has a significant impact on leaf gas exchange because of its sensitivity to drought. Gener-

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ally, the abatement availability of CO_2 due to stomatal closure under mild water stress, decreases photosynthesis (Mansfield and Davies, 1985). Therefore, carbon accumulation per unit leaf area, due to changes in RUE should be important influences decreasing biomass production during drought. When drought is extended or prolonged, reduction in photosynthesis will be controlled by “non-stomatal” mechanisms of gas exchange connected with harm to mesophyll cells, membranes and chloroplasts, thereby reducing the chlorophyll content, and by disturbances that conflict with assimilation synthesis and transport (Keutgen et al., 1997). Under water stress conditions, increases in chlorophyll content are commonly observed. It has been reported that drought stress damages the thylakoid membrane, disturbs its function and ultimately decreases photosynthesis and crop yield (Huseynova et al., 2007). Under severe water stress conditions, leaf stomatal conductance (g_s) is also of great importance (Flexas and Medrano, 2002) because it restricts CO_2 penetration into the leaf. Furthermore, under deficit conditions, the transpiration rate declined severely in all cereals under water-limited conditions. The effect of a water deficit in plants can be compensated for by the closure of stomata to avoid further water loss through transpiration (Lawlor, 1995).

Few studies have reported the influence of sowing date on RUE and quite often the impact of sowing date on RUE has been ignored in crop models. The sowing date affects crop growth, the size of the canopy, and thus the RUE (Bassu et al., 2011). Moreover, sowing the barley seeds at an intermediate date can produce a greater yield potential than late planting. The reason for higher yield in intermediate planting is the increased number of tillers and spikes, and the seed weight. Some researchers have studied the effects of sowing time on phenological development (Han et al., 2014; Sun et al., 2013). They have found that delaying the sowing date generally shortens the lapse between germination and flowering. It also reduced the time and chance for proper grain filling. Their results indicate that delaying the date of sowing can largely shorten the growth period in the vegetative stage and also slightly shorten the span of the reproductive stage. However, most of these studies have failed to consider the growth pattern and how it is affected by solar radiation in relation to the variety of combined of sowing dates and deficit irrigation.

The ability of a plant to intercept light can be estimated by using an exponential function based on the leaf area's variation of light extinction coefficient during the growing season (Sinclair and Muchow, 1999). The use of light can be modeled based on this principle that more radiation can be absorbed parallel to increases in leaf area, but the mutual shading of leaves reduces the efficiency of light. The ratio between the intercepted photosynthetic active radiation by the plant and its value above canopy (*f*) is estimated by the Lambert–Beer method as follows (Marcelis et al., 1998):

$$f = 1 - e^{-K.LAI} = 1 - \frac{PAR}{PAR_T} = \frac{IPAR}{PAR_T} \quad (1)$$

where *f* is fractional radiation interception; PAR is the photosynthetic active radiation under the canopy (MJ m^{-2}); PAR_T is the photosynthetic active radiation above the canopy (MJ m^{-2}); IPAR is the intercepted photosynthetic active radiation by the plant (MJ m^{-2}); K is the extinction coefficient and LAI is the leaf area index.

Under sufficient water and nutrient conditions, crop growth and development are affected by air temperature. Previous studies have indicated that wheat photosynthesis is correlated with daily air temperature (Kobza and Edwards, 1987; Tafteh and Sepaskhah, 2012). Kobza and Edwards (1987) found that wheat photosynthesis decreased sharply when the air temperature exceeded 30 °C. Changes in temperature have often been reported as one of the main causes of RUE variations and therefore a temperature function has been incorporated into crop models (Arkin et al., 1976; Kemanian et al., 2004; Sharpley and Williams, 1990). In most crop simulation models, air temperature is used to calculate and predict the unwanted factor of reduced crop photosynthesis due to non-optimal air temperatures for plant growth. In the APSIM-wheat model (Asseng et al., 2002; Wang et al., 2002), RUE is reduced when the average daily air temperature is less than 10 °C and greater than 25 °C. In the CERES-wheat model (Arkin et al., 1976; Smith, 1990), the weighted air temperature was calculated from minimum and maximum air temperatures to estimate a photosynthesis temperature reduction factor. In this model, the optimal mean air temperature was considered to be 18 °C. Kemanian et al. (2004) used hourly air temperature to adjust the intercepted solar radiation to calculate the RUE for barley under non-optimal temperatures for plant photosynthesis. One objective was to consider the difference between using the hourly and the average (or the process) daily air temperature to estimate the effective radiation for crop photosynthesis. Previous studies, however, have not reported the integrated effects of the sowing date and deficit irrigation on crop growth and RUE of winter barley in semi-arid regions. Furthermore, contrasting results have been reported in previous studies in terms of the impact of different sowing dates on RUE. On the other hand, an hourly extinction coefficient is needed in some crop models that predict dry mater hourly. An hourly extinction coefficient has rarely been reported in previous studies. This study focuses more on an hourly extinction coefficient rather than a daily extinction coefficient, which is more available in literature. The objectives of this study were as follows: (I) to determine the hourly extinction coefficient for winter barley, (II) to investigate the effects of sowing time and irrigation regimes on crop growth and RUE, and (III) to ascertain the optimum sowing date based on RUE for winter barley.

Table 1
Soil physical characteristics of the experimental site.

Physical properties	Soil depth (cm)			
	0–30	30–60	60–90	90–120
FC* (cm^3 cm^{-3})	0.32	0.33	0.33	0.33
PWP (cm^3 cm^{-3})	0.16	0.18	0.19	0.19
ρb (g cm^{-3})	1.43	1.43	1.43	1.43
Clay (%)	31	38	35	30
Silt (%)	57	52	49	53
Sand (%)	12	10	16	17
Soil texture	Silty clay loam			

* FC: Field Capacity, PWP: Permanent Wilting Point, ρb: bulk density.

2. Materials and methods

2.1. General

Field experiments were carried out at the Experimental Research Station in the College of Agriculture at Shiraz University in Iran, in 2012 and 2013. The physical properties of soil at different depths are shown in Table 1. The average electrical conductivity (EC) of the irrigation water was 0.6 dS m^{-1}. The experimental design was carried out in a split plot arrangement via a randomized complete block design with irrigation treatments as the main plot and sowing dates as the subplot in three replicates. The irrigation treatments included the following: a full crop irrigation requirement (W1); 75% and 50% of full irrigation (W2 and W3); and dry land (rain-fed, W4) in both growing seasons. The ‘Bahman’ barley cultivar (a local cultivar) was used for sowing. The sowing dates were October 23^{rd} (T1), November 6^{th} and 22^{nd} (T2 and T3) and December 6^{th} (T4). A total of 48 plots were arranged for barley cultivation. The size of each plot was 3 × 4 m^2 and the distance between

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