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Radiation interception and radiation use efficiency of wheat and pea under different P availabilities

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ABSTRACT

Above-ground biomass of crops can be expressed as the product between the cumulative intercepted radiation by the crop canopy (IR) and the radiation use efficiency (RUE) of the crop. The aim of the present study was to comparatively evaluate in wheat and pea these ecophysiological determinants of biomass under different P supplies at field conditions. Two field experiments were conducted in southern Chile combining two crops (wheat and pea) and three P supply levels (P0: 0; P1: 100 and P2: 250 kg P ha^{-1}). In both experiments, the crop phenology of wheat and pea were slightly affected by P supply. Above-ground biomass of wheat ranged between 1352 and 2930 g m^{-2}, while in pea this variable fluctuated between 1005 and 1562 g m^{-2}. Wheat showed a higher ($P < 0.01$) crop growth rate than pea and this variable was also affected ($P < 0.01$) by the P supply. Averaged over the experiments, crop growth rate of wheat relative to P2 was decreased by 38 and 16%, respectively, in P0 and P1 treatments, while in pea these reductions were 35 and 9%, respectively. Above-ground biomass of both crops was highly related to crop growth rate. In turn, both crop growth rate and above-ground biomass of wheat and pea were highly related to IR. Responses of IR were the results of changes in LAI during the crop cycle affecting the fraction of intercepted radiation by the crop. Relative to the P2 treatment, the maximum leaf area index (LAI) of wheat and pea was decreased across experiments by P0 treatments on average by 52 and 49%, respectively. Regarding RUE, this trait was not affected ($P < 0.05$) by the P supply in either crop suggesting that this variable is conservative under moderated P deficiency. However, wheat showed consistently higher RUE than pea, 1.63 vs 1.13 g MJ^{-1}, respectively, possibly owing to their differences in relation to the energetic cost of biomass synthesis.

1. Introduction

Although absorbed P is quite abundant in many soils, it is largely unavailable for crop uptake. Therefore, application of P-containing fertilizers is usually recommended (depending on soil test result) for enhancing P availability and increasing crop yields since more than 30% of the world's arable land has a limited P supply (Vance et al., 2003). Traditionally, crop responses to P availability have been analyzed relating different crop traits (biomass or yield) to P supply (Batten et al., 1999; Brennan and Bolland, 2001, 2009; Li et al., 2011), but there are very few studies evaluating the effect of P supply on the ecophysiological determinants of above-ground biomass. Crop biomass accumulation is directly related to the amount of photosynthetically active intercepted radiation by the canopy during the crop's cycle (Monteith, 1977). The slope of this relationship represents the radiation use efficiency (RUE), defined as crop biomass produced per unit of total solar or photosynthetically active intercepted radiation (IR) (Sinclair and Muchow, 1999; Stöckle and Kemanian, 2009). Therefore, above-ground biomass (g m^{-2}) can be expressed as a product of the cumulative IR (MJ m^{-2}) during the crop cycle and RUE (g MJ^{-1}). Until now, these variables have been studied principally in cereals under different P supplies (maize: Pellerin et al., 2000; Colomb et al., 2000; Plénet et al., 2000a; Fletcher et al., 2008a; wheat: Rodríguez et al., 2000; Lázaro et al., 2010; Sandaña and Pinochet, 2011), but there is a lack of information on this subject for temperate legumes such as pea. In southern Chile, pea could be an alternative crop to wheat owing to its high yield potential (Sandaña et al., 2009). Recently, it was reported that above-ground biomass and grain yield of wheat was more sensitive to P supply than pea when N was not deficient (Li et al., 2011). However, the ecophysiological determinants of this difference have not yet been comparatively studied in these crops under different P supplies.

The amount of IR depends on the length of the crop cycle over which radiation is accumulated, the fraction of intercepted radiation (FIR) by the canopy each day and the total incident solar

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radiation. The length of crop cycle is affected by the genotype and/or environmental factors mainly temperature and photoperiod (Slafer and Rawson, 1994; Slafer et al., 2009). Indeed, soil constraints such as nutritional deficiencies or Al toxicity have shown minor impacts on the crop cycle (N deficiency: Abeledo et al., 2003; P deficiency: Gregory et al., 1984; Sandaña and Pinochet, 2011; Al toxicity: Valle et al., 2009). FIR depends on the leaf area index (LAI) and the canopy light extinction coefficient (k) (Massignam et al., 2009). Several studies on different crops have shown that IR is negatively affected by N deficiency (sunflower: Hall et al., 1995; Massignam et al., 2009; wheat: Dreccer et al., 2000; Salvagiotti and Miralles, 2008; maize: Massignam et al., 2009; oilssed rape: Dreccer et al., 2000), S deficiency (Salvagiotti and Miralles, 2008) and Al toxicity (Sierra et al., 2003; Valle et al., 2009). IR responses have been primarily related to changes in LAI with minor variations in k under different levels of N (Muurinen and Peltonen-Sainio, 2006); N and S (Salvagiotti and Miralles, 2008), P (Rodríguez et al., 2000) and Al toxicity in wheat (Valle et al., 2009). Until now, research on P deficiency in maize, sunflower and wheat decreased IR because of its effect on LAI (maize: Pellerin et al., 2000; Colomb et al., 2000; Plénet et al., 2000a; Fletcher et al., 2008a; sunflower: Rodríguez et al., 1998a; wheat: Lázaro et al., 2010; Sandaña and Pinochet, 2011). However, no information has been reported for pea or other grain legumes.

RUE is affected by the crop species, environmental conditions and also by management factors such as crop nutritional status (Sinclair and Muchow, 1999; Stöckle and Kemanian, 2009). Information about the negative response of RUE under N deficiency has previously been published for different crops (Hall et al., 1995; Sinclair and Muchow, 1999; Muurinen and Peltonen-Sainio, 2006; Massignam et al., 2009; Lemaire and Gastal, 2009). RUE reductions have been related to changes in the specific leaf N (SLN; $\mathrm{g\,N\,m^{-2}}$ leaf) (Muchow and Davis, 1988; Muchow and Sinclair, 1994; Sinclair and Muchow, 1999). On the other hand, RUE seems to be little affected by S deficiency (Salvagiotti and Miralles, 2008) and Al toxicity (Sierra et al., 2003; Valle et al., 2009). In relation to P, fewer studies are available and contrasting results have been found since RUE was not affected by P deficiency in maize (Plénet et al., 2000b; Fletcher et al., 2008b), but in wheat, Rodríguez et al. (2000) found that RUE was reduced by P deficiency during the first 61 days after emergence. More recently Lázaro et al. (2010) reported contradictory RUE responses during the spike growth period under P deficiency in wheat. Considering the whole wheat crop cycle, Sandaña and Pinochet (2011) showed that RUE was not affected by P deficiency in a high yielding environment. Suggesting that moderated reduction in RUE may be expected under strong P deficiencies. With regards to pea, there are no studies evaluating this trait under P deficiency.

In both crops RUE could be more conservative than IR in response to P. However, wheat and pea may have different sensitivity to P supply, considering their lower and higher nutrient requirement per unit of biomass or yield, respectively (del Pozo et al., 2000; Brennan and Bolland, 2001; Sadras, 2006; Li et al., 2011). Therefore, in order to improve our knowledge about the effect of P availability on this biomass component, the aim of the present study was to comparatively evaluate in wheat and pea their responses on IR, RUE and related traits under different P availabilities at field conditions.

2. Materials and methods

2.1. Site and management

Two field experiments were conducted during the growing season 2009–2010. The soil was a Duric Hapludand located at the Universidad Austral de Chile's experimental station in, Valdivia (39°47′S, 73°14′W, 19 m a.s.l.), Chile. Sowing dates were August 20th and September 12th of 2009 for experiments 1 and 2, respectively.

In both experiments seed rates of wheat and pea were 350 and 70 seed $\mathrm{m^{-2}}$, respectively. Each plot consisted of 9 rows of 3 m length. Row widths were 0.15 and 0.2 m for wheat and pea, respectively. Rows were orientated in a N-S direction. In order to achieve proper seed distribution along rows, strip paper containing seeds were used for wheat while pea was hand-sown. Crops were fertilized with 100 $\mathrm{kg\,N\,ha^{-1}}$ and 150 $\mathrm{kg\,K\,ha^{-1}}$ at sowing and complemented with 150 $\mathrm{kg\,N\,ha^{-1}}$ at the beginning of tillering in wheat and at the vegetative node number 8 in pea (Exp. 1: September 26th; Exp. 2: October 13th of 2009). At sowing all fertilizers were incorporated into the soil with a cultivator up to a soil depth of 20 cm. To avoid water shortages all plots were surface-irrigated weekly from flowering to harvest (Exp. 1: 200 mm; Exp. 2: 244 mm), replacing the cumulative daily difference between daily rainfall and daily evaporation. The experiments were maintained free of biotic stresses. Thus, weeds were periodically removed by hand, while diseases and insects were prevented with the use of fungicides and insecticides at the rates recommended by their manufacturers.

2.2. Treatments and design

In both experiments, treatments were the combination of (i) two crops and (ii) three levels of P fertilization. The two crops were wheat (cv. Pandora) and pea (semi-leafless cv. Nitouche). The P fertilization rates were 0 (P0), 100 (P1) and 250 (P2) $\mathrm{kg\,P\,ha^{-1}}$. At sowing P was incorporated into the soil with a cultivator up to a soil depth of 20 cm. The initial soil P availabilities were 9.7 and 13.1 ppm of P-Olsen for experiments 1 and 2, respectively. In both experiments factors were arranged in a split-plot design, where P levels were assigned to main plots and crops to sub-plots randomized into three blocks.

2.3. Plant measurements

In both experiments, phenological observations were done weekly. The date of wheat anthesis was recorded using the decimal code scale proposed by Zadoks et al. (1974). In pea, flowering dates were recorded according to the scales proposed by Knott (1987). In both crops, anthesis and flowering dates were registered when 50% of the plants reached this stage at each plot.

For wheat and pea nine samples of the above-ground biomass were taken during the crop cycle, including the last measurement at physiological maturity. The sample sizes were 0.5 and 1 m length of inner row before and at physiological maturity, respectively. Wheat samples were separated into green and senescent leaves, stems plus leaf sheaths and spikes when they were present. Pea samples were separated into stems plus tendrils, green and senescent stipules, pods and grains when they were present. For both wheat and pea, green leaves and green stipules were, respectively, used to measure leaf area using an electronic leaf area meter (LI 3100, Licor Inc., Lincoln NE, USA). LAI was accordingly calculated from the leaf area data. All samples were weighed after oven drying for 48 h at 65 °C with an electronic balance (Mettler Toledo XP205DR, Greifensee, Switzerland). Crop growth rate was the slope of the linear regression between six above-ground biomass samples and the cumulative time (days) after emergence for each sample. The six samples represented the lineal growth phase of crops. All regressions were significant ($P < 0.01$) and all R^2 were greater than 0.90.

In all experiments the FIR by the crops were determined using measurements of the incident and the transmitted radiation on clear days at noon (±15 min.) using a 1 m long linear sensor (LI 191