Mitigating thermal and water stress in lentils via cultivar selection and phosphorus fertilization

Georgia S. Theologidou, Demetrios Baxevanos and Ioannis T. Tsialtas

ABSTRACT

Climate change affects the Mediterranean region stressing lentil crops during flowering and seed set. Early maturation and drought tolerance are desirable traits in these conditions. Phosphorus (P) is considered to enhance early flowering, maturity and thus yields. Four P rates (0, 30, 60, 90 kg P$_2$O$_5$ ha$^{-1}$) were applied on four cultivars (Samos, Thessaly, Flip, Ikaria) during two seasons. Growing degree-days (GDD) were calculated for vegetative (V4–V5, V7–V8) and reproductive stages (R1, R2, R4, R6, R8). At R2 (full bloom) carbon isotope discrimination ($\Delta$) was used to assess water-use efficiency. At R8 (full maturity), the seed weight (SW) was determined by harvest. Cultivars, P and the P $\times$ cultivar and P $\times$ growth season interactions affected the earliness in reproductive stages; P had no effect on GDD of vegetative stages. Phosphorus both induced earliness (Flip, Thessaly) and delayed maturity (Samos, Ikaria). GDD and SW were negatively correlated for the P $\times$ cultivar interaction at R1 (first bloom), R2, R4 (flat pod) and R6 (full pod filling) stages; being the strongest at R1. Negative correlations were evident for the P $\times$ growth season interaction at R2, R4 and R6 stages; being the strongest at R4. Cultivars and P did not affect $\Delta$. A proper combination of cultivar and P rate can mitigate lentil yield losses under changing Mediterranean climate.

Key words | basal temperature, carbon isotope discrimination, growing degree-days, growth stages

INTRODUCTION

Human activity contributes to increasing the concentration of greenhouse gases in the atmosphere thereby increasing the radiation absorbed, and subsequently affecting the air temperature. Climate change is a daunting environmental challenge because of its direct biophysical effects on plant physiological processes and consequently on crop production. In recent years, extreme climate events, including heat waves, heavy precipitation and drought incidents, have strongly affected Europe and led to crop failure (Reidsma et al. 2010).

Although higher temperatures in northern Europe are expected to increase crop yields, in the Mediterranean and south-western Balkans increasing temperatures, in combination with reduced rainfall, are expected to lead to large yield reductions (Olesen et al. 2011). However, it is reported that elevated levels of carbon dioxide (eCO$_2$), due to climate change, can mitigate the effects of drought in grain legumes such as soybean (Li et al. 2015), as plants reduce stomatal and canopy conductance and therefore limit soil water absorption. While it is difficult to predict accurate scenarios regarding future climate change, crop productivity is a key factor affecting food security and economic stability (Hatfield et al. 2011).

Lentils (Lens culinaris Medik.) are grain legumes which have been grown around the Mediterranean basin since antiquity and still remain a structural block of the Mediterranean diet pyramid. Apart from their high nutritional value, legumes, and lentils in particular, constitute a food group which can effectively meet the demands imposed by climate change as the impact on the environment is minimal (Graham & Vance 2005). In the Mediterranean region, lentils are usually sown during the wet winter months, but

doi: 10.2166/wcc.2018.021
decreasing soil moisture and increasing temperatures during the reproductive stages result in terminal drought and low seed yields (Shrestha et al. 2006). To cope with such phenomena, it is necessary to exploit genetic variation reported to reside among cultivated germplasm as well as within wild Lens spp. (Erskine et al. 2011).

Earliness in flowering is a desirable trait, especially under the semi-arid conditions prevailing in the Mediterranean region. Early sowing has been an effective strategy in regions. Early sowing has been an effective strategy in many areas to avoid high temperatures and low rainfall during the reproductive stages, and thus to increase seed yields (Hajarpoor et al. 2014); however, earlier sowing was reported to increase susceptibility to disease due to longer favorable pre-winter weather conditions (Colbach et al. 1997). On the other hand, earliness owing to genotypic variation leading to drought avoidance could be exploitable. In addition, previous studies have reported the beneficial effect of increased phosphorus (P) rates on earliness in flowering and maturity. This effect is possibly caused by an alteration of the nitrogen/phosphorus (N/P) ratio in plant tissues and/or by the beneficial role of P in stimulation of the reproductive parts of plants (Sawan et al. 2008). Genotypic variation and environmental effects on water economy and productivity of C3 species can easily and reliably be assessed by carbon isotope discrimination (Δ values) in above-ground biomass. Δ values (a measure of the 13C/12C ratio in plant tissues compared to the air) are related to the ratio of intercellular to ambient CO2 concentrations (Ci/Ci) being a surrogate of the intrinsic water use efficiency [(WUEi, the ratio of CO2 assimilation rate to stomatal conductance (gs)] (Farquhar & Richards 1984). Moreover, Δ values have been proved a reliable, indirect and long-term indicator of water use efficiency at biomass level (WUE, the ratio of biomass produced to the water consumed to produce it) for many species; relationships between Δ and yield have also been established (Turner 1996).

In the Mediterranean region, soils are usually P-deficient, thus the use of P fertilizers remains relatively high (Harmsen & El Mahmoud 2004). Phosphorus is an essential macronutrient with a pivotal role in numerous plant processes. Since lentils meets their needs for N through N2-fixation, P is the most common limiting nutrient for both growth and grain yield (Yadav et al. 2009). Moreover, Jin et al. (2014) mentioned that eCO2 increased drought tolerance as well as water use efficiency (WUE) of field pea (Pisum sativum), especially when plants are grown under sufficient P supply.

Temperature is perhaps the most critical factor in all biological processes, therefore heat units are often used to estimate phenological development of plant species. Growing degree-days (GDD) provide a simple estimate of the accumulated heat available during the growth season or life cycle of an organism (Robertson et al. 2013). The concept of degree-days is based on three assumptions: (i) there is a basal temperature for all species below which no growth is observed, (ii) the growth of all kinds is proportional to the total accumulation of energy over a specific period, and (iii) species’ maturity occurs only when a specific total of degree-days is achieved (Fealy & Fealy 2008).

Therefore, the aim of this work was to study the effect of four P rates (0, 30, 60 and 90 kg P2O5 ha−1) on the earliness of four lentil cultivars at seven growth stages, through the calculation of GDD. Furthermore, in order to elucidate whether P supply can affect WUE and seed yield under P-deficient Mediterranean soil, Δ values were determined in above-ground biomass at full bloom.

**MATERIALS AND METHODS**

**Study area and plant material**

A field experiment was conducted for two growth seasons (2013–2014, hereafter 2014 and 2014–2015, hereafter 2015) in the farm of the Aristotle University of Thessaloniki (AUTH; 40°52'12" N, 22°59'21" E, 6 m a.s.l.). The climate is typically Mediterranean. Mean monthly temperature and monthly precipitation during the growth seasons (December to May) are shown in Figure 1 while Table 1 presents soil characteristics of the experimental site.

Under rainfed conditions, four lentil cultivars [Samos, Thessaly, Flip 2003-24 L (Flip), Ikaria], provided by the Hellenic Agriculture Organization (HAO)-DEMETER, Institute of Industrial and Fodder Plants, Larissa, Greece, were supplemented, before sowing, with four phosphorus (P) rates [0 (P0), 30 (P30), 60 (P60) and 90 kg P ha−1 (P90)] in a split-plot design with P rates in the main plots and cultivars in
the subplots. The treatments were triplicated. Phosphorus was applied as triple superphosphate (460 g P2O5 kg⁻¹). Seeding was conducted by hand on 6 December 2014 and 5 December 2015. Each subplot consisted of six rows, 4 m long and 0.25 m apart (6 m²), at a sowing density of 100–110 seeds m⁻². Breeder’s seeds were used for all the four cultivars.

For each subplot, the Julian date, by which specific growth stages were achieved, was recorded. Seven growth stages, following Erskine et al. (1990), were monitored: two vegetative, the stages of 4–5th and 7–8th leaves (V4–5 and V7–8, respectively), and five reproductive stages, namely first bloom (R1), full bloom (R2), flat pod stage (R4), full pod filling stage (R6) and full maturity (R8). The achievement of the growth stage was considered when at least 50% of the plants in each subplot had reached the defined stage.

Calculation of growing degree-days

The calculation of GDD, for each growth stage and subplot, was based on the standard single triangle method above the basal temperature (T_base) as reported by Fealy & Fealy (2008) and daily data for both maximum (T_max) and minimum (T_min) temperatures were obtained from the meteorological station in the farm of Aristotle University, when T_min > T_base

\[
GDD = \frac{(T_{\text{max}} + T_{\text{min}})}{2} - T_{\text{base}}.
\]

when \( T_{\text{max}} < T_{\text{base}} \), there were no GDD above the \( T_{\text{base}} \), therefore degree-days below the \( T_{\text{base}} \) were calculated as:

\[
GDD = T_{\text{base}} - \frac{(T_{\text{max}} + T_{\text{min}})}{2};
\]

when \( T_{\text{max}} > T_{\text{base}} \), \( T_{\text{min}} < T_{\text{base}} \) and mean temperature \( (T_{\text{mean}}) > T_{\text{base}} \), degree-days above the \( T_{\text{base}} \) were calculated as:

\[
GDD = \frac{(T_{\text{max}} - T_{\text{base}})}{2} - \frac{(T_{\text{base}} - T_{\text{min}})}{4};
\]

when \( T_{\text{max}} > T_{\text{base}} \), \( T_{\text{min}} < T_{\text{base}} \) and mean temperature \( (T_{\text{mean}}) < T_{\text{base}} \), degree-days above the \( T_{\text{base}} \) were calculated as:

\[
GDD = \frac{(T_{\text{max}} - T_{\text{base}})}{4}.
\]
\( T_{\text{base}} \) was set to 2 °C (Ghanem et al. 2015). The lower the GDD, the earlier the cultivar.

**Determination of carbon isotope discrimination and seed weight**

At full bloom stage (R2), above-ground biomass, over a surface of 0.125 m\(^2\), was sampled from each subplot, oven-dried at 75 °C till constant weight and then ground to fine powder using a Tube Mill 100 control (IKA®-Werke GmbH & Co. KG, Staufen, Germany). Carbon isotope ratio (\( \delta^{13}C \)) in biomass samples was measured on a continuous flow isotope ratio mass spectrometer (CF-IRMS, Delta PlusXP, Thermo Finnigan, Bremen, Germany) coupled with an elemental analyzer (ECS 4010, Costech Analytical, Valencia, CA, USA) for on-line sample preparation. \( \delta^{13}C \) was calculated as:

\[
\delta^{13}C(\%o) = \left[ \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 10^3 \right]
\]

where \( R_{\text{sample}} \) and \( R_{\text{standard}} \) were the \( ^{13}C/^{12}C \) ratio in the plant tissue and the standard, respectively. The universally accepted standard of Pee Dee Belemnite (PDB) limestone was used.

Carbon isotope ratio was used to calculate carbon isotope discrimination (\( \Delta \)) as:

\[
\Delta(\%o) = \frac{(\delta_a - \delta_p)}{(1 + \delta_p/1000)}
\]

where \( \delta_a \) and \( \delta_p \) were \( ^{13}C \) of the air and biomass sample, respectively. \( \delta_a \) is ca. −8‰.

At full maturity (R8 growth stage), a 0.125 m\(^2\) surface was harvested and threshed by hand in order to determine seed weight (SW) per subplot (in g m\(^{-2}\)) after normalization at 10% seed moisture.

**Statistical analyses**

Data of GDD for each growth stage were subjected to analysis of variance (ANOVA) as an over-year, split-plot design with P rates in the main plots and cultivars in the subplots and with three replications. Means were compared by the least significant difference (LSD) test at \( P < 0.05 \) and analyses were run using the statistical software JMP 5.1 (SAS Institute Inc., Cary, NC, USA).

**RESULTS AND DISCUSSION**

In the present study, over the years, cv. Flip had the highest SW (406.34 g m\(^{-2}\)) while it was the earliest among the three cultivars; it was followed by Thessaly (343.03 g m\(^{-2}\)), Samos (299.36 g m\(^{-2}\)) and finally Ikaria (283.59 g m\(^{-2}\)), the latest maturing cultivar. The effects of climate change include high temperatures and prolonged drought periods in the Mediterranean region (Iglesias & Garrote 2015); thus earliness in flowering is a desirable trait under the prevailing hot and dry conditions. Moreover, lentil, as a cool season legume, is more sensitive to high temperatures, especially when they occur during the flowering and pod-filling stages resulting in high yield losses (Farooq et al. 2017). In most lentil producing areas, yield does not exceed half the potential yield, mostly due to scarcity of water combined with extreme temperatures, indicating the need to increase crop yield through genetic improvement and/or better crop management (Ghanem et al. 2015).

Breeding for stress tolerant cultivars is more intricate because of the complex nature of the mechanism that gives tolerance. Thus, a range of different crop management practices can be applied to mitigate the effects of drought stress including sowing date, early maturing cultivars and appropriate fertilizer use. In the present work, neither cultivars nor P rates had a significant effect on GDD of the vegetative stages but both factors affected earliness of the reproductive stages; the interactions P rate \( \times \) cultivar and P rate \( \times \) growth season were significant as well. More specific, at the beginning of flowering (R1 growth stage), cv. Flip was the earliest showing no significant differences between P rates. On the contrary, in cvs. Samos, Thessaly and Ikaria, P additions induced earliness compared to the control (P0) treatments (Table 2). The highest GDD were recorded for P0 in cvs. Ikaria and Samos (1033.30 °C and 1042.15 °C, respectively). Similar results were evident at full bloom (R2 growth stage) when cv. Flip recorded the lowest GDD (998.89 °C) regardless of the P rate. At flat pod stage (R4), P additions began
to stand out in comparison to $P_0$. Treatments $P_{60}$ and $P_{90}$ induced earliness in Flip and Ikaria while in cv. Thessaly, all the $P$ additions ($P_{30}, P_{60}$ and $P_{90}$) scored lower GDD than the control ($P_0$). In cv. Samos, only treatment $P_{90}$ induced earliness (Table 2). At R6 stage, cv. Flip remained the earliest while in cv. Thessaly, all the $P$ rates scored the same GDD. On the contrary, in cvs. Samos and Ikaria, $P$ additions caused delayed maturity (Table 2). The stages and the duration required to mature a plant are determined by many factors such as climate, genetic material, agronomic practices and soil fertility (Miller et al., 2001). It is mentioned that $P$ fertilization is more beneficial in legumes, as it regulates the N/P ratio in the soil resulting in vigorous growth and higher yields (Li et al., 2011). According to Rasheed et al. (2010), despite the fact that $P$ application in lentils induces earliness in flowering, it can delay maturity due to increased nitrogenase activity of active nodules and due to modification of the ratio of $P$ to other nutrients. For the $P$ rate × cultivar interaction, significant negative correlations between GDD and SW were found at R1, R2, R4 and R6 stages, with that at R4 stage being the strongest (Figure 2).

For the $P$ rate × growth season interaction, all reproductive stages but R8 showed significant differences in GDD (Table 3). In general, for R1, R2 and R4 stages, $P$ additions caused earliness, especially in 2014. However, this trend was adverse in R6 growth stage. For the above interaction, early maturity affected SW positively as negative correlations between GDD and SW were found at R2, R4 and R6 stages with that at R4 being the strongest (Figure 3).

Table 2 | Mean comparison of growing degree-days (GDD, °C) for the $P$ rate × cultivar interaction for the four reproductive growth stages (R1, R2, R4 and R6) that showed significant differences

<table>
<thead>
<tr>
<th>Interaction</th>
<th>$P_0$</th>
<th>$P_{30}$</th>
<th>$P_{60}$</th>
<th>$P_{90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samos</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>1042.15a</td>
<td>1168.50a</td>
<td>1298.38a</td>
<td>1443.52c</td>
</tr>
<tr>
<td>R2</td>
<td>1015.28b</td>
<td>1162.53a</td>
<td>1303.67a</td>
<td>1466.52a</td>
</tr>
<tr>
<td>R4</td>
<td>990.85c</td>
<td>1139.11b</td>
<td>1295.63a</td>
<td>1466.52a</td>
</tr>
<tr>
<td>R6</td>
<td>1004.08cb</td>
<td>1139.11b</td>
<td>1279.55b</td>
<td>1466.52a</td>
</tr>
<tr>
<td>Thessaly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>993.53c</td>
<td>1114.49c</td>
<td>1263.51c</td>
<td>1429.17d</td>
</tr>
<tr>
<td>R2</td>
<td>971.37d</td>
<td>1060.70d</td>
<td>1235.07d</td>
<td>1429.17d</td>
</tr>
<tr>
<td>R4</td>
<td>969.21d</td>
<td>1055.46d</td>
<td>1235.07d</td>
<td>1429.17d</td>
</tr>
<tr>
<td>R6</td>
<td>969.21d</td>
<td>1057.96d</td>
<td>1235.07d</td>
<td>1429.17d</td>
</tr>
<tr>
<td>Flip</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>921.70c</td>
<td>998.89e</td>
<td>1186.72c</td>
<td>1355.85e</td>
</tr>
<tr>
<td>R2</td>
<td>914.80c</td>
<td>998.89e</td>
<td>1150.27f</td>
<td>1355.85e</td>
</tr>
<tr>
<td>R4</td>
<td>910.75e</td>
<td>998.89e</td>
<td>1140.17fg</td>
<td>1327.53f</td>
</tr>
<tr>
<td>R6</td>
<td>910.75e</td>
<td>998.89e</td>
<td>1129.85g</td>
<td>1330.37f</td>
</tr>
<tr>
<td>Ikaria</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>1033.30a</td>
<td>1147.78b</td>
<td>1265.65c</td>
<td>1443.52c</td>
</tr>
<tr>
<td>R2</td>
<td>993.60c</td>
<td>1104.72c</td>
<td>1265.65c</td>
<td>1450.80b</td>
</tr>
<tr>
<td>R4</td>
<td>990.85c</td>
<td>1102.22c</td>
<td>1242.45d</td>
<td>1450.80b</td>
</tr>
<tr>
<td>R6</td>
<td>990.85c</td>
<td>1109.23c</td>
<td>1242.45d</td>
<td>1450.80b</td>
</tr>
</tbody>
</table>

Within columns, means labeled with the same letter did not differ significantly at $P < 0.05$ using the LSD test.
Full maturity (R8) was influenced only by cultivars and the cultivar × growth season interaction, with cv. Flip recording the lowest GDD (1649.33 °C) and showing no significant differences for the two growth seasons (Table 4). On the contrary, cv. Ikaria showed the highest GDD, summed up to 1790.02 °C, a score very close to the upper limit (1806 °C) of GDD necessary for lentil maturity in Montana (Miller et al. 2013), an environment contrary to the Mediterranean of the present study. Early flowering and maturity genotypes have been proposed to avoid drought but because of their inability to react when there is available soil moisture they show low yields (Materne & Siddique 2009). However, no significant correlation was evident between GDD and SW for the cultivar × growth season interaction at R8 stage. It has been reported that P fertilization leads to earliness in many crops, however it was not always correlated with higher yields (Borges & Mallarino 2000).

In general, P supply stimulates root growth by increasing root biomass and length especially in P-deficient soils (Li et al. 2011). As a result, P addition has been reported to improve drought tolerance by increasing WUE in leguminous crops (Jin et al. 2014). Carbon isotope discrimination (Δ) has been extensively used as an indirect, long-term assessment of WUE and it was found to correlate with yield in C₃ species (Turner 1996; Lopes & Reynolds 2010). However, in the present study, neither cultivars nor P rates had a significant effect on Δ (Table 5) indicating that any yield differentiation among the cultivars or P

Table 3 | Mean comparison of growing degree-days (GDD, °C) for the P rate × growth season interaction for the four reproductive growth stages (R1, R2, R4 and R6) that showed significant differences

<table>
<thead>
<tr>
<th>Interaction</th>
<th>GDD (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
</tr>
<tr>
<td>P₀</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>1025.24a</td>
</tr>
<tr>
<td>2015</td>
<td>970.09bc</td>
</tr>
<tr>
<td>P₃₀</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>971.99bc</td>
</tr>
<tr>
<td>2015</td>
<td>975.53b</td>
</tr>
<tr>
<td>P₆₀</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>965.90c</td>
</tr>
<tr>
<td>2015</td>
<td>966.93bc</td>
</tr>
<tr>
<td>P₉₀</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>970.52bc</td>
</tr>
<tr>
<td>2015</td>
<td>966.93bc</td>
</tr>
</tbody>
</table>

Within columns, means labeled with the same letter did not differ significantly at P < 0.05 using the LSD test.

Table 4 | Mean comparison of GDD for the cultivar × growth season interaction for the full maturity (R8) stage

<table>
<thead>
<tr>
<th>Interaction</th>
<th>GDD (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Samos</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>1748.23b</td>
</tr>
<tr>
<td>2015</td>
<td>1731.01c</td>
</tr>
<tr>
<td>Thessaly</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>1748.23b</td>
</tr>
<tr>
<td>2015</td>
<td>1704.49d</td>
</tr>
<tr>
<td>Flip</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>1645.03e</td>
</tr>
<tr>
<td>2015</td>
<td>1653.63e</td>
</tr>
<tr>
<td>Ikaria</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>1748.23b</td>
</tr>
<tr>
<td>2015</td>
<td>1831.82a</td>
</tr>
</tbody>
</table>

Within columns, means labeled with the same letter did not differ significantly at P < 0.05 using the LSD test.

Figure 3 | Correlation between GDD and seed weight for the P rate × growth season interaction at R2, R4 and R6 growth stages. Where GDD, growing degree-days; R2, full bloom stage; R4, flat pod stage; R6, full pod filling stage.
treatments was not ascribed to a variation in water economy of the lentils. Previously, significant variation for \( \Delta \) was found in lentil genotypes but no correlation with yield was reported (Matus et al. 1996), being in agreement with findings in other grain legumes like dry beans (Tsialtas et al. 2011).

CONCLUSIONS

Phosphorus effects on earliness were cultivar specific, inducing earliness in cvs. Flip and Thessaly and causing delayed maturity in Samos and Ikaria. The critical stage was found to be the beginning of flowering and earliness seems to be a factor contributing to higher yields. Neither cultivars nor P rates had a significant effect on water economy of the lentils. A proper combination of cultivar and P rate can be a means to increase lentil yields under changing Mediterranean conditions.

ACKNOWLEDGEMENTS

The authors are grateful to Dr D. Vlachostergios, HADO-DEMETER, Institute of Industrial and Fodder Plants, Larissa, Greece for providing the lentil seeds for the experimentation. We also thank Dr B. Harlow, Washington State University, School of Biological Sciences, Pullman, WA, USA for the carbon isotope determinations.

REFERENCES


---

Table 5 | Carbon isotope discrimination (\( \Delta \), ‰) measured on the above-ground biomass at R2 growth stage for cultivars and P rates

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>( \Delta ) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samos</td>
<td>22.78</td>
</tr>
<tr>
<td>Thessaly</td>
<td>22.65</td>
</tr>
<tr>
<td>Flip</td>
<td>22.85</td>
</tr>
<tr>
<td>Ikaria</td>
<td>22.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P rates</th>
<th>( \Delta ) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td>22.72</td>
</tr>
<tr>
<td>P30</td>
<td>22.75</td>
</tr>
<tr>
<td>P60</td>
<td>22.73</td>
</tr>
<tr>
<td>P90</td>
<td>22.56</td>
</tr>
</tbody>
</table>

No significant differences were found at \( P < 0.05 \) using the LSD test.
Phosphorus application and elevated CO2 enhance drought
tolerance in field pea grown in a phosphorus-deficient

leguminous and nonleguminous crops in utilization of soil
phosphorus and responses to phosphorus fertilizers. *Advances
00005-7.

Li, D., Liu, H., Qiao, Y., Wang, Y., Cai, Z., Dong, B., Shi, C., Liu,
Y., Li, X. & Liu, M. 2015 Effects of elevated CO2 on the
growth, seed yield, and water use efficiency of soybean
(*Glycine max* (L.) Merr.) under drought stress. *Agricultural
07.014.

Lopes, M. S. & Reynolds, M. P. 2010 Partitioning of assimilates to
dereper roots is associated with cooler canopies and increased
yield under drought in wheat. *Functional Plant Biology*
**37** (2), 147–153. doi:https://doi.org/10.1071/FP09121.

Materne, M. & Siddique, K. H. M. 2009 Agroecology and crop
adaptation. In: *The Lentil: Botany, Production and Uses* (W.
Erskine, F. Muehlbauer, F. Sarker & F. Sharma, eds). CABI,

discrimination and indirect selection for transpiration
efficiency at flowering in lentil (*Lens culinaris* Medikus),
spring bread wheat (*Triticum aestivum* L.) durum wheat
(*T. turgidum* L.), and canola (*Brassica napus* L.). *Euphytica*
**87** (2), 141–151. doi:https://doi.org/10.1007/BF00021887.

Miller, P., Lanier, W. & Brandt, S. 2001 *Using Growing Degree
Days to Predict Plant Stages*. Ag/Extension Communications
Coordinator, Communications Services, Montana State
University-Bozeman, Bozeman, MO.

Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin,
B., Peltonen-Sainio, P., Rossi, F., Kozyra, J. & Micale, F. 2011
Impacts and adaptation of European crop production
systems to climate change. *European Journal of Agronomy*
**34** (2), 96–112. doi:https://doi.org/10.1016/j.eja.2010.11.003.

Improved lentil production by utilizing genetic variability in
response to phosphorus fertilization. *Acta Agriculturae
Scandinavica, Section B-Soil & Plant Science* **60** (6),

Reidsma, P., Ewert, F., Lansink, A. O. & Leemans, R. 2010
Adaptation to climate change and climate variability in
European agriculture: the importance of farm level

Robertson, S. M., Jeffrey, S. R., Unterschultz, J. R. & Boxall, P. C.
2015 Estimating yield response to temperature and identifying
critical temperatures for annual crops in the Canadian prairie

Influence of potassium fertilization and foliar application of
zinc and phosphorus on growth, yield components, yield and
fiber properties of Egyptian cotton (*Gossypium barbadense*
or/10.1093/jpe/rtn021.

Speijers, J. 2006 A water deficit during pod development in
lentils reduces flower and pod numbers but not seed size.
doi:https://doi.org/10.1071/AR05225.

Tsialtas, J. T., Papadopoulos, I. I., Tamoutsidis, E. G. & Tokatlidis,
I. S. 2012 Relationships of grain carbon isotope discrimination
(Δ) and ash content with yield and quality in dry bean.
doi.org/10.1017/S0021861601000766.

Turner, N. C. 1996 Further progress in crop water relations.
1016/S0065-2113(08)60258-8.

Yadav, S. S., McNeil, D. L., Andrews, M., Chen, C., Brand, J.,
Singh, G., Shivakumar, B. G. & Gangaiah, B. 2009 Soil
Nutrient Management. In: *The Lentil: Botany, Production
and Uses* (W. Erskine, F. Muehlbauer, F. Sarker & F. Sharma,