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Effect of water deficit stress on benzoylprop-ethyl performance and physiological traits of winter wild oat (*Avena sterilis* subsp. *ludoviciana*)

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ABSTRACT

Increasing the diversity in the sites of action of herbicides is an important method for delaying and preventing herbicide resistance in weed populations. Benzoylprop-ethyl, a lipid biosynthesis inhibitor, is used to increase the diversity of herbicide sites of action and control ACCase- and ALS-resistant *Avena sterilis* subsp. *ludoviciana* (Durieu.) Gillet & Magne) populations in Iran. Drought stress, especially in arid and semiarid areas, affects weed physiology and performance of herbicides. Accordingly, a series of dose-response assays was conducted to evaluate the efficacy of benzoylprop-ethyl under drought- (60% Field Capacity) and non-drought-stress (90% Field Capacity) conditions on *A. sterilis* subsp. *ludoviciana*. Also, some biochemical and physiological traits of *A. sterilis* subsp. *ludoviciana* including leaf chlorophyll content, leaf greenness index, photosynthesis rate and stomatal conductance were investigated under the drought and non-drought regimes. The efficacy of benzoylprop-ethyl decreased significantly under drought condition. The effective dose reducing dry weight by 90% in relation to the untreated control (i.e., ED_{90}) for the drought-stressed plants was significantly ($P < 0.01$) higher than that of the non-drought-stressed plants, where it was 895 (±112.6) and 1543 (±205.3) g a.i. ha^{-1}, respectively. The drought index (the ratio of the ED_{90} at 60% FC relative to ED_{90} at 90% FC) was 1.68 (±0.16) and thus, significantly higher than 1. Leaf chlorophyll content (chl *a* and chl *b*) and leaf greenness index increased under drought conditions, while the photosynthesis rate, stomatal conductance, and the chl *a*/*b* decreased. The efficacy reduction of benzoylprop-ethyl on drought-stressed plants might be due to photosynthesis reduction and reduced stomatal conductance leading to reduced herbicide uptake. Tracking local weather forecasts, monitoring water soil content and irrigating the field before herbicide application were suggested to overcome the detrimental effect of drought stress on the efficacy of benzoylprop-ethyl. Potential tactics such as using adjuvants, different formulations and early application timing of benzoylprop-ethyl to tackle the problem were proposed for future studies.

1. Introduction

Avena sterilis subsp. *ludoviciana* (Durieu.) Gillet & Magne (winter wild oat) is one important weed species competing with major crops (Bajwa et al., 2017). This noxious weed species is a common weed in sub-tropical, temperate and semi-arid regions around the world. As a competitive weed species of cereal crops, *A. sterilis* subsp. *ludoviciana* can cause substantial crop yield reduction (e.g., up to 44% in wheat (*Triticum aestivum* L.)) (Montazeri, 2007).

Herbicides are often reliable and cost-effective for weed control, however; the dominance and overreliance on herbicides leads to herbicide-resistant weed biotypes, (also in *A. sterilis* subsp. *ludoviciana*). Herbicide resistant *A. sterilis* subsp. *ludoviciana* populations have been reported from Australia, France, and Iran (Heap, 2019). ACCase- and ALS-inhibiting herbicides continue to be used for the control of many weed species, including *Avena* spp. Not surprisingly, ACCase- and ALS-resistant *A. sterilis* subsp. *ludoviciana* populations continue to be a major concern in cereal production. Delaying and preventing herbicide resistance is vital to increasing the diversity in herbicide sites of action (SOA) i.e., herbicide rotation in the field.

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Accordingly, it may make sense to re-adopt herbicide active ingredients that are no longer frequently used in the field. Benzoylprop-ethyl, a lipid biosynthesis inhibitor, is an old post-emergence selective herbicide belonging to dichloroaniline propionate family. Benzoylprop-ethyl was introduced for control of *Avena* spp. and *Hordeum spontaneum* (K. Koch.) (wild barley) in winter wheat (Zand et al., 2017). Benzoylprop-ethyl was introduced under the trade name of Suffix in Iran in 1975 (Zand et al., 2017) but, due to high-use rate (recommended field rate of 1000 g a.i. ha^{-1}) and narrow weed control spectrum (only controlling *Avena* spp. and *H. spantaneum*), benzoylprop-ethyl was replaced by more effective, broad control spectrum and low-use herbicides, including ACCase- and ALS-inhibitors since the 1990s. Nevertheless, due to the widespread distribution of *H. spantaneum* and ACCase- and ALS-resistant *A. sterilis* subsp. *ludoviciana* populations around Iran, benzoylprop-ethyl was re-introduced to the market in 2017 under a new trade name, Piraffix®. However, the efficacy of this new product has been questioned under drought stress conditions.

The performance of herbicides is influenced by environmental factors such as light, CO_2, temperature, and soil water content (Varanasi et al., 2016). Environmental conditions not only influence herbicide performance but also affect the physiological traits and growth of the plant. For instance, it was shown that ultraviolet light reduced the performance of clethodim and tralkoxydim due to photodegradation (McMullan, 1996). Elevated CO_2 concentration reduced the efficacy of glyphosate on *Chloris gayana* Kunth (rhodes grass) and *Paspalum dilatatum* Poir. (dallisgrass) due to increased plant biomass and leaf area (Manea et al., 2011).

Climate changes more often than not, relate to an increase in the concentration of greenhouse gases such as atmospheric CO_2 that may lead to high global temperature and drought (Jugulam et al., 2018). Due to global climate change, herbicide performance reduction caused by environmental factors might be pronounced, possibly due to alterations in climate factors, such as increased CO_2 concentration, high temperatures and drought. These factors not only modify the physicochemical traits of the herbicide, leading to changes in the penetration and translocation of herbicides in the plants, but can also change the anatomy (e.g., an increased leaf thickness and a decreased stomata number), morphology, growth and fundamental physiological mechanisms, through which herbicides absorb, translocate and sequestrate in plants (Varanasi et al., 2016).

Drought stress increases the environmental factors affecting herbicide performance, due to lower precipitation rate and higher air temperature caused by global climatic change, especially in arid areas. Several studies have investigated the effect of drought on the performance of herbicides and physiological traits of plants. For example, it was reported that the efficacy of fenoxaprop, diclofop, flamprop, sethoxydim, imazamethabenz, mesosulfuron + iodosulfuron was reduced under drought conditions (Aghabeigi and Khodadadi, 2017; Radchenko et al., 2014; Xie et al., 1993, 1997). Even though it was generally accepted that drought stress, as a side effect of climate change, can reduce the efficacy of some herbicides, it may not be generalized to all herbicides, because it has been stated that the effects of climate change might not only change herbicides having dissimilar SOAs but also within herbicides with similar SOAs (Varanasi et al., 2016). Therefore, it is necessary to assess the efficacy of each herbicide under drought stress conditions individually. If a performance reduction occurs, it is necessary to calculate the amount of efficacy reduction and determine the field rates required to reach an adequate control level, i.e., ED_{90}, for weeds grown under drought condition.

In addition to the influence on the performance of herbicides, drought stress can affect the physiological parameters of plants. It is necessary to know the biology and behavior of weeds under different environmental and climate change conditions, especially drought stress situations, in order to achieve appropriate weed management. Fortunately, attentions were directed to this issue (Jugulam et al., 2018; Varanasi et al., 2016; Ziska and Dukes, 2011). The first reaction of plants to drought stress is stomatal conductance reduction or stomatal closure (Cornic, 2000). Also, photosynthesis reduction occurs due to a limitation in CO_2 uptake (Flexas et al., 2002). Plant leaf chlorophyll content can also be affected by drought stress condition (Schütz and Fangmeier, 2001).

As a country located in arid and dry regions of the earth, Iran faces a lack of precipitation and spatial and temporal variability in rainfall. Drought stress conditions do affect herbicide efficacy. Accordingly, the objective of this study was to assess the possible effect of drought stress on the efficiency of benzoylprop-ethyl and the physiological traits of *A. sterilis* subsp. *ludoviciana*. Also, we wanted to determine the dose of benzoylprop-ethyl required for an adequate control level of this noxious weed species under drought stress condition.

2. Materials and methods

2.1. Plant material and seed germination

Seeds of *A. sterilis* subsp. *ludoviciana* were collected at maturity in July 2017 from the research field of the Faculty of Agriculture, Tabiat Modares University, Tehran, Iran (35° 44′ 25.941″N, 51° 9′ 56.747″E, 1265 m asl). The seeds were stored at room temperature under dry conditions until the start of experiments in November 2017 and in March 2018. To promote germination and to break dormancy, the seeds were dehulled and kept at 4 °C for seven days. The seeds were placed in 9-cm diameter glass Petri-dishes containing one layer of filter paper (Whatman No. 1), which was saturated with 10 ml distilled water. Subsequently, the dishes were put in zipped polythene bags and were incubated in a darkened growth chamber (4 °C for seven days) at the Department of Agronomy, Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran. Seeds with a visible radicle were considered germinated and they were used in greenhouse experiments.

2.2. Dose-response experiment

Ten germinated seeds were selected and seeded at 1 cm soil depth in 2 L (10-cm diameter) black plastic bags. The bags were filled with a potting mixture of field soil and peat (1:1 v/v). After emergence, the plants were thinned to five plants per bag. The experiments were carried out at the Department of Agronomy, Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran in a greenhouse with a 25/17 ± 3 °C and 16/8-h day/night cycle with a supplemental light (457 μmol m^{-2} s^{-1}).

The plants grew at two different irrigation regimes. Half of them were irrigated to 90% of field capacity (90% FC, from now on referred to as non-drought-stressed), while the rest were watered to 60% of FC (from now on referred to as drought-stressed). The non-drought-stressed plants were watered to reach a soil water content equal to 90% of FC throughout the experiments. The drought-stressed plants were watered similarly to the non-drought-stressed plants except for 14 days where the soil moisture was kept to be 60% of FC from seven days before herbicide spraying to seven days after herbicide spraying. According to Monaco et al. (2002) environmental factors one to two weeks before and after using herbicides can affect absorption of foliar applied herbicides. To measure volumetric soil water content, a TRIME-FM TDR (Time Domain Reflectometry, IMKO Micromodultechnik, Ettlingen, Germany) was used.

The seedlings of *A. sterilis* subsp. *ludoviciana* were sprayed with nine different doses of benzoylprop-ethyl (piraffix 20% EC, manufactured by Pira Kesht Chemical Co., Tehran 1413884511, Iran) at the one-to the two-tillering stage (growth stage BBCH 21–22 according to Hess et al. (1997). The doses of benzoylprop-ethyl were 0, 96,172, 290, 556, 1000 (recommended label rate), 1800, 3240, 5832 g a.i. ha^{-1}. There were four replications (bags) per dose. The herbicide was sprayed with a rechargeable electric-knapsack sprayer equipped with an even nozzle (8001 E, Ag Spray Equipment), delivering 283.4 L ha^{-1} at a pressure of

250 kPa. The speed of spraying was 5 km h^{-1} with a nozzle height of 50 cm above the top of weed plants. The bags were arranged in a completely randomized design with four replications (bags). The experiment was repeated twice in the same greenhouse with two week intervals. Four weeks after herbicide treatment, the plants were cut at the soil surface and dried at 80 °C for 72 h and weighed.

2.3. *Physiological properties of A. sterilis subsp. ludoviciana under drought stress*

Similar to the dose-response experiment above, the plants were subjected to two irrigation regimes (FC 90% and 60%) seven days before the tillering stage (growth stage BBCH 21–22). One week after the start of the irrigation treatment, physiological properties were measured. Herbicide was also applied at the same growth stage in the previous experiment.

Chlorophyll contents, including Chl *a*, Chl *b*, and Chl *a/b* ratio, were measured as described by Hiscox and Israelstam (1979). Photosynthetic rate and stomatal conductance of the youngest leaf were measured simultaneously using a portable gas exchange system (LI-COR 6400, Li-Cor Inc, Lincoln, NE, USA). Within the measuring chamber, the following conditions were maintained: leaf temperature 35 °C, reference CO_2 content 350 μmol mol^{-1}, and PAR 1400 μmol m^{-2} s^{-1}. The IRGA (infra-red gas analyzer) was matched manually, and levels of reference CO_2 and reference H_2O were stable before taking measurements. A Plant Chlorophyll Content Meter (SPAD-502 plus, Konica Minolta, Osaka, Japan) measured the plant leaf greenness index of the same leaf used for measuring photosynthesis rate and stomatal conductance. The plant leaf greenness was recorded in order to compare it with the extracted chlorophyll content. There is a strong correlation between the extracted chlorophyll content and the plant leaf greenness index (Ferrell et al., 2003).

2.4. *Statistical analysis*

2.4.1. *Dose-response experiment*

A new two-step analytical approach was used to summarize the dose-response analyses (Ritz et al., 2019).

At step one, a four-parameter log-logistic model (Eq. (1)) (Seefeldt et al., 1995) describes the relationship of the dry weight, *Y,* as a function of the dose, *x* (g a.i. ha^{-1}).

$$Y = c + \frac{d - c}{1 + \exp\left[b(\log(x) - \log(ED_{50}))\right]} \tag{1}$$

Parameter *c* is the lower limit of the response curve at infinite large herbicide dose, and *d* is the upper limit of mean response when herbicide was not used, i.e., herbicide doses are zero. ED_{50} denotes the effective dosage (g a.i. ha^{-1}) that reduces dry weight by 50% (halfway between the *d* and *c* parameter), and *b* is the relative slope of the curve around ED_{50}.

Based on the analysis of residuals, a transform both sides technique (Box-Cox data transformation) was used because of variance heterogeneity (Ritz et al., 2019). The transform-both-sides method implies that both the left and the right side of Eq. (1) are transformed with a suitable function λ. It will keep the original scale of the parameter estimates, but make sure that the variance and the distribution of the residuals have constant variance and are normally distributed (Ritz et al., 2019).

A sequential reduction of parameters within an experiment was tested using a lack of fit test ($P > 0.05$) (Jeske et al., 2009; Ritz et al., 2019). For both dose-response experiments, the test for lack of fit allowed us to assume the *b*, *d*, and *c* were similar within experiments.

After fitting the dose-response models (Ritz et al., 2015a, 2015b), the effective doses (g a.i. ha^{-1}) reducing dry weight by 90% (ED_{90}), 50% (ED_{50}), and 10% (ED_{10}) were calculated for each herbicide drought combination. To quantify the relative efficacy of benzoylprop-ethyl under drought condition, the ratio called Drought Index, (DI) was calculated (Eq. (2)).

$$DI = \frac{ED_{90}(Drought)}{ED_{90}\ (No\ Drought)} \tag{2}$$

If the DI is not significantly different from 1.00, the ED_x is not different from unity meaning there is no difference of efficacy in relation to drought.

In the second step, a meta-analytic random effects model (Ritz et al., 2019) was used to analyze the parameters, including: *b*, *c*, *d,* ED_{10}, ED_{50} and ED_{90}, and DI, obtained from Eqs (1) and (2) as responses. The number of experiments and irrigation regimes were considered as random and fixed effects, respectively. Finally, appropriate pairwise comparisons were made to compare the parameres of drought-stressed and non-drought-stressed plants. The DIs averaged by meta-analytic approach was compared to 1.00 using a Z-test. As mentioned above, the DI equal to 1.00 signifies similar efficacy of benzoylprop-ethyl for the two irrigation regimes.

The add-on packages *drc* (Ritz et al., 2015a) and *metafor* (Viechtbauer, 2010), were used for fitting the log-logistic models and the meta-analytic approach, respectively. The multiple comparisons was carried out using *multcomp* package (Hothorn et al., 2008). The three mentioned add-on packages are available in the R statistical software (R Core Team, 2013).

2.4.2. *Physiological properties of A. sterilis subsp. ludoviciana*

The effects of irrigation regimes on the physiological properties of *A. sterilis* subsp. *ludoviciana* were determined using a *t*-test. Whenever the variances were unequal, an unequal variance *t*-test, i.e. Welch's *t*-test was carried out. The significant difference between the two irrigation regimes was tested at the 0.05 probability level.

3. Results

3.1. *Dose-response experiment*

Fig. 1 illustrates the dose-response curves for the two identical experiments. The sequential test for lack of fit tests ($P > 0.05$) showed that the slope (*b*), upper (*d*) and lower limits (*c*) were similar within experiments. The curves were parallel, which means that the DI is independent of the response levels considered within each experiment. In experiment 1, the *b*, *c,* and *d* parameters were 2.6, 1.4, and 5.5, respectively; while in experiment 2, they were estimated to be 1.8, 1.4, and 4.6. The ED_{50} varied somewhat between the experiments (Fig. 1A and B). In experiment 1, the ED_{50} was 633 (±57.7) and 419 (±41.8) for the drought- and non-drought-stressed plants, respectively. In experiment 2, they were 624 (±99.9) and 220 (±30.0) for the drought- and non-drought-stressed plants, respectively. The differences between the two experiments are not surprising, as Ritz et al. (2015b) also stated this is due to variability of responses in biology. It is also worth noting that dose-response curves are not always similar for many reasons. For example, various environmental factors in an experiment are not always the same in other, otherwise identical, experiments.

The meta-analysis approach averaged the parameters and DI (Table 1). The ED_{10}, ED_{50}, and ED_{90} were significantly different between the drought-stress and the non-drought-stress conditions (Table 1). The estimated ED_{90} for the non-drought-stressed was 895 g. a.i. ha^{-1}, being lower than the recommended label rate (1000 g. ai. ha ˉ1), while the ED_{90} for the drought-stressed was 1543 g a.i. ha^{-1}, and thus well above the recommended rate. In addition, the DI (Eq. (2)) of 1.68 (±0.16) was significantly higher than 1.00, which means that drought-treated plants at ED_{90} required about 1.7 more herbicide than the no-drought plants. The higher *ED* values (e.g., ED_{50} and ED_{90}) under the drought condition and the DI > 1 clearly showed that bezoylprop-ethyl efficacy was reduced significantly, due to lack of water in the soil.

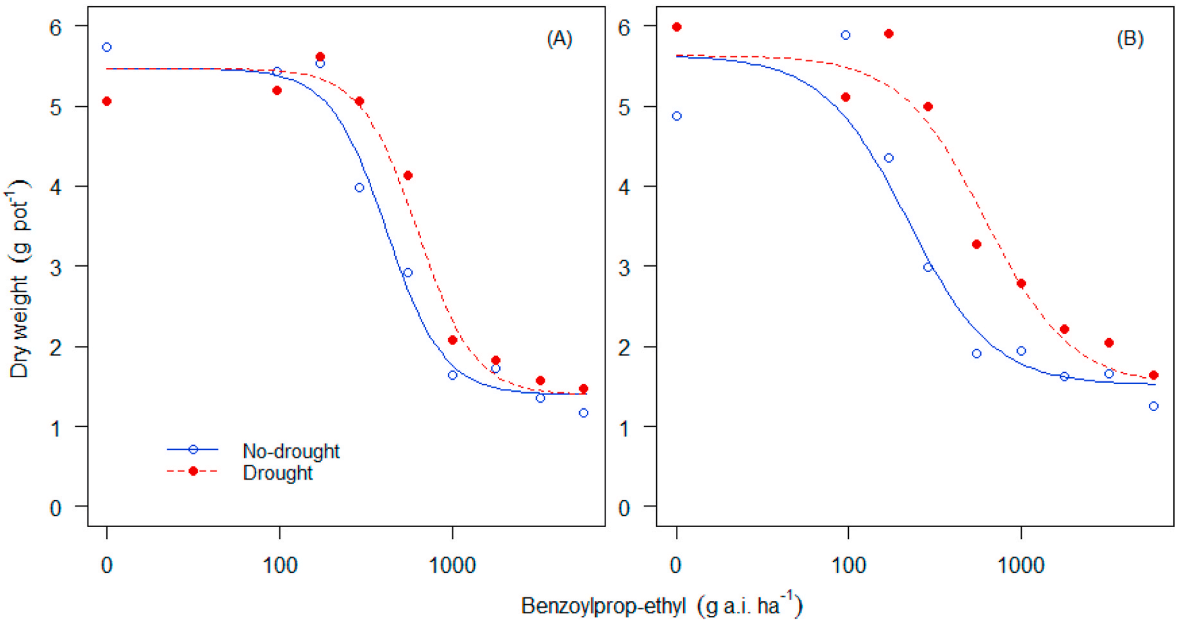

Fig. 1. Response of drought-treated (FC = 60%) and non-drought-treated (FC = 90%) *A. sterilis* subsp. *ludoviciana* to benzoylprop-ethyl in experiment 1 (A) and experiment 2 (B). The estimated parameters (ED_{10}, ED_{50}, ED_{90}, Lower limit, Upper limit, and slope) and drought index (DI) are presented in Table 1.

Table 1
The parameters estimated by the log-logistic model for the drought-treated and the non-drought-treated plants were averaged over the experiments using the meta-analysis approach. The values in parenthesis represent standard errors.

Irrigation regimes (FC%)	Slope (*b*)	Upper limit (*d*)	Lower limit (*c*)	ED_x (g a.i. ha^{-1})			DI[a]
				ED_{10}	ED_{50}	ED_{90}	
90	2.2 (0.48) ns	5.5 (0.16) ns	1.4 (0.076) ns	118 (66.1) *	312 (84.1) ***	895 (112.6) **	1.68 (0.16) ***
60	2.2 (0.48)	5.5 (.16)	1.4 (0.076)	227 (57.3)	592 (95.1)	1543 (205.3)	

^{ns} Non-significant.
*** Significant at 0.001 level.
** Significant at 0.01 level.
* Significant at 0.05 level.
[a] Drought Index is the ratio of the ED_{50} of the drought-treated plants (FC 60%) to the non-drought-treated plants (FC 90%) i.e. $ED_{50\ \mathrm{drought}}/ED_{50\ \mathrm{Non\text{-}drought}}$.

3.2. *Physiological properties of A. sterilis subsp. ludoviciana*

The *t*-test result showed a significant difference ($P < 0.05$) between the two irrigation regimes considering the chlorophyll contents (chl *a* and chl *b*), chl *a/b* ratio and leaf greenness index. The leaf chlorophyll contents including chl *a* and chl *b* for the plants exposed to the drought-stress conditions were 1.5- and 3.5-times higher than that of the non-drought-treated plants, respectively (Fig. 2A and B). A similar trend was observed for the leaf greenness index, where the leaf greenness index of the drought-treated plants was 1.2-times higher than that of the non-drought-treated plants (Fig. 2D). In contrast, it was found that *A. sterilis* subsp. *ludoviciana* leaves grown in drought conditions had a chl *a/b* ratio of 1.6 compared with 3.5 in those plants grown under normal conditions (Fig. 2C). There were also significant differences ($P < 0.05$) in the photosynthesis rate and stomatal conductance between the two irrigation regimes, where the non-drought-stressed plants had a higher photosynthesis rate and stomatal conductance than that of the drought-stressed plants (Fig. 3A and B).

4. Discussion

Under drought stress conditions, the dose of benzoylprop-ethyl required for obtaining a 90% reduction in dry weight was increased by a factor 1.7. It means that the stressful drought condition significantly diminished the efficacy of benzoylprop-ethyl. In order to overcome the inhibition inefficacy caused by drought at the ED_{90} level, an extra amount of around 648 g a.i. ha^{-1} of benzoylprop-ethyl was required as opposed to normal conditions. The adverse effect of drought on herbicide performance was similar in previous studies, e.g., the efficacy of fenoxaprop, diclofop, flamprop, and imazamethabenz on *A. fatua* was reduced when the plants were exposed to drought (Xie et al., 1993, 1997). Aghabeigi and Khodadadi (2017) reported that the efficiency of clodinafop-propargyl and mesosulfuron-methyl also decreased by drought stress when they were applied to control *A. sterilis* subsp. *ludoviciana*. However, the adverse effect level of drought depended on the type of herbicide used and the weed population. That means it is necessary to quantify the adverse effects of drought on the performance of each herbicide in controlling individual weed species separately, due to the diversity of herbicide sites of action, formulation, and physico-chemical properties (e.g., pKa, K_{ow}, and water solubility).

Our results clearly provided evidence for the efficacy reduction of benzoylprop-ethyl due to soil water deficit. Understanding and quantifying the relationship between drought stress and herbicide performance may help describe observed *A. sterilis* subsp. *ludoviciana* control failures with benzoylprop-ethyl. The lower performance of the herbicide can be related to the alteration of the physiological traits of *A. sterilis* subsp. *ludoviciana* as discussed below. Several studies have investigated the effect of drought on the physiological traits of different horticultural

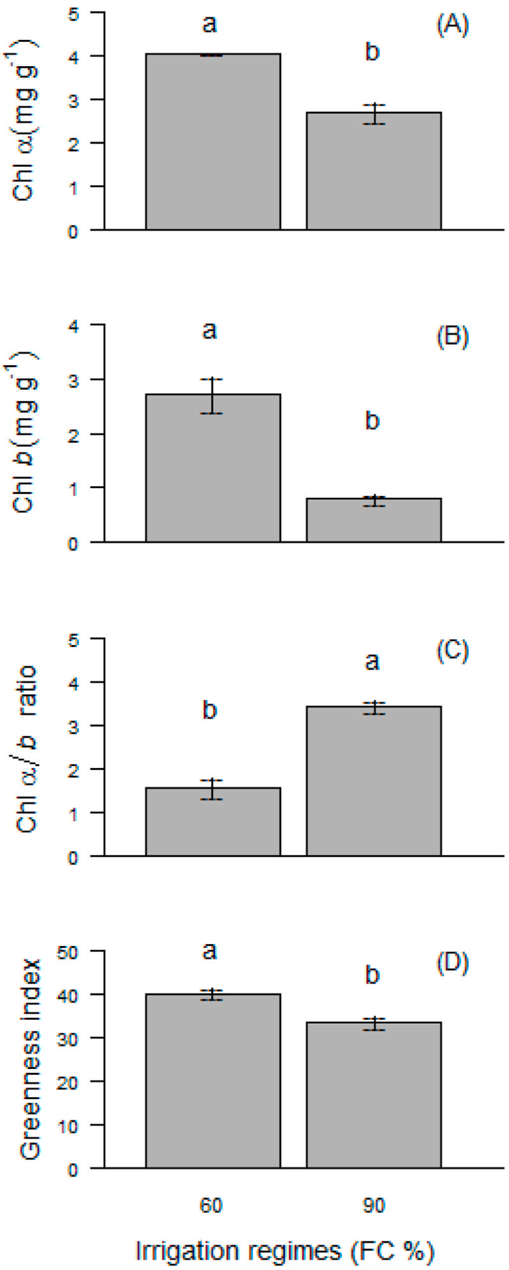

Fig. 2. Effect of drought-stress (FC 60%) and non-drought-stress (FC 90%) conditions on the chlorophyll (Chl) *a* (A), Chl *b* (B), Chl *a/b* ratio (C), and greenness index (D) of *A. sterilis* subsp. *ludoviciana.* Different letters on each column show statistically significant differences between treatments at $P < 0.05$.

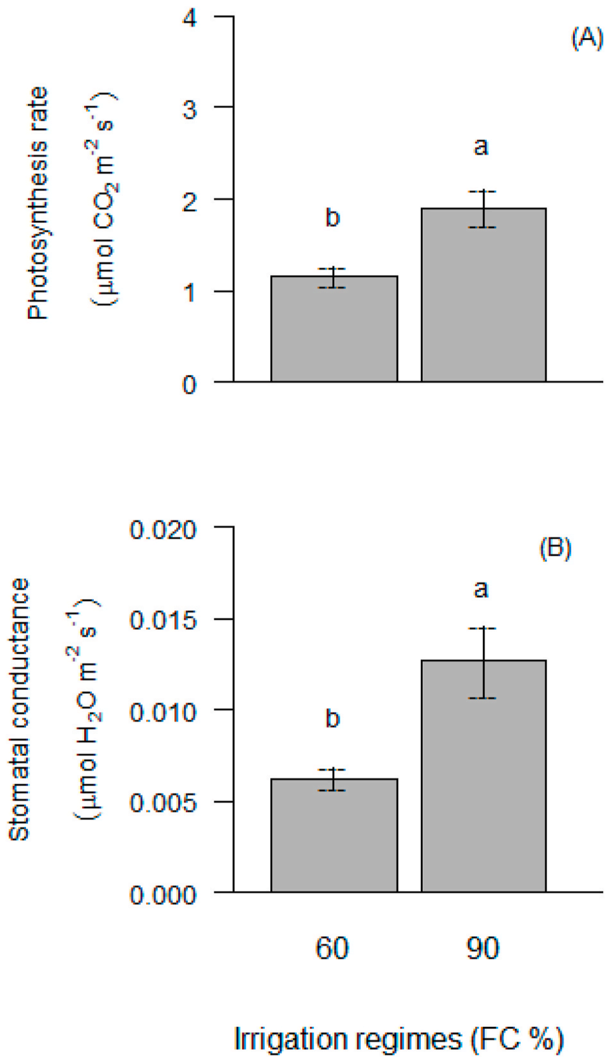

Fig. 3. Effect of drought-stress (FC 60%) and non-drought-stress (FC 90%) conditions on the photosynthesis rate (A) and stomatal conductance (B) of *A. sterilis* subsp. *ludoviciana.* Different letters on each column show statistically significant differences between treatments at $P < 0.05$.

and agronomic plants but arrived at different conclusions. To our knowledge, this is the first report evaluating the effect of drought on the physiological characteristics of the troublesome weed species, *A. sterilis* subsp. *ludoviciana*.

In the present study, the content of chl *a* and chl *b*, and leaf greenness index increased due to drought conditions, while the photosynthesis rate, stomatal conductance, and the chl *a/b* ratio decreased. There is a general agreement that chlorophyll content of leaves decrease under drought stress conditions (Guerfel et al., 2009; Mafakheri et al., 2010; Sanchez et al., 1983; Schütz and Fangmeier, 2001). In contrast to the mentioned general agreement i.e., the reduction of chlorophyll content of leaves due to drought stress, there are evidences showing that the chlorophyll content of leaves including chl *a* and chl *b*, and leaf greenness index increased under drought conditions (Rahbarian et al., 2011), as we observed in this study. The increased chlorophyll content has been attributed to a decrease in leaf area (Rahbarian et al., 2011). A negative relationship between leaf greenness index (i.e., SPAD values) and specific leaf area and leaf water content was reported by Marenco et al. (2009). Accordingly, we also assumed that increased chlorophyll content and greenness index might be related to a reduction in specific leaf area and leaf water content of *A. sterilis* subsp. *ludoviciana* due to drought stress. Also, Ziska and Dukes (2011) stated that water-stressed plants tend to reduce their leaf area leading to an adverse effect on foliar herbicide efficacy.

Thickness, chemical composition and permeability of the cuticle barrier for herbicide entrance into plant leaf are influenced by environmental factors, such as heat and drought stress conditions (Hance and Cessna, 1990). For instance, it was shown that cuticle thickness and epicuticular wax in *Xanthium strumarium* L. (cocklebur) and *Abutilon theophrastic* Medicus (velvetleaf) increased through drought stress (Levene and Owen, 1995). So, cuticle thickness can decrease herbicide performance as stated by Aghabeigi and Khodadadi (2017).

Photosynthetic reduction and reduced stomatal conductance can modify the performance of herbicides (Varanasi et al., 2016). It was also speculated, that the decreased stomatal conductance might have reduced glyphosate uptake, resulting in lower performance (Fernando et al., 2016). The reduced benzoylprop-ethyl efficacy could have been associated with photosynthesis reduction and reduced stomatal conductance under drought stress conditions, because stomatal apertures are closed during drought-stress conditions, which leads to a decrease in stomatal conductance (Cornic, 2000). Finally, photosynthesis is reduced (Flexas et al., 2002; Kogan and Bayer, 1996). Moreover, the leaf absorption of benzoylprop-ethyl as a post-emergence foliar applied herbicide might be decreased due to stomatal closure leading. It is stated that changes in photosynthesis rate can affect herbicide efficacy indirectly by altering the absorption and translocation of herbicides (Varanasi et al., 2016).

Another explanation for the efficacy reduction of benzoylprop-ethyl can be a higher activity of antioxidant enzymes, as efficacy reduction of fenoxaprop under drought condition also has been attributed to an increase in the activity of antioxidant enzymes, such as catalase and peroxidase (Radchenko et al., 2014).

5. Conclusions

Avena sterilis subsp. *ludoviciana* developed resistance to many ALS and ACCase inhibiting herbicides in some parts of the world. Benzoylprop-ethyl is used to increase the chemical diversity of herbicides allowing the farmers to delay and prevent ALS- and ACCase-resistant *A. sterilis* subsp. *ludoviciana* populations. The efficacy of benzoylprop-ethyl was questionable in Iran, an arid and semiarid area, due to drought stress. We documented that drought stress significantly reduced benzoylprop-ethyl efficacy. The performance of benzoylprop-ethyl under drought stress conditions was reduced by a factor of 1.68 in comparison with non-drought-stressed conditions. The benzoylprop-ethyl efficacy reduction associated with photosynthesis reduction and reduced stomatal conductance for the plants grown in drought stress conditions. Water scarcity in the arid area can cause a lack of weed control. The increasing benzoylprop-ethyl rate cannot be an appropriate suggestion to overcome the issue as increased herbicide dose is not allowed and can also result in environmental hazards and extra costs. To avoid the efficacy reduction of benzoylprop-ethyl, we recommend that farmers monitor the water soil content of the field regularly and irrigate the field before herbicide application, so that at the time of herbicide application the water soil content is equal to the field capacity. Tracking local weather forecasts before herbicide application can help farmers in arid regions. The use of adjuvants can also overcome the performance reduction of benzoylprop-ethyl (Zhou et al., 2007). Levene and Owen (1995) also showed that adjuvants, including urea ammonium nitrate and crop oil concentrate, increased absorption of bentazon into the leaves of water-stressed *X. strumarium* and *A. theophrastic*. In addition, using different formulations of benzoylprop-ethyl and early herbicide application timing may also help for compensate the adverse effects of drought stress on benzoylprop-ethyl efficacy for the control of *A. sterilis* subsp. *ludoviciana*. However, future studies are required to evaluate these suggested approaches i.e., using adjuvants, different formulations and early application timing of benzoylprop-ethyl under field conditions to overcome the problem. Doing further field experiments is also suggested in order to see if selectivity changes between crops and the target weeds under drought stress conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Saeid Alizade: Methodology, Data curation, Writing - review & editing. **Eshagh Keshtkar:** Conceptualization, Software, Writing - original draft, Writing - review & editing, Supervision. **Ali Mokhtasi-Bidgoli:** Conceptualization, Writing - review & editing. **Hamid-Reza Sasanfar:** Conceptualization, Writing - review & editing. **Jens C. Streibig:** Software, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

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