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Growth of weeds and their chemical control under climate change conditions

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Abstract

Climate change has a great influence on weed growth and susceptibility of weeds to herbicides. This study determined the effect of six herbicides on three weed species under different CO_2 concentrations and temperature levels. The weeds in the study were: (i) wild oat (*Avena fatua*), (ii) lambsquarter (*Chenopodium album*), and (iii) wild mustard (*Sinapis arvensis*). The herbicides used in this study were: (i) 240 g · l^{-1} clodinafop-propargyl, (ii) 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl, (iii) 40 g · l^{-1} nicosulfuron, (iv) 480 g · l^{-1} glyphosate isopropylamine salt, (v) 75% tribenuron methyl and (vi) 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl + 300 g · l^{-1} bromoxynil + 300 g · l^{-1} MCPA. The study was carried out in a fully automated greenhouse which could be adjusted with desired CO_2 concentration and temperature. The weeds were exposed to three different temperatures (day/night 26/16 ± 1, 29/19 ± 1 and 32/22 ± 1°C) and CO_2 (400 ± 50, 600 ± 50 and 800 ± 50 ppm) levels. A temperature of 26/16 ± 1°C plus a CO_2 level of 400 ± 50 ppm was considered as the control. Results showed that 26/16°C × 800 ppm CO_2 produced the highest plant length (65.05 cm), plant fresh weight (7.42 g) and plant dry weight (1.31 g) for *A. fatua*. Similarly, for *S. arvensis*, the same treatment showed the highest plant length (31.63 cm), plant fresh weight (23.99 g) and plant dry weight (1.82 g) while for *C. album*, different climatic conditions did not show a significant effect on the growth of this weed. The ED_{50} values of herbicides for controlling *A. fatua*, *C. album* and *S. arvensis* increased (112.8, 0.6 and 199.4) with an increase in temperature and CO_2 levels, respectively. It is predicted that the control of some weeds will be difficult in the climate change that includes an increase in temperature and carbon dioxide in the future.

Keywords: *Avena fatua, Chenopodium album*, climate change, herbicide application, *Sinapis arvensis*

Introduction

Climate change is one of the most important environmental constraints that affect agriculture, food security, and natural ecosystems (Howden *et al.* 2007). Continuous climate change (a long-term shift in weather patterns and temperatures) has been observed to provide various benefits to different weed species, increasing their growth, spread, colonization capacity, and environmental tolerance (Mgidi *et al.* 2007; Carboni *et al.* 2015; Seebens *et al.* 2015; Bajwa *et al.* 2018; Jabran and Dogan 2020).

An increase in CO_2 concentration is seen as one of the major global changes of the last half-century

(Prentice *et al.* 2001; Jiménez *et al.* 2018). The increase in atmospheric levels of CO_2 and other greenhouse gases has increased global surface temperatures and the frequency of extreme temperature events (IPCC 2007; 2014). CO_2 concentration in the atmosphere was 280 ppm in the pre-industrial period; today this value has reached to over 400 ppm (IPCC 2007). The Intergovernmental Panel on Climate Change (IPCC) has predicted that the CO_2 concentration in the atmosphere will approach 700 ppm by the end of this century and the temperature will increase from 1.4 to 5.8°C (IPCC 2021). Global warming is one of the consequences of climate change due to which the physiological and phenological processes of plants are impacted and subsequently significant differences occur in vegetation (Rustad *et al.* 2001).

The most important crop biotic stresses are weeds (34% potential yield losses globally), insect pests (18%), and diseases (16%) (Oerke 2006). *Avena fatua* L. is a problematic weed in more than 20 crops in 55 countries of the world where it causes huge yield losses, especially in winter crops (Holm *et al.* 1977; Sharma and Born 1983; Bajwa *et al.* 2017; Mahajan *et al.* 2020). This weed is widely distributed in temperate and subtropical regions of Asia, Canada, Europe, Australia, and the USA (Holm *et al.* 1977; Beckie *et al.* 2012; Ahmad-Hamdani *et al.* 2013; Harker *et al.* 2016; Bajwa *et al.* 2017; Mahajan *et al.* 2020). Similarly, *Sinapis arvensis* L. is another common weed found in the temperate regions of Asia, Europe, North Africa, and Mediterranean countries (Luzuriaga *et al.* 2006). Its origin is in the Mediterranean region, and the weed is mainly seen in crop fields, orchards, and pasture areas. *Chenopodium album* L. is another common and problematic weed, which has expanded itself across almost the entire globe and infests crops such as cotton (*Gossypium hirsutum* L.), wheat (*Triticum aestivum* L.) and horticultural crops (Jabran *et al.* 2017; Bajwa *et al.* 2019).

Evidence from recent literature shows that climate change is likely to support the growth and spread of weeds (Ziska *et al.* 2019; Jabran *et al.* 2020), making the control of weeds more difficult. Generally, different management approaches have been used for controlling these weeds, for example, physical control (flaming, solarization), mechanical control (tillage, hoeing), and cover crops. However, control with herbicides is the most widely used method worldwide (Fernando *et al.* 2016). Changing climatic conditions are expected not only to impact the growth and development of weeds, but also to modify the activity of herbicides against weeds (Dukes 2000; Hellmann *et al.* 2008; Sutherland *et al.* 2017). The reason for this variation in the activity of herbicides is their classification and modes of action. For example, clodinafop-propargyl inhibits acetyl-coenzyme A carboxylase (ACCase), which is considered to be a key enzyme in the biosynthesis of fatty acids, while tribenuron-methyl and nicosulfuron are herbicides that inhibit acetolactate synthase (ALS), which is the key enzyme in the biosynthesis of branched-chain amino acids (Dollinger 2005; BKÜ 2021).

Herbicides containing mesosulfuron methyl (3%) + + iodosulfuron methyl sodium (0.6%) as an active ingredient inhibit ALS. These herbicides control weeds in wheat fields (RBKÜ 2009). The 2-methyl-4-chlorophenoxyacetic acid also known as MCPA is an important herbicide of the chlorophenoxy family (Auxin mimics Group 4) while bromoxynil (photosynthesis inhibitors at PSII Group 6) is also an important herbicide available in several countries around the world, including Europe. These herbicides inhibit the ALS enzyme and weed mortality rates are higher when these two herbicides are used in combination (Berling *et al.* 2015).

Glyphosate is a non-selective herbicide that is applied during the active growth period. This herbicide is used to control annual, biennial, and perennial weeds, and for controlling shrubs and some woody species (Richmond 2018). Glyphosate inhibits the biosynthesis of aromatic amino acids (phenylalanine, tyrosine, and tryptophan), leading to the disturbance of protein production and the prevention of secondary metabolite formation (Grossbard and Atkinson 1985; Franz *et al.* 1997). Glyphosate also inhibits enzyme 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase (Duke 2018).

Increases in atmospheric CO_2 concentrations and global warming are likely to impact the activity of herbicides against weeds (Jabran and Doğan 2018). Previously, some researchers have reported that growing weeds under high CO_2 concentration levels could increase their tolerance to glyphosate (Ziska and Teasdale 2000; Archambault *et al.* 2001; Ziska *et al.* 2004; Manea *et al.* 2011). However, subsequent studies examining a different set of weed species (Marble *et al.* 2015; Zhang *et al.* 2015; Jabran 2016) provided certain evidence contradictory to these studies (Marble *et al.* 2015; Zhang *et al.* 2015; Jabran 2016).

With global climate change, it is predicted that weed problems will increase in areas where agricultural practices are performed and as a result, the crop yield will decrease. It is necessary to know the efficacy of herbicides in the future against increasing temperatures and CO_2 levels. This study hypothesized that weeds growing under simulated CO_2 levels and temperature conditions will diminish the effect of herbicides. Accordingly, this study aimed to investigate how weeds such as *A. fatua*, *C. album,* and *S. arvensis* grow and respond to herbicides at different temperatures and CO_2 levels.

Materials and Methods

Site and plant material

A greenhouse study was carried out to determine the effect of the application of herbicides on three weeds when grown under different CO_2 and temperature levels. The study was performed at the Faculty of Agriculture, Malatya Turgut Özal University, Turkey during 2019 and 2020. Seeds of *A. fatua*, *C. album* and *S. arvensis* were collected from crop fields, fruit orchards and fallow fields covering large geographical areas of Turkey. The collected seeds were stored at +4°C by placing them in a plastic bag until used.

Experimental conditions and treatments

The study was carried out in a fully automated greenhouse that possessed independent chambers (area = = 5 m × 5 m = 25 m^2) each of which could be adjusted with desired CO_2 concentrations and temperature levels. The greenhouse roof was covered with a green cover that had a shading system of 75% (i.e., 25% of the sunlight was able to enter the greenhouse) to reduce the direct effect of sunlight on weeds. The light intensity in the rooms varied from 3000 to 5000 lux. It was possible to automatically adjust temperature, CO_2 and humidity values in all chambers. Furthermore, each of the chambers had sensors for recording and subsequently monitoring the temperature, CO_2 and humidity levels. These sensors worked synchronously, and the environment was controlled by regulating the temperature, CO_2 and humidity levels inside the greenhouse. During the experiments, the relative humidity was adjusted to approximately 60 ± 10%. There was no additional lighting system inside the greenhouse. The day/night length was set to 14/10 h. In this study, three temperature levels (day/night 26/16 ± 1°C, 29/19 ± 1°C and 32/22 ± 1°C) and three CO_2 concentrations (400 ± 50 ppm, 600 ± 50 ppm, and 800 ± 50 ppm) were maintained. A temperature of 26/16 ± 1°C plus a CO_2 level of 400 ± 50 ppm was considered as the control (IPCC 2007). The temperature and CO_2 values (treatment combinations) in this study were as follows: (i) 26/16°C + 400 ppm (constant temperature and CO_2) (control), (ii) 26/16°C + + 600 ppm (constant temperature and increased CO_2), (iii) 26/16°C + 800 ppm (constant temperature and increased CO_2), (iv) 29/19°C + 400 ppm (high temperature and constant CO_2), (v) 29/19°C + 600 ppm (high temperature and increased CO_2), (vi) 29/19°C + + 800 ppm (high temperature and increased CO_2), (vii) 32/22°C + 400 ppm (high temperature and constant CO_2), (viii) 32/22°C + 600 ppm (high temperature and increased CO_2), and (ix) 32/22°C + 800 ppm (high temperature and increased CO_2).

Potting medium and experimental design

Experiments were carried out according to the randomized complete block design with four replications. Peat (perlite mixture) was added to pots at a ratio of 2 : 1. Ten seeds were planted in pots that had a dimension of 10 × 8 cm. After planting, irrigation was done until the soil reached its water holding capacity. After the weeds emerged, thinning was carried out to maintain one plant in each pot.

Effect of herbicide applications on control of weeds under different climatic conditions

Herbicide application was done during the 4–6 leaf stage while different herbicides were applied to each weed (Table 1). For *A. fatua*, 240 g · l^{-1} clodinafop-propargyl and 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl, for *C. album* 40 g · l^{-1} nicosulfuron and 480 g · l^{-1} glyphosate isopropylamine salt and for *S. arvensis* 75% tribenuron methyl and 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl + + 300 g · l^{-1} bromoxynil + 300 g · l^{-1} MCPA herbicides were used. Herbicides were chosen because they are licensed for these weeds in wheat, corn and orchards in Turkey and are used intensively. The herbicide application was carried out in an automated closed spraying cabinet that has a rainfall simulator that uses Veejet nozzles and produces droplets with kinetic energies. In the trials conducted under different temperatures and CO_2 conditions, six different doses were used for each of the herbicides in the study. These quantity of these herbicide doses was as following: "clodinafop-propargyl" = 50, 100, 200 (recommended dose), 400, 800 and 1600 ml · ha^{-1}, "3% mesosulfuron-methyl + + 0.6% iodosulfuron-methyl sodium" = 62.5, 125, 250 (recommended dose), 500, 1000 and 2000 g · ha^{-1}, "nicosulfuron" = 31.25, 62.5, 125 (recommended dose), 250, 500 and 1000 ml · ha^{-1}, "glyphosate" = 750, 1500, 3000 (recommended dose), 6000, 12 000 and 24 000 ml · ha^{-1}, "tribenuron methyl" = 2.5, 5, 10 (recommended dose), 20, 40 and 80 g · ha^{-1}, and "bromoxynil + MCPA" = 87.5, 175, 350 (recommended dose), 700, 1400 and 2800 ml · ha^{-1}. That is, X/4 (25%), X/2 (50%), 1X (100%), 2X (200%), 4X (400%) and 8X (800%) multiples of the doses for any of the herbicides were used in the experiment using a volume of spray of 200 l · ha^{-1}. While adjusting the herbicide doses, the highest dose was adjusted, and then the lowest dose was prepared by dilution. The weeds that were sprayed at 5 km · h^{-1} and under 300 kPa pressure in the spray booth were taken back to their own growing environment. Percent symptom values were taken weekly 1 week after spraying, for a total of 4 weeks (Bajwa 2019).

Table 1. List of weeds, the herbicides applied, formulations and the doses used in the current study

Weed species	Herbicide	Commercial name (a.i. percentage)	Formulation	Rates
Avena fatua	240 g · l^{-1} clodinafop-propargyl	Koropik 240	EC	Control, 50, 100, 200 (recommended dose), 400, 800 and 1600 ml · ha^{-1}
	3% mesosulfuron-methyl + + 0.6% iodosulfuron-methyl sodium + + 9% mefenpyr-diethyl	Atlantis	WG	Control, 62.5, 125, 250 (recommended dose), 500, 1000 and 2000 g · ha^{-1}
Chenopodium album	40 g · l^{-1} nicosulfuron	Sanspor 75%	WP	Control, 31.25, 62.5, 125 (recommended dose), 250, 500 and 1000 ml · ha^{-1}
	480 g · l^{-1} glyphosate isopropylamine salt	Best Stopper	SL	Control, 750, 1500, 3000 (recommended dose), 6000, 12 000 and 24 000 ml · ha^{-1}
Sinapis arvensis	75% tribenuron methyl	Granstar	WG	Control, 2.5, 5, 10 (recommended dose), 20, 40 and 80 g · ha^{-1}
	3% mesosulfuron-methyl + + 0.6% iodosulfuron-methyl sodium + + 9% mefenpyr-diethyl + + 300 g · l^{-1} bromoxynil + 300 g · l^{-1} MCPA	Atlantis + Buctril	WG	Control, 87.5, 175, 350 (recommended dose), 700, 1400 and 2800 ml · ha^{-1}

Data recording

Plants were observed on a weekly basis to determine the response of weeds to applied herbicides. Harvesting was carried out 4 weeks after spraying. The parameters recorded in the experiment were plant length, fresh and dry weights. All parameters were recorded post-harvest. In the experiment, all parameters were taken from the control plants (without herbicide application), while only the plant fresh and dry weights were taken from the treated plants. Plant length was measured from the root collar to the top of the plant. The harvesting process was carried out by cutting the plants from the root collar with the help of scissors. After harvest, the fresh weights of the plants were taken using precision scales and placed in paper bags. The plants in the paper bags were kept in an oven at 105°C for 1 day, and after the plants reached their constant dry weight, their dry weights were takena with the help

Data analysis

Statistical analyses of the data were done using General Linear Model (GLM) and analysis of variance (ANOVA) using IBM SPSS STATISTICS 25.0 package program. Differences between the treatments were determined by Duncan's multiple range test. DM reduction (%) data were subjected to a nonlinear regression analysis over herbicide dose using the four-parameter log-logistic model (Knezevic *et al.* 2007; Ulloa *et al.* 2011):

$$Y = C + \frac{(D - C)}{1 + \exp\,[b(\log(x) - \log(\mathrm{ED}_{50})}\,,$$

where: Y – response to herbicide rate (x), C – is the lower limit, D – the upper limit, b – the slope, and ED_{50} – the dose causing 50% response.

Analyses of the dose-response curves were performed using the R software (R version 2.15.3, R Development Core Team 2013) utilizing the DRC (dose--response curves) statistical add-on package (Knezevic *et al.* 2007). A lack-of-fit test at the 5% level was not significant for any of the dose-response curves indicating that the log-logistic model was appropriate for the data analyses (Ulloa *et al.* 2011; Datta *et al.* 2013). ED_{90} values were calculated using the same program.

Results

The temperature levels and temperature × CO_2 interactions had a significant effect on plant length, plant fresh and dry weights of *A. fatua* (Table 2). However, CO_2 concentrations only affected plant fresh weight of *A. fatua*, and did not have a significant effect on plant length and dry weight. The effects of temperature levels, CO_2 concentrations and temperature × CO_2 interactions on plant fresh weight of *A. fatua* were found to be significant. Plant length, plant fresh and dry weights were decreased with an increase in temperature. With increased CO_2 concentrations, plant fresh

Table 2. The effect of increased temperature and carbon dioxide levels on the growth of *Avena fatua* L., *Chenopodium album* L. and *Sinapis arvensis* L.

Treatment	*Avena fatua*			*Chenopodium album*			*Sinapis arvensis*		
	plant length [cm]	plant fresh weight [g]	plant dry weight [g]	plant length [cm]	plant fresh weight [g]	plant dry weight [g]	plant length [cm]	plant fresh weight [g]	plant dry weight [g]
Temperature [°C]									
26	61.45 A	7.32 A	1.18 A	69.00 A	9.80 B	2.06 B	28.56 A	20.45 A	1.59 A
29	59.32 A	2.70 B	0.28 B	65.42 A	15.07 A	3.53 A	15.74 B	0.82 B	0.06 B
32	53.89 B	2.04 C	0.25 B	65.79 A	12.24 B	2.88 AB	8.67 C	0.32 B	0.04 B
CO_2 Concentration [ppm]									
400	57.34 A	4.56 A	0.59 A	66.71 A	11.03 A	2.59 A	19.10 A	8.66 A	0.66 A
600	57.75 A	3.67 B	0.55 A	63.13 A	12.79 A	2.80 A	16.21 A	6.23 B	0.54 A
800	59.57 A	3.84 B	0.57 A	70,38 A	13.29 A	3.08 A	17.65 A	6.70 B	0.48 A
Temperature × CO_2 levels									
26°C × 400 ppm	57.70 bcd	7.24 a	0.99 b	68.5 a	9.87 a	2.16 a	31.63 a	23.99 a	1.82 a
26°C × 600 ppm	61.60 abc	7.30 a	1.26 a	71.5 a	9.42 a	1.98 a	25.80 b	17.95 b	1.55 a
26°C × 800 ppm	65.05 a	7.42 a	1.31 a	67.0 a	10.10 a	2.05 a	28.25 b	19.40 b	1.39 a
29°C × 400 ppm	58.55 abc	3.53 b	0.40 c	57.38 a	10.65 a	2.23 a	18.67 c	1.77 c	0.13 a
29°C × 600 ppm	56.55 bcd	1.81 d	0.18 d	60.75 a	15.71 a	3.65 a	12.83 de	0.32 c	0.03 a
29°C × 800 ppm	62.85 ab	2.76 bc	0.26 cd	78.13 a	18.84 a	4.72 a	15.71 cd	0.36 c	0.03 a
32°C × 400 ppm	55.78 bcd	2.90 b	0.38 c	74.25 a	12.56 a	3.40 a	7.00 f	0.22 c	0.04 a
32°C × 600 ppm	55.09 cd	1.89 cd	0.21 cd	57.13 a	13.23 a	2.78 a	10.00 ef	0.40 c	0.04 a
32°C × 800 ppm	50.80 d	1.35 d	0.15 d	66.0 a	10.94 a	2.46 a	9.00 F	0.34 c	0.04 a

Means not sharing a letter (capital letter for main effects and small letters for interactive effects) in common differ significantly at 5% probability level

and dry weights were decreased, while plant length was increased. It was determined that 26°C was more suitable for *A. fatua* than the other two temperatures (29 and 32°C) in the study. Compared to other temperature levels, at 26°C, *A. fatua* plants produced the highest plant length, as well as plant fresh and dry weights. Also, the interaction of 26°C × various CO_2 levels had a positive influence on the growth of *A. fatua*. It was determined that 26°C × 800 ppm CO_2 interaction produced the highest plant length, as well as plant fresh and dry weights (Table 2).

CO_2 levels and temperature × CO_2 interactions did not have a significant effect on plant length, plant fresh weight and plant dry weight of *C. album* (Table 2). While temperature levels affected plant fresh and plant dry weight of *C. album*, it did not have a significant effect on plant length. For this weed, the plant length was decreased with increased temperature, while the fresh and dry weights of the plants were increased. It was determined that 29°C was the most suitable for *C. album* growth and produced the highest plant fresh and dry weights. Although the effect of CO_2 levels on the growth parameters of the weed was not significant, it was observed that the growth parameters increased as the CO_2 level increased and reached the highest value at 800 ppm CO_2 level as compared to other CO_2 levels. However, it was determined that plant length, as well as plant fresh and dry weights reached the highest levels at 29°C × 800 ppm CO_2 interaction (Table 2).

CO_2 levels and temperature × CO_2 interactions did not have a significant effect on the plant length of *S. arvensis* (Table 2). Temperature levels had a significant effect on plant length, plant fresh and dry weights while CO_2 levels only affected plant fresh weight. The interaction of temperature × CO_2 had significant effects on plant length and plant fresh and dry weights of *S. arvensis*. Plant length, plant fresh and dry weights were decreased with increased temperature. It was determined that 26°C was the most suitable for *S. arvensis* growth and it produced the highest plant length, plant fresh and dry weights as compared to other temperature levels. Although the effect of CO_2 levels on the growth parameters of weeds was not significant, except for the fresh weight of the plant, it was observed that the growth parameters decreased as the CO_2 level increased, and it reached the highest value at 400 ppm CO_2 level when compared to other CO_2 levels. The interaction of temperature × CO_2 was found to be effective on plant height and plant fresh weight. The maximum plant length, plant fresh and dry weights were observed at 26°C × 400 ppm CO_2 interaction (Table 2).

Table 3. Parameters of log-logistic model fitted to the response of *Avena fatua* L. dry matter reduction (% of control treatment) to clodinafop-propargyl rates at different temperatures and CO_2 levels (SE: Standard error)

CO_2 concentration [ppm]	Temperature [°C]																	
	26						29						32					
	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient
	B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}	
400	−2.0 (0.5)	−0.1 (4.7)	93.3 (3.4)	62.1 (6.4)	182.2 (15.5)	–	−2.1 (0.3)	0.5 (4.1)	90.5 (2.4)	62.8 (6.4)	180.7 (31.8)	1	−3.1 (0.7)	4 (3.3)	84.5 (1.8)	110.5 (6.4)	223 (31.4)	1.8
600	−2.2 (0.3)	1.2 (4)	92.1 (2.4)	82.5 (7.1)	220.9 (33.9)	1.3	−3.3 (0.6)	4.4 (2.8)	87.3 (1.7)	112.8 (5.4)	219.8 (25.4)	1.8	−2.7 (1.8)	5.9 (1)	85.7 (4.1)	112.1 (21.)	256.8 (45.1)	1.8
800	−2.1 (0.3)	−0.1 (3.9)	94.2 (2.6)	81.9 (6.8)	231.7 (41.2)	1.3	−3.1 (0.7)	2.7 (3.5)	86.4 (2.3)	112.4 (7.4)	227.2 (33.7)	1.8	−2.3 (0.9)	4.8 (7)	82.7 (3.6)	111.9 (18.2)	287.3 (42.1)	1.8

B – slope; C – lower limit; D – upper limit; ED_{50} – the dose causing 50% response; ED_{90} – the dose causing 90% response

Table 4. Parameters of log-logistic model fitted to the response of *Avena fatua* L. dry matter reduction (% of control treatment) to 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl rates at different temperatures and CO_2 levels (SE: Standard error)

CO_2 concentration [ppm]	Temperature [°C]																	
	26						29						32					
	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient
	B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}	
400	−2.5 (0.5)	−0.1 (3.7)	93.3 (2.1)	75.5 (5.4)	181.4 (31)	–	−2.2 (0.2)	−0.1 (2)	94.9 (1.2)	110.4 (4.5)	303.6 (24.4)	1.5	−1.7 (0.4)	−0.1 (4.7)	88 (3.4)	109.1 (1.7)	386.4 (56.4)	1.4
600	−2.6 (0.3)	−0.1 (2.6)	93.6 (1.5)	91.2 (4.3)	212.1 (21.8)	1.2	−2.3 (0.3)	−0.1 (2.7)	88.1 (2.1)	116.4 (7)	306.3 (52.7)	1.5	−0.1 (0.5)	−0.1 (5.8)	82.9 (4.1)	107.5 (17.7)	377.9 (84.8)	1.4
800	−2.3 (0.2)	0.2 (2)	93.9 (1.2)	92.8 (3.8)	243.8 (42.8)	1.2	−2.2 (0.4)	1 (4.9)	92.5 (3)	122.5 (12.9)	332.8 (65)	1.6	−1.7 (0.2)	−0.1 (2.8)	91.3 (2.1)	111.7 (8.1)	396 (67.8)	1.5

B – slope; C – lower limit; D – upper limit; ED_{50} – the dose causing 50% response; ED_{90} – the dose causing 90% response

The ED_{50} values of *A. fatua* increased with increased temperature and CO_2 levels for both clodinafop-propargyl 240 g · l^{-1} and 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl (safener) (Tables 3 and 4). This showed that with an increase in temperature it was necessary to use higher doses of herbicides to control the weed. The highest ED_{50} value 112.8 of *A. fatua* was obtained with clodinafop-propargyl 240 g · l^{-1} herbicide application at 29°C + 600 ppm CO_2. With increasing temperature and CO_2 levels, 1.8 times more herbicides should be applied to control *A. fatua* (Table 3). This means that it was required to use higher doses of herbicides to control these weeds. The ED_{50} value of *A. fatua*, which was treated with 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl (safener) herbicide, was calculated as 122.5 at the highest temperature of 29°C + 800 ppm CO_2. With increasing temperature and CO_2 levels, 1.6 times the herbicide dose were required to control *A. fatua*.

The ED_{50} values of *C. album* increased with increased temperature and CO_2 levels (Table 5). This means that it was crucial to use higher doses of herbicides to control the weed. The highest ED_{50} value 0.6 for 480 g · l^{-1} glyphosate isopropylamine salt herbicide was obtained at 26°C + 800 ppm CO_2, 32°C + 600 ppm CO_2 and 32°C + 800 ppm CO_2.With increasing temperature and CO_2 levels, two times more herbicides should be applied to control *C. album*. With the increase in temperature and CO_2 levels, there was an increase in the ED_{50} values of *S. arvensis* for tribenuron-methyl herbicide (Table 6). This means that it was compulsory to use higher doses of tribenuron-methyl herbicide to control the weed. The highest ED_{50} value (8.1) of *S. arvensis* was calculated when treated with 75% tribenuron-methyl herbicide, at the highest temperature of 29°C + 800 ppm CO_2. With increasing temperature and CO_2 levels three times more herbicides were required to control *S. arvensis*.

Table 5. Parameters of log-logistic model fitted to the response of *Chenopodium album* L. dry matter reduction (% of control treatment) to 480 g · l^{-1} glyphosate isopropylamine salt rates at different temperatures and CO_2 levels (SE: Standard error)

CO_2 concentration [ppm]	Temperature [°C]																	
	26						29						32					
	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient
	B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}	
400	−1.4 (1.2)	−0.1 (9)	93.9 (11.2)	0.3 (0.1)	1.4 (1.9)	–	−1.7 (0.4)	−0.6 (3.7)	92.7 (3.2)	0.4 (0.1)	1.4 (0.4)	1.3	−1.7 (0.4)	−0.1 (5.7)	102 (4.2)	0.5 (0.1)	1.6 (0.4)	1.7
600	−2.2 (0.4)	0.9 (5.6)	97.8 (3.6)	0.5 (0.1)	1.5 (0.3)	1.7	−1.9 (0.4)	−1.2 (4.6)	98.5 (3.8)	0.5 (0.1)	1.5 (0.4)	1.7	−2 (0.4)	−1.2 (5.8)	100.8 (4.6)	0.6 (0.1)	1.7 (0.5)	2
800	−2.2 (0.4)	−0.1 (3.9)	88 (2.5)	0.6 (0.01)	1.5 (0.3)	2	−1.8 (0.3)	−0.9 (3.9)	98.1 (3.3)	0.5 (0.1)	1.6 (0.4)	1.7	−2 (0.2)	−1 (2.2)	100.4 (1.7)	0.6 (0.1)	1.7 (0.2)	2

B – slope; C – lower limit; D – upper limit; ED_{50} – the dose causing 50% response; ED_{90} – the dose causing 90% response

Table 6. Parameters of log-logistic model fitted to the response of *Sinapis arvensis* L. dry matter reduction (% of control treatment) to 75% tribenuron-methyl rates at different temperatures and CO_2 levels (SE: Standard error)

CO_2 concentration [ppm]	Temperature [°C]																	
	26						29						32					
	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient
	B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}	
400	−5.8 (1.4)	−0.1 (2.4)	96.6 (1.2)	2.7 (0.1)	4 (0.5)	–	−2 (0.3)	1.7 (3.7)	91.6 (2.7)	5.4 (0.5)	15.8 (2.9)	1.3	−2.2 (0.6)	2.2 (4.4)	83.4 (3.6)	6.4 (0.6)	17.8 (5.3)	2.4
600	−7.2 (4)	−0.1 (4)	93.7 (2)	2.8 (0.2)	3.9 (0.9)	1	−2.1 (0.2)	1 (1.8)	89.4 (1.5)	6.9 (0.3)	19.8 (1.9)	1.7	−1.9 (0.8)	1.8 (6.6)	87.3 (6.9)	7.1 (1.1)	22.5 (12.4)	2.6
800	−9 (5.5)	−0.1 (1.7)	97.8 (0.9)	2.8 (0.2)	3.6 (0.8)	1	−2.6 (0.9)	5.8 (4.4)	85.6 (3.5)	8.1 (0.7)	18.8 (5.1)	1.7	−1.8 (0.2)	−0.1 (2.9)	92.7 (2.9)	7.3 (0.6)	24 (4.5)	2.7

B – slope; C – lower limit; D – upper limit; ED_{50} – the dose causing 50% response; ED_{90} – the dose causing 90% response

Table 7. Parameters of log-logistic model fitted to the response of *Sinapis arvensis* L. dry matter reduction (% of control treatment) to 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl + 300 g · l^{-1} bromoxynil + 300 g · l^{-1} MCPA rates at different temperatures and CO_2 levels (SE: Standard error)

CO_2 concentration [ppm]	Temperature [°C]																	
	26						29						32					
	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient	Parameters (±SE)					Co-efficient
	B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}		B	C	D	ED_{50}	ED_{90}	
400	−6.3 (3.9)	9.4 (3.5)	96.4 (2.6)	168.8 (11.6)	239 (64.8)	–	−3.8 (0.9)	7.1 (3.3)	93.5 (2.3)	186.4 (10.5)	330.7 (45.8)	1.1	−3 (0.7)	2.8 (3.7)	84.3 (2.5)	179.6 (13)	372.6 (63.2)	1.1
600	−6 (3.6)	14.6 (4.5)	98.5 (3.4)	177 (15.6)	255.4 (73.6)	1	−3.6 (1.4)	7 (4.9)	82.6 (2.8)	176.2 (15.3)	325.2 (71.7)	1	−3.1 (0.5)	3 (2.7)	90 (1.9)	189 (9)	380.9 (48.2)	1.1
800	−6.9 (3.2)	12.5 (3.7)	97.3 (3)	184.1 (18)	253.6 (59.6)	1.1	−4 (0.8)	7.7 (2.9)	88.7 (2.1)	199.4 (11.1)	344.1 (41.5)	1.2	−2.8 (0.9)	3.4 (5)	83.1 (3.4)	187.4 (19.4)	408.3 (67.8)	1.1

B – slope; C – lower limit; D – upper limit; ED_{50} – the dose causing 50% response; ED_{90} – the dose causing 90% response

With increased temperature and CO_2 levels, there was an increase in the ED_{50} values of *S. arvensis* for 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl + 300 g · l^{-1} bromoxynil + + 300 g · l^{-1} MCPA herbicide (Table 7). This means that a higher dose of herbicide is required to control *S.*

arvensis. The highest ED_{50} value (199.4) was obtained for 3% mesosulfuron-methyl + 0.6% iodosulfuron-methyl sodium + 9% mefenpyr-diethyl + 300 g · l^{-1} bromoxynil + 300 g · l^{-1} MCPA herbicide at 29°C + 800 ppm CO_2. This means that with increased temperatures and CO_2 levels, 1.2 times more herbicide is needed to control *S. arvensis*.

Discussion

In this study, the growth of three weeds i.e., *A. fatua* and *S. arvensis* and *C. album* was significantly affected by climate change. The study revealed that temperature and its interaction with CO_2 had significant effects on the growth of *A. fatua* and *S. arvensis* weeds but did not significantly affect *C. album*. Higher temperatures resulted in decreased length and weight in *A. fatua* and *S. arvensis*, while increased CO_2 concentrations had contrasting effects on weight and length. For *A. fatua*, the optimal conditions were 26°C and 800 ppm CO_2, whereas for *S. arvensis*, it was 26°C and 400 ppm CO_2. CO_2 levels had little impact on the growth of *C. album*, with temperature being the dominant factor. Increased temperature and CO_2 levels enhanced the plant growth parameters of *C. album*. As observed in our study, previous research has also reported an increase in the growth of weeds under simulated climate change scenarios. For example, elevated CO_2 levels (700 ppm) increased the number of leaves by 34-56% and weed dry biomass by 28–65% in *Datura stramonium* (Chada *et al*. 2020). Another study also reported the role of elevated CO_2 in increasing the dry biomass of weeds such as *Hordeum murinum* L., *Lactuca serriola* L., and *Bromus tectorum* L. (Jabran and Dogan 2020). It has been previously reported that increasing temperature from 21/12°C to 26/18°C and CO_2 from 400 to 800 μmol · mol^{-1} levels increased the competition of *C. album* with tomato (*Solanum lycopersicum* L.), resulting in a decrease in growth parameters and yield of the tomato (Valerio *et al.* 2013). Changes in CO_2 levels, humidity, temperature, and other growing conditions will affect the distribution of weeds and their competitiveness within the weed or crop population. Increases in any of the environmental conditions make the crop plants more vulnerable to insect pests, plant pathogens and make them less competitive to weeds (Amare 2016).

The rate of herbicide absorption depends upon environmental conditions and interaction between soil, atmosphere, and type of applied herbicides hence, it plays an important role in determining the efficacy of herbicides at the time of application. These environmental factors also influence the susceptibility of plants to applied herbicides. Evidence shows that changes in climatic conditions reduce the sensitivity of weeds to some herbicides. Ziska *et al*. (2004) reported that increased CO_2 concentrations in the atmosphere may decrease the effectiveness of herbicides. Weeds are greatly influenced by climate change conditions (Singer *et al*. 2013; Tørresen *et al*. 2020). For example, different invasive weed species have been found to benefit (directly or indirectly) from climate change (Blumenthal and Kray 2014; Sun *et al*. 2020). It has been forecasted that in the current climate change scenario, weeds may be benefited due to their broad range of environmental tolerance, huge dispersal rate and rapid colonization (Bajwa *et al*. 2020). However, this prediction may not be true for all types of weeds (Roger *et al*. 2015).

An increase in temperature and high CO_2 levels reduced the sensitivity of *C. album* to glyphosate (Matzrafiet *et al*. 2019). Elevated CO_2 concentrations can affect the different physiological processes in plants and produce a mixed response (both positive and negative) (Misra *et al*. 2019). It has been recorded that weeds can develop tolerance to applied herbicides (Qasem 2011). These weed species develop physiological and morphological adaptations against climate change due to which they can easily grow and reproduce efficiently as compared to native plants of that area (Ziska and McConnell 2015). It not only affects the physiological processes but also affects the efficacy of weed management programs.

Results of this study showed that the ED_{50} values of *C. album* increased with increased temperature and CO_2 levels. These results were similar to previous research by Norsworthy *et al.* (2008) who observed that the resistant biotype of *Amaranthus palmeri* S. Watson had an LD_{50} of 2,820 g · ha^{-1} glyphosate, which was 79 to 115-fold greater than that of the susceptible biotypes and 3.4 times a normal glyphosate-use rate of 840 g · ha^{-1}. Mohseni-Moghadam *et al.* (2013) also reported 50% biomass reduction of a glyphosate resistant *A. palmeri* biotype from New Mexico, USA with glyphosate applied at 458 g · ha^{-1}, which is about a 2.9-fold lower application rate than the level observed in this study. The effectiveness of the herbicide glyphosate isopropyl amine salt of 480 g · l^{-1} to *C. album* decreased with increased temperature and CO_2 levels, and under climate change, it should be used at higher doses to control it. Similarly, it has been stated that increased CO_2 levels can increase the tolerance of glyphosate in C_3 weeds and limit the effectiveness of some herbicides (Ziska *et al*. 1999).

Conclusions

This research provided interesting results, namely, that a high CO_2 level (800 ppm) improved growth for only two weeds (*A. fatua* and *S. arvensis*) but only at normal temperature conditions i.e., 26/16°C while the simulated climatic conditions did not affect the growth of *C. album*. An increase in temperature and high CO_2 concentrations reduced the efficacy of applied herbicides on the weeds and hence, the ED_{50} values of herbicides for controlling *A. fatua*, *C. album* and *S. arvensis* were increased with an increase in temperature and CO_2 levels. Based on the findings of this research, future weed control strategies should consider the potential impacts of high CO_2 levels and increased temperatures on the growth of weeds and efficacies of herbicides. It is important to focus on alternative control methods that can effectively control weeds under elevated CO_2 and temperature conditions. Additionally, an integrated weed management approach that incorporates cultural practices and prevention strategies could be explored to mitigate the reduced efficacy of herbicides under these changing climatic conditions.

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