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Interference of weeds in vegetable crop cultivation, in the changing climate of Southern Europe with emphasis on drought and elevated temperatures: a review

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Abstract

It is challenging to predict the changes in weed flora that may occur because of changes in global climate. Limited data are available on the effect of climate change and drought conditions on weed flora and their competitiveness in Southern Europe. Future predictions by scientists indicate reduced and untimely rainfall, along with increased temperatures in this region. Weeds possess a variety of developmental and physiological mechanisms, including senescing, increased leaf cuticular wax deposition, well-developed palisade parenchyma in the leaves, high root/shoot ratio, stomatal closure, peroxidase accumulation and symbiosis with endophytes that enable them to adapt to drought and high temperatures. Because of high adaptability of weeds to adverse environmental conditions, it can be assumed that under future warmer and drier environmental conditions, their growth will be favoured, while the competitiveness of vegetable crops against weeds will be decreased. It is important to highlight that the predicted decrease in overall rainfall levels throughout the year may lead to increased problems of herbicide residues (carryover effects) to following crops. The current paper provides an up-to-date overview of the adaptation mechanisms of weed species commonly found in Southern Europe, in order to expand the available knowledge regarding their response to drought and elevated temperatures. Emphasis is placed on revealing the effects of drought and increased temperatures on vegetable–weed competition and, most importantly, its effect on vegetable crop yield.

Introduction

A stable climate is vitally important for life on Earth. However, the Earth's climate is now facing rapid changes with profound effects on the environment and its inhabitants. Specifically, melting of the polar ice caps and glaciers is responsible for rising sea levels (Raper and Braithwaite, 2006; Paul, 2011), while heatwaves and droughts are becoming more severe and frequent in more and more regions of the globe (Olesen *et al*., 2011; Trenberth, 2018). All these changes have major consequences for human activities and the environment (Chen *et al*., 2012; Trenberth, 2018). Furthermore, the increased risk to agricultural production seems to be one of the most important consequences of climate change (Cline, 2007; Evangelista *et al*., 2013), while the distribution of several wild plant species is expected to change (McDonald *et al*., 2009; Castellanos-Frías *et al*., 2016; Reif *et al*., 2017). On the contrary, it is expected to have a positive effect on agricultural production in high-latitude regions such as Russia and Canada, while its effects on other areas of the world are debatable (Lewis and Witham, 2012). The overall global effects of climate change on agriculture will be negative, in terms of food security and stability (Nelson *et al*., 2009; Wheeler and Von Braun, 2013), while the effects are expected to be worse in countries already facing food shortages (Wheeler and Von Braun, 2013). Recent data have revealed that the number of undernourished people increased to 815 million in 2016, representing about 11% of the global population (FAO *et al*., 2017); according to Dawson *et al*. (2016), 31% of the global population is expected to face the risk of undernourishment by 2050.

In Southern Europe, climate change is predicted to result in temperature elevation and an increase in the frequency of drought (Lehner *et al*., 2006; Lovelli *et al*., 2012). In the same region, climate change will also cause declines in crop yields (Debaeke *et al*., 2017; Gammans *et al*., 2017); thus, restructuring of crops, as well as changes in cultivation practices, have been suggested as alternative strategies to solve this problem (Olesen *et al*., 2011; Nastis *et al*., 2012). Here, it is important to point out that vegetables, pulses and cereals are more vulnerable to climate change (e.g. increased temperatures, drought incidence) than other arable crops (Acikgoz, 2011; Bahl, 2015; Gammans *et al*., 2017). A recent study by Gammans *et al*. (2017) predicted yield losses of up to 21.0% for winter wheat, 17.3% for winter barley and 33.6% for spring barley due to yearly deviations from climate averages for temperature and precipitation.

Climate change is already occurring in Europe and it is anticipated that significant changes in weed flora will take place throughout Europe in the near future (Peters *et al*., 2014; Castellanos-Frías *et al*., 2016). Enhanced growth of C4 weeds (the species that use the C4 carbon fixation pathway [Hyvönen, 2011; Rodenburg *et al*., 2011]), spreading of perennial weeds such as *Solanum elaeagnifolium* Cav. (silverleaf nightshade) and *Sorghum halepense* (L.) Pers. (Johnsongrass) (Mekki, 2007; Leguizamón and Acciaresi, 2014) and invasion of new species (Clements and DiTommaso, 2012) are some of the effects of climate change (e.g. increased temperatures, drought) on weed flora in Europe and other parts of the world. Understanding crop–weed interference in response to climate change is also a major challenge, as weeds remain the most important limiting factor in economically viable crop production (Ziska and Dukes, 2011; Karkanis *et al*., 2012). According to Lovelli *et al*. (2012), weeds' competitiveness is already increasing as a result of elevated temperatures in the Mediterranean region. From this perspective, two critical questions need to be addressed (Neve *et al*., 2009):

- Are weeds capable of adapting to a changing environment?
- What effect does climate change have on vegetable–weed competition?

Taking the above questions into consideration, the current review aims to provide an up-to-date overview of the adaptation mechanisms in weed species commonly found in Southern Europe in order to expand the available knowledge regarding the adaptability of these weeds to drought and elevated temperatures. Emphasis is also placed on revealing the effects of drought and increased temperatures on vegetable–weed competition, and most importantly, its effect on crop yield, as well as on weed distribution and population composition in this region.

Weeds, drought and high temperatures

Plant response to drought is a complex biological process involving different mechanisms of defence (Karkanis and Petropoulos, 2017; Plesa *et al*., 2018). Therefore, several weed species possess a wide variety of developmental and physiological mechanisms that enable them to adapt to increased temperatures and the limited availability of water (Fig. 1). In this section, a description is presented of the most important adaptation mechanisms, while emphasis has been placed on weed species commonly found in regions where vegetable crops are cultivated in Southern Europe.

Weed plasticity and drought

Several weed species decrease their water requirements by reducing the total plant leaf area. According to Schmidt *et al*. (2011), *Abutilon theophrasti* Medicus (velvetleaf) responds to water stress by senescing its oldest leaves, allowing the young leaves to support plant development and seed production. Similarly, Ward *et al*. (1999) observed that *A. theophrasti* reacts to drought by senescing and reducing the leaf area, allowing the remaining leaves to maintain high leaf water potential.

Plants growing at high temperatures adapt to heat stress by reducing the absorption of solar radiation either by growing hairs, which form a thick layer on leaves' surfaces, or by rolling their leaves (Hasanuzzaman *et al*., 2013). In addition, Karkanis *et al*. (2011) reported that *A. theophrasti* plants have the ability to adjust their temperature by orienting their leaf blades parallel to incident sunlight (Fig. 2).

Furthermore, several weeds respond to drought by shortening their life-cycles. Indeed, *A. theophrasti* plants suffering from drought were observed to flower earlier compared with well-watered plants (Karkanis *et al*., 2011). Such an early onset of reproduction in plants in response to water stress has been reported by Volis *et al*. (2004) and Volis (2009) for *Hordeum spontaneum* Koch (wild barley) and *Avena sterilis* (wild oat) as well.

High root/shoot ratios also contribute to drought tolerance in plants (Heschel *et al*., 2004; Xu *et al*., 2006). Heschel *et al*. (2004) evaluated three populations of *Polygonum persicaria* L. (spotted ladysthumb) for their adaptation mechanisms to drought: the results of that study revealed that all populations increased their water use efficiency (WUE) and root biomass allocation under drought conditions. Similarly, drought resistance in *S. elaeagnifolium* is associated with its deep root system, which consists of creeping horizontal and deep vertical roots (Mekki, 2007). Travlos (2013) similarly observed that *S. elaeagnifolium* plants exhibited a high root/shoot ratio under water stress. Furthermore, Zhu *et al*. (2013) reported considerable morphological variations between plants collected from several regions with different rainfall levels. According to Zhu *et al*. (2013), *S. elaeagnifolium* plants originating from areas with high rainfall levels had greater heights and larger leaves compared with those from regions with low rainfall levels, indicating changes in plant morphology as an adaptation mechanism to drought stress. Similar to *S. elaeagnifolium*, *Convolvulus arvensis* L. (field bindweed), which is considered to be a drought-tolerant species, develops a deep root system in order to overcome limited water availability (Sosnoskie and Hanson, 2016). The increase of root/shoot ratio in rice plants under drought-stress conditions has been associated with higher accumulation of dry matter and soluble sugars in roots as a response to higher activities of sucrose-phosphate synthase in shoots and invertase in roots, thus a higher transportation rate of sucrose from shoots to roots (Xu *et al*., 2015). This function is a plant defence mechanism to sustain root growth by decreasing allocation of metabolites to shoots (Gargallo-Garriga *et al*., 2014). Moreover, these changes in root architecture and growth allow plants to increase water uptake from deeper soil layers and overcome the negative effects of drought stress, although this response is highly dependent on genotype, as well as severity and duration of exposure to stress conditions (Lemoine *et al*., 2013; Xu *et al*., 2015; Sosnoskie and Hanson, 2016).

Drought resistance of weeds is also associated with a variety of anatomical traits that enable them to minimize water loss. For instance, Hatterman-Valenti *et al*. (2011) observed that *A. theophrasti* plants grown under drought conditions had greater leaf epicuticular wax deposition as compared with leaves of well-watered plants. *Ecballium elaterium* (L.) A. Rich (squirting cucumber) is also considered to be drought-resistant because of its leaf structure. According to Christodoulakis *et al*. (2011), *E. elaterium* plants

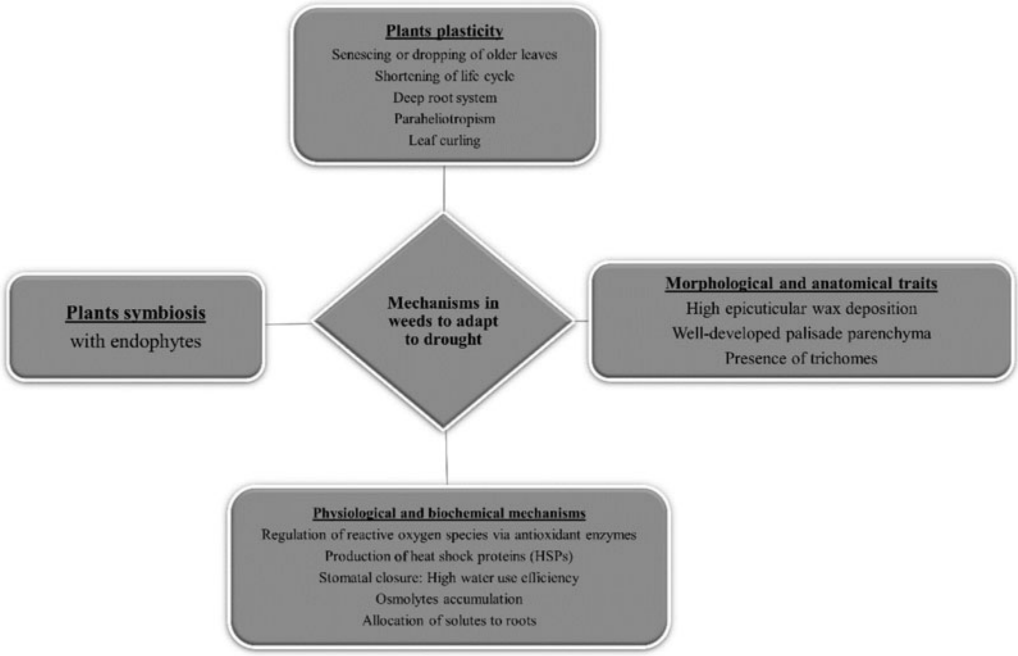

Fig. 1. Different mechanisms in weeds to adapt to drought and high temperatures.

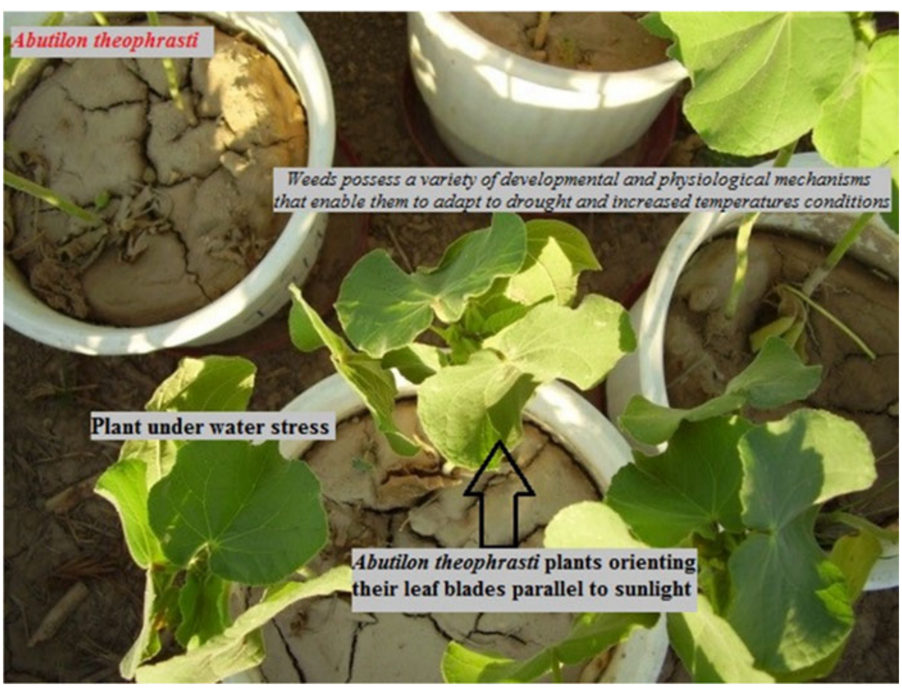

Fig. 2. (Colour online) Mechanism in *Abutilon theophrasti* plants to adapt to water stress.

present a well-developed palisade parenchyma in comparison with spongy parenchyma, which is relatively compact, while numerous multicellular trichomes exist on both leaf surfaces. High palisade to spongy parenchyma ratio is considered to be a xeromorphic trait (Christodoulakis *et al*., 2011). Christodoulakis *et al*. (2009) reported that the leaves of *S. elaeagnifolium* have four layers of palisade cells, while spongy parenchyma is absent from the mesophyll of its leaves. Similar to *E. elaterium* plants, numerous multicellular trichomes are also present on both leaf surfaces (Christodoulakis *et al*., 2009). The hairs on leaf surfaces are advantageous under drought conditions as they reduce the absorption of solar radiation, in addition to helping prevent water loss through the stomata (Hasanuzzaman *et al*., 2013).

Physiological and biochemical adaptations to drought

Weeds possess a variety of physiological mechanisms that enable them to adapt to water stress. For instance, under drought conditions, *A. theophrasti* plants retain water through stomatal closure (Schmidt *et al*., 2011). For the same species, Karkanis *et al*. (2011)

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reported that water stress resulted in lower stomatal conductance. *Amaranthus retroflexus* L. (redroot bigweed) is similarly considered to be a drought-tolerant weed, commonly found in Southern Europe. According to Lovelli *et al.* (2010*a*), the invasiveness of *A. retroflexus* increases under drought conditions because of its capacity to maintain a high WUE compared with other less-resistant crop and weed species.

Under drought conditions, an increased allocation of solutes in the roots of *Rumex obtusifolius* L. Rumob. (broadleaf dock) compared with its aerial parts has been reported by Gilgen and Feller (2013). The allocation of solutes to the roots helps *R. obtusifolius* plants to recover quickly from drought stress; this rapid recovery is a key factor for overall plant performance and competitiveness against other species, especially under stress (Gilgen and Feller, 2013, 2014).

Drought stress also affects plant photosynthesis, either through stomatal closure that impairs carbon dioxide (CO_2) diffusion or by inducing oxidative stress (Chaves *et al.*, 2009). Under these conditions, over-production of reactive oxygen species (ROS) causes oxidative damage in the cell (Shigeoka *et al.*, 2002), while several enzymes that play important roles in the metabolism of ROS, such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase, monodehydroascorbate reductase, dehydroascorbate reductase, glutathione reductase (GR), glutathione *S*-transferase, glutathione peroxidase (GPX) and peroxidases (POD), show lower activity (Shigeoka *et al.*, 2002; Hasanuzzaman *et al.*, 2012). In this regard, Pandey *et al.* (2010) reported that *A. sterilis* plants exhibit drought-stress tolerance by displaying a high POD activity.

Cynodon dactylon (L.) Pers. (Bermuda grass) is a perennial weed listed as one of the ten most notorious weeds in the world, although it also used as a turf grass for landscaping purposes (Holm *et al.*, 1997; Shi *et al.*, 2012). According to Shi *et al.* (2012), *C. dactylon* plants display a range of mechanisms to withstand drought stress, including the control of water loss from leaves, accumulation of osmolytes (proline and soluble sugars) and the regulation of ROS via antioxidant enzymes (SOD, CAT, POD, GR and GPX). Production of molecular chaperones (i.e. heat shock protein 70; HSP70) by *C. dactylon* plants in response to drought has been reported by Shi *et al.* (2014) and Ye *et al.* (2015). Moreover, it is important to highlight a particular mechanism of drought resistance here, which is observed in *Portulaca oleracea* L. plants (common purslane). This species uses the C4 carbon fixation pathway, but under conditions of water stress shifts its photosynthetic process to crassulacean acid metabolism, which allows the plants to close their stomata during the day and open them at night in order to retain water (Lara *et al.*, 2003, 2004).

Drought and endophytes

Several winter grass weeds, such as *Briza*, *Bromus* and *Poa*, are infected by fungal symbionts, *Epichloë*/*Neotyphodium* endophytes, which grow asymptomatically in the intercellular spaces of the tissues of the aerial parts of these weeds (Iannone *et al.*, 2011). *Lolium rigidum* and *L. multiflorum* Lam. (Italian ryegrass) are two important and commonly found weeds in areas cultivated with cereal crops that infected by the endophytic fungus, *Neotyphodium occultans* (Yamashita *et al.*, 2010; Kirkby *et al.*, 2011), while *L. perenne* L. (perennial ryegrass) is also infected by the fungal endophyte species, *N. lolii* (Kane, 2011). Recently, Leuchtmann *et al.* (2014) recommended the reassignment of *Neotyphodium* species to the *Epichloë* genus with the exception of two species, *Acremonium chilense* and *N. starrii*.

The symbiosis of grasses with fungal endophytes helps the former alleviate the effects of drought stress (Kane, 2011), while also improving their establishment, competitiveness and invasiveness (Yamashita *et al.*, 2010; Casas *et al.*, 2016). The infection of cool grasses with endophytes induces a range of adaptation mechanisms to drought stress, such as control of transpiration, improvement of water uptake due to a greater and deeper root system, and osmotic adjustment via the synthesis of various solutes (Malinowski and Belesky, 2000). Loline alkaloids (i.e. *N*-formylloline *N*-acetyllolin) have been identified in various endophyte-infected grasses (Schardl *et al.*, 2007; Adhikari *et al.*, 2016) and are known to play a significant role in drought tolerance of plants (Malinowski and Belesky, 2000; Schardl *et al.*, 2004).

Seed dormancy and soil moisture

The persistence of weed seeds in soil is a key factor that affects the density and competitiveness of weeds within a field (Efthimiadou *et al.*, 2009). The environmental conditions during seed development and maturation of maternal plants have been reported as factors that affect seed dormancy (Swain *et al.*, 2006; Hoyle *et al.*, 2008). According to Swain *et al.* (2006), the seeds of *Alopecurus myosuroides* Huds. (blackgrass) plants grown under warm and dry conditions were less dormant than those of plants grown under cool and wet conditions. Steadman *et al.* (2004) also reported that seeds of *L. rigidum* Gaud. (annual ryegrass) developed at warm temperatures were also less dormant than those produced at low temperatures. Similar results were obtained by Figueroa *et al.* (2010), who found that the seeds of *Senecio vulgaris* L. (common groundsel) plants grown under cold conditions were more dormant as compared with those grown under warm conditions and which showed no dormancy.

Soil moisture in the maternal environment during seed development also affects the dormancy level of seeds. Wright *et al.* (1999) observed that seeds from *Sinapis arvensis* L. (wild mustard) plants subjected to water at 70% field capacity (FC) were more dormant than those from the plants subjected to water at 10% FC. Similar to these results, Luzuriaga *et al.* (2006) found that the provision of water in the maternal environment significantly reduced seed germination rate in *S. arvensis*, probably due to a higher dormancy level of the seeds.

In summary, the environmental conditions, particularly soil moisture and air temperature, during seed development in maternal plants of several weed species significantly affect the seed dormancy level; warm dry conditions have a positive effect on the germination rate of weed seeds, mostly due to lack of dormancy.

Allelopathy and drought

The allelopathic ability of weeds enhances their competitiveness against crops, while allelochemical production is influenced by both genetic and environmental factors (Qasem and Foy, 2001). Usually, water stress enhances the production of allelochemicals in several weed species, such as *A. theophrasti* Medic. (velvetleaf), *Datura stramonium* L. (jimsonweed) and *Xanthium italicum* Mor. (cocklebur; Borbély and Dávid, 2008; Dávid and Borbély, 2009).

Cyperus rotundus L. (purple nutsedge) is one of the most noxious weed species worldwide, which exhibits considerable allelopathic activity against vegetable crops due to its ability to release allelochemicals (i.e. alkaloids and phenolic acids) from its root system, while tolerating adverse environmental conditions (Dhima *et al*., 2016; Peerzada, 2017). Other important weed species that present significant allelopathic activity against various crops are *A. retroflexus*, *Chenopodium album* L. (fat-hen), *Cirsium arvense* (L.) Scop. (creeping thistle), *C. dactylon*, *Papaver rhoeas* L. (corn poppy), *Solanum nigrum* L. (black nightshade) and *Xanthium strumarium* L. (cocklebur) (Qasem and Hill, 1989; Tanveer *et al*., 2008; Rezaie and Yarnia, 2009; Ravlić, 2016).

Vegetables' production in an environment with changing climate

Any changes in environmental conditions are expected to significantly affect crop physiology and growth, yield, product quality and pesticide behaviour. However, the overall effects of climate change on agriculture depend on the extent of temperature increase, total rainfall and distribution in a region, the severity and frequency of storms and droughts, and the changes in plant × pathogens, plant × pests and plant × weeds interactions (IPCC, 2007; Siikamäki 2008). A brief overview of the effects of climate change on open-field vegetable production is presented in this section.

Overall, changes in temperatures and precipitation, as well as the limited availability of irrigation water and increased hailstorms and thunderstorms, are likely to affect vegetable yield significantly (Prasad and Chakravorty, 2015). In the current century, an increase of 1.6 ± 0.27 °C in mean temperature is predicted in the Mediterranean region (Saadi *et al*., 2015). Moreover, the distribution of precipitation will vary significantly throughout the year, as well as between several countries of Southern Europe; however, in most of these countries, a decline in precipitation is also expected (Olesen *et al*., 2011; Saadi *et al*., 2015). These changes in environmental conditions may affect vegetable production significantly, particularly production of spring crops, because of high temperatures and drought stress. For example, Ventrella *et al*. (2012) reported that in the future climatic scenarios, an increase of air temperatures in the range of 2–5 °C may occur, which will decrease tomato yields in Italy. In addition, in areas that are suitable for open-field cultivation of tomato, yield is predicted to decline because of increased temperatures and drought stress (Silva *et al*., 2017). Moreover, high temperatures have been found to increase the length of the life-cycle of broccoli due to decreased developmental and growth rates, which result in delayed flowering (Lindemann-Zutz *et al*., 2016). Root development may also be affected by elevated soil temperatures due to alterations in several root functions (nutrient uptake, respiration, etc.) and architectural parameters (length and lateral root number, root branching) (Gray and Brady, 2016).

Rising temperatures also affect vegetable quality negatively by affecting photosynthetic processes, such as the time taken for photoassimilation and the biosynthesis of sugars, organic acids and phenolic compounds (Mattos *et al*., 2014; Bisbis *et al*., 2018). Furthermore, according to Potts *et al*. (2010) and Nielsen *et al*. (2017), a declining trend has already been observed in domesticated and wild pollinator species in Europe and other parts of the world; climatic changes have been reported as potential drivers of the reduction in pollinator species. Such changes can, therefore, indirectly affect vegetable production by affecting their respective pollinators (Prasad and Chakravorty, 2015).

It should also be emphasized that decreasing soil moisture levels due to climatic change may lead to an increased persistence of herbicides, and thus, may lead to herbicide carryover to following crops, causing severe problems. It is well known that residues of soil-applied herbicides (i.e. sulphonylureas, triketones and imidazolinones) can cause severe damage to various vegetables, whereas according to Rahman *et al*. (2011), herbicide persistence is influenced by soil type and other environmental conditions (moisture, temperature). Ball *et al*. (2003) observed that reduced soil moisture leads to a decline in imazamox degradation, while Wang *et al*. (2007) reported that an increase in soil moisture enhances microbial activity, as well as metsulphuron-methyl degradation. In other research, increased soil temperatures are reported to enhance herbicide dissipation via hydrolysis (Grey and McCullough, 2012). In this regard, Bailey (2004) asserted that the duration of isoproturon efficacy against weeds declined by 25% in the UK over the period from 1980 to 2001 due to an increase in soil temperature. Consequently, the degradation of herbicides in soil is a complex process; the prediction of herbicide persistence in soil under the expected climate change scenarios of the future will provide useful information to help avoid crop damage by herbicide residues.

Effects of climate change on weed distribution and vegetable–weed competition in Southern Europe

Climate change is already occurring in Europe. Based on climate data from 1900 to 2005, rainfall has been increasing significantly in Northern Europe, while a decline has been witnessed in the Mediterranean region. By the end of the current century, a global temperature increase between 1.1 and 6.4 °C is predicted to occur under different climate scenarios (IPCC, 2007). Weiß *et al*. (2007) reported that in the imminent future, incidences of drought are expected to increase by ten times in Southern Europe. If these projections are realized, it is anticipated that significant changes in weed flora composition and distribution will take place throughout Europe (Fig. 3) and other parts of the globe (McDonald *et al*., 2009; Castellanos-Frías *et al*., 2016). Predicting weed invasion in a specific region undergoing climate change is a major challenge (Clements and DiTommaso, 2012). The spread of some weed species over new areas has already been recorded. Recently, Clements and DiTommaso (2012) reported that several weed species have already expanded from the United States into Canada, while in Europe, climatic change during recent decades have already altered the weed flora in arable ecosystems (Peters *et al*., 2014).

Irrespective of weed species, the projections about their geographical distribution under future climate conditions provide useful information for their early detection and management. For instance, Castellanos-Frías *et al*. (2016) reported that the geographic distribution of *L. rigidum* in Europe is expected to change, expanding to regions that are currently too cold for its survival but may not be in the near future. According to Castellanos-Frías *et al*. (2016), suitable regions in Europe for this weed species are predicted to increase by 108.7 or 167.3% depending on different climate change scenarios. Climate change can also influence the geographical distribution of crops and their losses caused by *A. myosuroides*. The effect of this weed on crop production has been projected to decline in regions where climate scenarios expected in the future predict more frequent periods of drought, whereas the diffusion of this weed is expected to increase from areas with higher temperatures to areas with lower temperatures (Stratonovitch *et al*., 2012). Castellanos-Frías *et al*. (2014) reported that future environmental conditions may favour the

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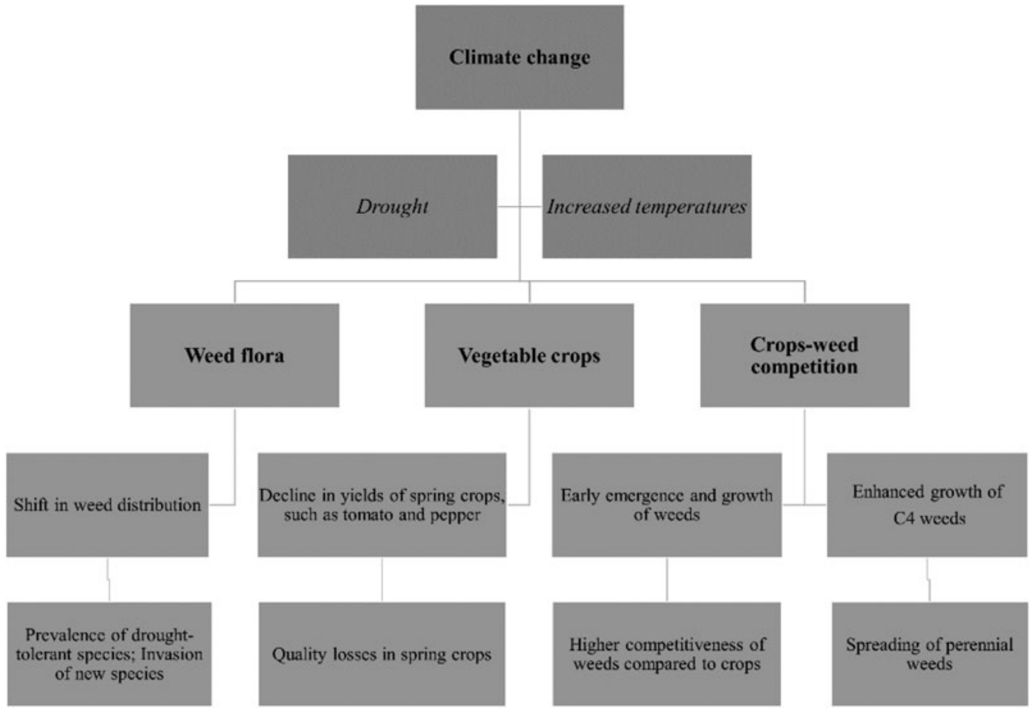

Fig. 3. Main effects of climate change on weed flora, vegetable production, and crop–weed competition in Southern Europe.

spread of *A. sterilis* to Central and Northern Europe, while certain areas of the Mediterranean region may become unsuitable for its survival. Therefore, in Southern Europe, the winter weed species that are favoured by high soil moisture may spread to more suitable areas in the north, while its effect on winter pulses, cereals and vegetables that are commonly cultivated in the region is expected to decline.

Furthermore, climate change may favour the spread of drought-resistant perennial or spring weed species mentioned in previous sections of the current review; therefore, the negative effect of these weeds on crop production is projected to increase in southern Europe. Indeed, the present distribution of *S. elaeagnifolium* in several countries of southern Europe reveals the risk of further spread of the species to be noteworthy (Mekki, 2007). Moreover, rising temperatures are expected to enhance the early growth of *D. stramonium* as, according to Jursík *et al.* (2004), its minimum germination temperature is approximately 20 °C, while its optimum germination occurs at high temperatures of about 30 °C. These temperature requirements of *D. stramonium* seed germination prevent its earlier emergence at the ongoing temperatures in the regions (Cavero *et al.*, 1999).

The projection of yield losses for vegetable crops due to weed competition under future climate conditions is also a challenge. It is important to point out once again that vegetable crops are more vulnerable to drought and increased temperatures due to their high water requirements and high water content. Moreover, crop–weed competition is a complex process that is influenced by several factors, including soil properties, environmental conditions, cultural practices and crop–weed competitiveness (Bilalis *et al.*, 2009; Efthimiadou *et al.*, 2009; Valerio *et al.*, 2013). Drought-tolerant weed species may have a major effect on vegetable crops, making early management of these species necessary in the future (Table 1). Rodenburg *et al.* (2011) reported that under conditions of drought and high temperatures, weed species with the C4 carbon fixation pathway will adapt better, thereby having a competitive advantage over C3 crop plants that use the C3 carbon fixation pathway in the photosynthesis process. Similarly, Hyvönen (2011) speculated that rising temperatures will enhance the growth of C4 weeds, such as *A. retroflexus*, while Zand *et al.* (2006) observed that drought stress had a more negative effect on the competitiveness of *C. album* (C3 weed) compared with *A. retroflexus* (C4 weed). Regarding the effect of these conditions on crop–weed competition, Valerio *et al.* (2013) concluded that yield losses during processing of tomatoes from weeds were greater under drought conditions. These results are related to the greater ability of weeds to adapt to drought stress than the vegetable crops (Korres *et al.*, 2016). Similarly, Lovelli *et al.* (2010*b*) reported *A. retroflexus* to be more drought-resistant than pepper by exhibiting significant competition with this crop for water. Therefore, under drought conditions, weed control in pepper crop is more critical in order to achieve high yields (Lovelli *et al.*, 2013). Several other vegetables similarly exhibit lower competitiveness against weeds than field crops, such as maize and sunflower that have more vigorous early growth, higher leaf area and a deeper root system. It is important to highlight that the available herbicides for use on vegetable crops are limited in comparison with those for field crops, where pendimethalin is the major herbicide registered for control of grass and broad-leaved weeds in several vegetable crops, such as tomato, pepper, eggplant, cabbage, cauliflower, broccoli, leek, onion and parsley. Thus, timely weed control is pivotal for obtaining high yields, as well as for reducing the overall cost of weed management in vegetable crops. Moreover, the need for development of new herbicides that are suitable for vegetable crops is extremely important to achieve adequate weed control and to eradicate troublesome and noxious weeds, such as *D. stramonium*, *P. oleracea*, *S. nigrum*, *X. strumarium*, *C. dactylon*, *C. rotundus*, *S. halepense* and *S. elaeagnifolium*, which are projected

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Table 1. Adaptation mechanisms to drought and high temperatures in different weed species commonly found in Southern Europe

Adaptation mechanisms	Scientific name	Common name	References
Senesce of oldest leaves and change in leaf orientation	Velvetleaf	*Abutilon theophrasti*	Schmidt *et al.* (2011)
			Karkanis *et al.* (2011)
Deep root system	Silverleaf nightshade	*Solanum elaeagnifolium*	Mekki (2007)
	Field bindweed	*Convolvulus arvensis*	Sosnoskie and Hanson (2016)
Increased leaf epicuticular wax	Velvetleaf	*A. theophrasti*	Hatterman-Valenti *et al.* (2011)
Well-developed palisade parenchyma	Squirting cucumber	*Ecballium elaterium*	Christodoulakis *et al.* (2011)
	Silverleaf nightshade	*S. elaeagnifolium*	Christodoulakis *et al.* (2009)
Shortened life cycle	Wild oat	*Avena sterilis*	Volis (2009)
	Wild barley	*Hordeum spontaneum*	Volis *et al.* (2004)
	Velvetleaf	*A. theophrasti*	Karkanis *et al.* (2011)
Closure of stomata and lower stomatal conductance	Velvetleaf	*A. theophrasti*	Karkanis *et al.* (2011)
			Schmidt *et al.* (2011)
	Common purslane	*Portulaca oleracea*	Lara *et al.* (2003, 2004)
			Karkanis and Petropoulos (2017)
Allocation of solutes to roots	*Broadleaf dock*	*Rumex obtusifolius*	Gilgen and Feller (2013)
Osmolytes accumulation	Bermuda grass	*Cynodon dactylon*	Shi *et al.* (2012)
Synthesis of heat-shock proteins (HSPs)			Shi *et al.* (2014)
			Ye *et al.* (2015)
ROS regulation via antioxidant enzymes	Wild oat	*A. sterilis*	Pandey *et al.* (2010)
	Bermuda grass	*C. dactylon*	Shi *et al.* (2012)

to be more competitive under future climate conditions. Furthermore, according to Duke (2012), for almost two decades, no herbicide with a new mode of action has been introduced because of the increased cost of herbicide discovery and development. For the above-mentioned reasons, there is a growing need for new herbicides, especially for use in vegetable crops that are expected to be more vulnerable to weeds in the near future.

In southern Europe, climate change is predicted to result in warmer winters. Rising temperatures may have a positive effect on weed growth, giving them an advantage in comparison with crops (Tungate *et al.*, 2007). In this regard, Wolfe *et al.* (2018) reported that warmer winters can lead to increased weed pressure. Indeed, a long-term study conducted in Denmark during the period of 1987–1989 to 2001–2004 revealed that changes in environmental conditions (e.g. increased temperatures and rainfall levels) favour crop production, while the frequency of occurrence of several weed species increases (Andreasen and Stryhn, 2012). Moreover, the base temperatures for shoot growth in *A. myosuroides* and *G. aparine* plants are 0.8 and −1.4 °C, respectively (Storkey and Cussans, 2000). Considering that the critical temperatures for growth of several winter species are significantly low, it can be concluded that warmer winter temperatures will enhance their competitive ability against winter vegetable crops, particularly during the early growth stages. This is emphasized in the work of Mealor *et al.* (2012), who found that the rise in spring temperatures enhanced early growth of *Bromus tectorum* L. (downy brome), while the frequency of its occurrence increased by 36% over a 5-year-long experiment. Ultimately, knowledge of the growth patterns of weeds during their early growth stages will prove to be a valuable decision support tool for weed management (Royo-Esnal *et al.*, 2012).

Crop adaptation to climate change – future prospects

Under the projected future climate conditions, a multi-step approach must be implemented in order to minimize the negative effects of weeds on crop production. Firstly, it is important to develop maps predicting the geographical distribution of weeds under the expected climate change scenarios for specific areas (Chauhan *et al.*, 2017). Secondly, extended trials should be conducted in order to evaluate the effect of extreme or increased temperatures and water stress on crop–weed competition, while combined effects of elevated CO_2, increased temperatures and drought on weed and crop growth should also be examined. Moreover, studying the phenomenon of climate change can help understand the complex effects of climate change on weed-crop interference; in this context, it is also important to develop weed management strategies that are adapted to the expected future environmental conditions (Hayman and Sadras, 2006).

The adaptation of cultural practices (i.e. planting and sowing dates) to changing environmental conditions can help minimize the effect of climate change on crop production (Debaeke *et al.*, 2017; Wiréhn, 2018). Under future climate scenarios, the discovery and development of new herbicides could make a significant contribution to the reduction of negative effects of weeds on crop production. It has furthermore been suggested that breeding of cultivars with improved stress tolerance (Chen *et al.*, 2012) and enhanced competitiveness could help mitigate the negative effects of climate change on vegetable production (Korres *et al.*, 2016). In this context, screening for drought tolerance and yield stability under stress conditions is pivotal for crop production, as well as a key step for the development of drought-tolerant cultivars (Cicevan *et al.*, 2016; Ganança *et al.*, 2018). Finally, raising awareness among farmers regarding the effect of climate change on crop production is extremely important (Thi Lan Huong *et al.*, 2017), as some farmers consider climate change to be significant for their farming practices, while others do not believe in its occurrence (Takahashi *et al.*, 2016).

Conclusions

Several commonly found weeds in Southern Europe exhibit great potential to adapt to drought conditions and increased temperatures. Under future climate scenarios, the prediction of weed invasion in a specific region and the spread of weed species over new areas is a major challenge. In southern Europe, weed species that are favoured by high soil moisture may be spread over new areas to the north and their negative effects on vegetable production in these areas are thus expected to increase. Moreover, C4 weed species will be better adapted to future climate conditions; therefore, they will be more competitive in comparison with C3 weeds and crops. In addition, increasing temperatures can enhance the early growth of several weed species, giving them an advantage over vegetable crops. Accordingly, adaptation of cultural systems to these environmental conditions will be crucial in terms of minimizing the negative effects of climate change on crop production.

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References

Acikgoz FE (2011) Potential effects of global climate changes on field vegetable growing in the Thrace region. *Journal of Environmental Protection and Ecology* **12**, 240–244.

Adhikari KB, Boelt B and Fomsgaard IS (2016) Identification and quantification of loline-type alkaloids in endophyte-infected grasses by LC-MS/MS. *Journal of Agricultural and Food Chemistry* **64**, 6212–6218.

Andreasen C and Stryhn H (2012) Increasing weed flora in Danish beet, pea and winter barley fields. *Crop Protection* **36**, 11–17.

Bahl PN (2015) Climate change and pulses: approaches to combat its impact. *Agricultural Research* **4**, 103–108.

Bailey SW (2004) Climate change and decreasing herbicide persistence. *Pest Management Science* **60**, 158–162.

Ball DA, Yenish JP and Alby T (2003) Effect of imazamox soil persistence on dryland rotational crops. *Weed Technology* **17**, 161–165.

Bilalis D, Karkanis A and Efthimiadou A (2009) Effects of two legume crops, for organic green manure, on weed flora, under Mediterranean conditions: competitive ability of five winter season weed species. *African Journal of Agricultural Research* **4**, 1431–1441.

Bisbis MB, Gruda N and Blanke M (2018) Potential impacts of climate change on vegetable production and product quality – a review. *Journal of Cleaner Production* **170**, 1602–1620.

Borbély M and Dávid I (2008) Changeability of allelopathy depending on several factors. *Cereal Research Communications* **36**, 1383–1386.

Casas C, Gundel PE, Semmartin M, Schnyder H and Omacini M (2016) The enhancement of invasion ability of an annual grass by its fungal endophyte depends on recipient community structure. *Biological Invasions* **18**, 1853–1865.

Castellanos-Frías E, García De Leõn D, Pujadas-Salva A, Dorado J and Gonzalez-Andujar JL (2014) Potential distribution of *Avena sterilis* L. in Europe under climate change. *Annals of Applied Biology* **165**, 53–61.

Castellanos-Frías E, Garcia De León D, Bastida F and Gonzalez-Andujar JL (2016) Predicting global geographical distribution of *Lolium rigidum* (rigid ryegrass) under climate change. *Journal of Agricultural Science* **154**, 755–764.

Cavero J, Zaragoza C, Suso ML and Pardo A (1999) Competition between maize and *Datura stramonium* in an irrigated field under semi-arid conditions. *Weed Research* **39**, 225–240.

Chauhan BS, Matloob A, Mahajan G, Aslam F, Florentine SK and Jha P (2017) Emerging challenges and opportunities for education and research in weed science. *Frontiers in Plant Science* **8**, article no. 1537, 1–13. doi: 10.3389/fpls.2017.01537.

Chaves MM, Flexas J and Pinheiro C (2009) Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. *Annals of Botany* **103**, 551–560.

Chen CC, McCarl B and Chang CC (2012) Climate change, sea level rise and rice: global market implications. *Climatic Change* **110**, 543–560.

Christodoulakis NC, Lampri PN and Fasseas C (2009) Structural and cytochemical investigation of the leaf of silverleaf nightshade (*Solanum elaeagnifolium*), a drought-resistant alien weed of the Greek flora. *Australian Journal of Botany* **57**, 432–438.

Christodoulakis NS, Kollia K and Fasseas C (2011) Leaf structure and histochemistry of *Ecballium elaterium* (L.) A. Rich. (squirting cucumber). *Flora – Morphology, Distribution, Functional Ecology of Plants* **206**, 191–197.

Cicevan R, Al Hassan M, Sestras AF, Prohens J, Vicente O, Sestras RE and Boscaiu M (2016) Screening for drought tolerance in cultivars of the ornamental genus *Tagetes* (asteraceae). *PeerJ* **4**, article no. e2133, 1–20. Available at https://doi.org/10.7717/peerj.2133.

Clements DR and DiTommaso A (2012) Predicting weed invasion in Canada under climate change: evaluating evolutionary potential. *Canadian Journal of Plant Science* **92**, 1013–1020.

Cline WR (2007) *Global Warming and Agriculture: Impact Estimates by Country*. Washington, DC, USA: Center for Global Development and Peterson Institute for International Economics.

Dávid I and Borbély M (2009) Effects of some stress factors on allelopathy. *Cereal Research Communications* **37**(suppl. 1), 313–316.

Dawson TP, Perryman AH and Osborne TM (2016) Modelling impacts of climate change on global food security. *Climatic Change* **134**, 429–440.

Debaeke P, Casadebaig P, Flenet F and Langlade N (2017) Sunflower crop and climate change: vulnerability, adaptation, and mitigation potential from case-studies in Europe. *OCL-Oilseed & Fats Crops Lipids* **24**, article no. D102, 1–15. Available at https://doi.org/10.1051/ocl/2016052.

Dhima K, Vasilakoglou I, Stefanou S, Gatsis T, Paschalidis K, Aggelopoulos S and Eleftherohorinos I (2016) Differential competitive and allelopathic ability of *Cyperus rotundus* on *Solanum lycopersicum*, *Solanum melongena* and *Capsicum annuum*. *Archives of Agronomy and Soil Science* **62**, 1250–1263.

Duke SO (2012) Why have no new herbicide modes of action appeared in recent years? *Pest Management Science* **68**, 505–512.

Efthimiadou AP, Karkanis AC, Bilalis DJ and Efthimiadis P (2009) The phenomenon of crop–weed competition; a problem or a key for sustainable weed management? *Journal of Food, Agriculture & Environment* **7**, 861–868.

Evangelista P, Young N and Burnett J (2013) How will climate change spatially affect agriculture production in Ethiopia? Case studies of important cereal crops. *Climatic Change* **119**, 855–873.

FAO, IFAD, UNICEF, WFP and WHO (2017) *The State of Food Security and Nutrition in the World 2017. Building Resilience for Peace and Food Security*. Rome, Italy: FAO. Available at http://www.fao.org/3/a-I7695e.pdf (Accessed 11 January 2019).

Figueroa R, Herms DA, Cardina J and Doohan D (2010) Maternal environment effects on common groundsel (*Senecio vulgaris*) seed dormancy. *Weed Science* **58**, 160–166.

Gammans M, Mérel P and Ortiz-Bobea A (2017) Negative impacts of climate change on cereal yields: statistical evidence from France. *Environmental Research Letters* **12**, article no. 054007, 1–9. Available at https://doi.org/10.1088/1748-9326/aa6b0c.

Ganança JFT, Freitas JGR, Nóbrega HGM, Rodrigues V, Antunes G, Gouveia CSS, Rodrigues M, Chaïr H, Pinheiro De Carvalho MAA and Lebot V (2018) Screening for drought tolerance in thirty three taro cultivars. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **46**, 65–74.

Gargallo-Garriga A, Sardans J, Pérez-Trujillo M, Rivas-Ubach A, Oravec M, Vecerova K, Urban O, Jentsch A, Kreyling J, Beierkuhnlein C, Parella T and Peñuelas J (2014) Opposite metabolic responses of shoots and roots to drought. *Scientific Reports* **4**, article no. 6829, 1–7. Available at https://doi.org/10.1038/srep06829.

Gilgen AK and Feller U (2013) Drought stress alters solute allocation in broadleaf dock (*Rumex obtusifolius*). *Weed Science* **61**, 104–108.

Gilgen AK and Feller U (2014) Effects of drought and subsequent rewatering on *Rumex obtusifolius* leaves of different ages: reversible and irreversible damages. *Journal of Plant Interactions* **9**, 75–81.

Gray SB and Brady SM (2016) Plant developmental responses to climate change. *Developmental Biology* **419**, 64–77.

Grey TL and McCullough PE (2012) Sulfonylurea herbicides' fate in soil: dissipation, mobility, and other processes. *Weed Technology* **26**, 579–581.

Hasanuzzaman M, Hossain MA, da Silva JAT and Fujita M (2012) Plant response and tolerance to abiotic oxidative stress: antioxidant defense is a key factor. In Venkateswarlu B, Shanker A, Shanker C and Maheswari M (eds), *Crop Stress and its Management: Perspectives and Strategies*. Dordrecht, the Netherlands: Springer, pp. 261–315.

Hasanuzzaman M, Nahar K, Alam M, Roychowdhury R and Fujita M (2013) Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. *International Journal of Molecular Sciences* **14**, 9643–9684.

Hatterman-Valenti H, Pitty A and Owen M (2011) Environmental effects on velvetleaf (*Abutilon theophrasti*) epicuticular wax deposition and herbicide absorption. *Weed Science* **59**, 14–21.

Hayman P and Sadras V (2006) Climate change and weed management in Australian farming systems. In Preston C, Watts JH and Crossman ND (eds), *Proceeding of the 15th Australian Weeds Conference: Managing Weeds in a Changing Climate*. Torrens Park, SA, Australia: Weed Management Society of South Australia, pp. 22–26.

Heschel MS, Sultan SE, Glover S and Sloan D (2004) Population differentiation and plastic responses to drought stress in the generalist annual *Polygonum persicaria*. *International Journal of Plant Sciences* **165**, 817–824.

Holm LG, Plucknett DL, Pancho JV and Herberger JP (1977) *The World's Worst Weeds. Distribution and Biology*. Honolulu, USA: University of Hawaii Press.

Hoyle GL, Steadman KJ, Daws MI and Adkins SW (2008) Pre- and post-harvest influences on seed dormancy status of an Australian Goodeniaceae species, *Goodenia fascicularis*. *Annals of Botany* **102**, 93–101.

Hyvönen T (2011) Impact of temperature and germination time on the success of a C4 weed in a C3 crop: *Amaranthus retroflexus* and spring barley. *Agricultural and Food Science* **20**, 183–190.

Iannone LJ, White Jr JF, Giussani LM, Cabral D and Novas MV (2011) Diversity and distribution of *Neotyphodium*-infected grasses in Argentina. *Mycological Progress* **10**, 9–19.

IPCC (2007) *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K. and Reisinger, A. (eds.)]. Geneva, Switzerland: IPCC.

Jursík M, Holec J and Tyser L (2004) Biology and control of sugar beet significant weeds-Jimson weed (*Datura stramonium* L.). *Listy Cukrovarnické a Řepařské* **120**, 300–302.

Kane KH (2011) Effects of endophyte infection on drought stress tolerance of *Lolium perenne* accessions from the Mediterranean region. *Environmental and Experimental Botany* **71**, 337–344.

Karkanis A, Bilalis D and Efthimiadou A (2011) Architectural plasticity, photosynthesis and growth responses of velvetleaf (*Abutilon theophrasti* Medicus) plants to water stress in a semi-arid environment. *Australian Journal of Crop Science* **5**, 369–374.

Karkanis A, Bilalis D, Efthimiadou A and Katsenios N (2012) The critical period for weed competition in parsley (*Petroselinum crispum* (Mill.) Nyman ex A.W. Hill) in Mediterranean areas. *Crop Protection* **42**, 268–272.

Karkanis AC and Petropoulos SA (2017) Physiological and growth responses of several genotypes of common purslane (*Portulaca oleracea* L.) under Mediterranean semi-arid conditions. Notulae Botanicae Horti Agrobotanici Cluz-Napoca **45**, 569–575.

Kirkby KA, Pratley JE, Hume DE, Faville MJ, An M and Wu H (2011) Incidence of endophyte *Neotyphodium occultans* in *Lolium rigidum* from Australia. *Weed Research* **51**, 261–272.

Korres NE, Norsworthy JK, Tehranchian P, Gitsopoulos TK, Loka DA, Oosterhius DM, Gealy DR, Moss SR, Burgos NR, Miller MR and Palhano M (2016) Cultivars to face climate change effects on crops and weeds: a review. *Agronomy for Sustainable Development* **36**, article no. 12, 1–22. doi:10.1007/s13593-016-0350-5.

Lara MV, Disante KB, Podestá FE, Andreo CS and Drincovich MF (2003) Induction of a Crassulacean acid like metabolism in the C4 succulent plant, *Portulaca oleracea* L.: physiological and morphological changes are accompanied by specific modifications in phosphoenolpyruvate carboxylase. *Photosynthesis Research* **77**, 241–254.

Lara MV, Drincovich MF and Andreo CS (2004) Induction of a crassulacean acid-like metabolism in the C4 succulent plant, *Portulaca oleracea* L.: study of enzymes involved in carbon fixation and carbohydrate metabolism. *Plant and Cell Physiology* **45**, 618–626.

Lehner B, Döll P, Alcamo J, Henrichs T and Kaspar F (2006) Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. *Climatic Change* **75**, 273–299.

Leguizamón ES and Acciaresi HA (2014) Climate change and the potential spread of *Sorghum halepense* in the central area of Argentina based on growth, biomass allocation and eco-physiological traits. *Theoretical and Experimental Plant Physiology* **26**, 101–113.

Lemoine R, La Camera S, Attanassova R, Dédaldéchamp F, Allario T, Pourtau N, Bonnemain JL, Laloi M, Coutos-Thévenot P, Maurousset L, Faucher M, Girousse C, Lemonnier P, Parrilla J and Durand M (2013) Source-to-sink transport of sugar and regulation by environmental factors. *Frontiers in Plant Science* **4**, article no. 272, 1–21. doi:10.3389/fpls.2013.00272.

Leuchtmann A, Bacon CW, Schardl CL, White Jr JF and Tadych M (2014) Nomenclatural realignment of *Neotyphodium* species with genus *Epichloë*. *Mycologia* **106**, 202–215.

Lewis K and Witham C (2012) Agricultural commodities and climate change. *Climate Policy* **12**(suppl. 1), S53–S61.

Lindemann-Zutz K, Fricke A and Stützel H (2016) Prediction of time to harvest and its variability in broccoli (*Brassica oleracea* var. *italica*) part I. Plant developmental variation and forecast of time to head induction. *Scientia Horticulturae* **198**, 424–433.

Lovelli S, Perniola M, Ferrara A, Amato M and Di Tommaso T (2010*a*) Photosynthetic response to water stress of pigweed (*Amaranthus retroflexus*) in a Southern-Mediterranean Area. *Weed Science* **58**, 126–131.

Lovelli S, Di Tommaso T, Amato M, Valerio M and Perniola M (2010*b*) Competition between weeds and pepper in Southern Italy. *Italian Journal of Agronomy* **5**, 249–256.

Lovelli S, Perniola M, Scalcione E, Troccoli A and Ziska LH (2012) Future climate change in the Mediterranean area: implications for water use and weed management. *Italian Journal of Agronomy* **7**, 44–49.

Lovelli S, Valerio M, Di Tommaso T and Perniola M (2013) Soil profile water content in pepper crop production as affected by different weed infestation. *Journal of Agronomy* **12**, 122–129.

Luzuriaga AL, Escudero A and Pérez-García F (2006) Environmental maternal effects on seed morphology and germination in *Sinapis arvensis* (Cruciferae). *Weed Research* **46**, 163–174.

Malinowski DP and Belesky DP (2000) Adaptations of endophyte-infected cool-season grasses to environmental stresses: mechanisms of drought and mineral stress tolerance. *Crop Science* **40**, 923–940.

Mattos LM, Moretti CL, Jan S, Sargent SA, Lima CEP and Fontenelle MR (2014) Climate changes and potential impacts on quality of fruit and vegetable crops. In Ahmad P and Rasool S (eds), *Emerging Technologies and Management of Crop Stress Tolerance, Volume 1: Biological Techniques*. San Diego, USA: Elsevier, pp. 467–486.

McDonald A, Riha S, DiTommaso A and DeGaetano A (2009) Climate change and the geography of weed damage: analysis of U.S. maize systems suggests the potential for significant range transformations. *Agriculture, Ecosystem and Environment* **130**, 131–140.

Mealor BA, Cox S and Booth DT (2012) Postfire downy brome (*Bromus tectorum*) invasion at high elevations in Wyoming. *Invasive Plant Science and Management* **5**, 427–435.

Mekki M (2007) Biology, distribution and impacts of silverleaf nightshade (*Solanum elaeagnifolium* Cav.). *Bulletin OEPP/EPPO Bulletin* **37**, 114–118.

Nastis SA, Michailidis A and Chatzitheodoridis F (2012) Climate change and agricultural productivity. *African Journal of Agricultural Research* **7**, 4885–4893.

Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, Zhu T, Ringler C, Msangi S, Palazzo A, Batka M, Magalhaes M, Valmonte-Santos R, Ewing M and Lee D (2009) *Climate Change: Impact on Agriculture and Costs of Adaptation*. Washington, DC, USA: International Food Policy Research Institute.

Neve P, Vila-Aiub M and Roux F (2009) Evolutionary-thinking in agricultural weed management. *New Phytologist* **184**, 783–793.

Nielsen A, Reitan T, Rinvoll AW and Brysting AK (2017) Effects of competition and climate on a crop pollinator community. *Agriculture, Ecosystems and Environment* **246**, 253–260.

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J and Micale F (2011) Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy* **34**, 96–112.

Pandey HC, Baig MJ, Chandra A and Bhatt RK (2010) Drought stress induced changes in lipid peroxidation and antioxidant system in genus *Avena*. *Journal of Environmental Biology* **31**, 435–440.

Paul F (2011) Sea-level rise: melting glaciers and ice caps. *Nature Geoscience* **4**, 71–72.

Peerzada AM (2017) Biology, agricultural impact, and management of *Cyperus rotundus* L.: the world's most tenacious weed. *Acta Physiologiae Plantarum* **39**, article no. 270, 1–14. doi: https://doi.org/10.1007/s11738-017-2574-7.

Peters K, Breitsameter L and Gerowitt B (2014) Impact of climate change on weeds in agriculture: a review. *Agronomy for Sustainable Development* **34**, 707–721.

Plesa IM, González-Orenga S, Al Hassan M, Sestras AF, Vicente O, Prohens J, Sestras RE and Boscaiu M (2018) Effects of drought and salinity on European Larch (*Larix decidua* Mill.) seedlings. *Forests* **9**, article no. 3201, 1–18. Available at https://doi.org/10.3390/f9060320.

Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O and Kunin WE (2010) Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution* **25**, 345–353.

Prasad BVG and Chakravorty S (2015) Effects of climate change on vegetable cultivation-a review. *Nature Environment and Pollution Technology* **14**, 923–929.

Qasem JR and Foy CL (2001) Weed allelopathy, its ecological impacts and future prospects. *Journal of Crop Production* **4**, 43–119.

Qasem JR and Hill TA (1989) Possible rôle of allelopathy in the competition between tomato, *Senecio vulgaris* L. and *Chenopodium album* L. *Weed Research* **29**, 349–356.

Rahman A, James TK, Trolove MR and Dowsett C (2011) Factors affecting the persistence of some residual herbicides in maize silage fields. *New Zealand Plant Protection* **64**, 125–132.

Raper SCB and Braithwaite RJ (2006) Low sea level rise projections from mountain glaciers and icecaps under global warming. *Nature* **439**, 311–313.

Ravlić M (2016) Allelopathic effects of some plant species on growth and development of crops and weeds. *Poljoprivreda* **22**, 53–57.

Reif A, Xystrakis F, Gärtner S and Sayer U (2017) Floristic change at the drought limit of European Beech (*Fagus sylvatica* L.) to Downy Oak (*Quercus pubescens*) forest in the temperate climate of Central Europe. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **45**, 646–654.

Rezaie F and Yarnia M (2009) Allelopathic effects of *Chenopodium album*, *Amaranthus retroflexus* and *Cynodon dactylon* on germination and growth of safflower. *Journal of Food, Agriculture & Environment* **7**, 516–521.

Rodenburg J, Meinke H and Johnson DE (2011) Challenges for weed management in African rice systems in a changing climate. *Journal of Agricultural Science* **149**, 427–435.

Royo-Esnal A, Torra J, Conesa JA and Recasens J (2012) Emergence and early growth of *Galium aparine* and *Galium spurium*. *Weed Research* **52**, 458–466.

Saadi S, Todorovic M, Tanasijevic L, Pereira LS, Pizzigalli C and Lionello P (2015) Climate change and Mediterranean agriculture: impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield. *Agricultural Water Management* **147**, 103–115.

Schardl CL, Leuchtmann A and Spiering MJ (2004) Symbioses of grasses with seedborne fungal endophytes. *Annual Review of Plant Biology* **55**, 315–340.

Schardl CL, Grossman RB, Nagabhyru P, Faulkner JR and Mallik UP (2007) Loline alkaloids: currencies of mutualism. *Phytochemistry* **68**, 980–996.

Schmidt JJ, Blankenship EE and Lindquist JL (2011) Corn and velvetleaf (*Abutilon theophrasti*) transpiration in response to drying soil. *Weed Science* **59**, 50–54.

Shi H, Wang Y, Cheng Z, Ye T and Chan Z (2012) Analysis of natural variation in bermudagrass (*Cynodon dactylon*) reveals physiological responses underlying drought tolerance. *PLoS ONE* **7**, article no. e53422, 1–12. Available at https://doi.org/10.1371/journal.pone.0053422.

Shi H, Ye T and Chan Z (2014) Comparative proteomic responses of two bermudagrass (*Cynodon dactylon* (L). Pers.) varieties contrasting in drought stress resistance. *Plant Physiology and Biochemistry* **82**, 218–228.

Shigeoka S, Ishikawa T, Tamoi M, Miyagawa Y, Takeda T, Yabuta Y and Yoshimura K (2002) Regulation and function of ascorbate peroxidase isoenzymes. *Journal of Experimental Botany* **53**, Sp. Issue, 1305–1319.

Siikamäki J (2008) Climate change and U.S. Agriculture: examining the connections. *Environment: Science and Policy for Sustainable Development* **50**, 36–49.

Silva RS, Kumar L, Shabani F and Picanço MC (2017) Assessing the impact of global warming on worldwide open field tomato cultivation through CSIRO-Mk3.0 global climate model. *Journal of Agricultural Science* **155**, 407–420.

Sosnoskie LM and Hanson BD (2016) Field bindweed (*Convolvulus arvensis*) control in early and late-planted processing tomatoes. *Weed Technology* **30**, 708–716.

Steadman KJ, Ellery AJ, Chapman R, Moore A and Turner NC (2004) Maturation temperature and rainfall influence seed dormancy characteristics of annual ryegrass (*Lolium rigidum*). *Australian Journal of Agricultural Research* **55**, 1047–1057.

Storkey J and Cussans JW (2000) Relationship between temperature and the early growth of *Triticum aestivum* and three weed species. *Weed Science* **48**, 467–473.

Stratonovitch P, Storkey J and Semenov MA (2012) A process-based approach to modelling impacts of climate change on the damage niche of an agricultural weed. *Global Change Biology* **18**, 2071–2080.

Swain AJ, Hughues ZS, Cook SK and Moss SR (2006) Quantifying the dormancy of *Alopecurus myosuroides* seeds produced by plants exposed to different soil moisture and temperature regimes. *Weed Research* **46**, 470–479.

Takahashi B, Burnham M, Terracina-Hartman C, Sopchak AR and Selfa T (2016) Climate change perceptions of NY state farmers: the role of risk perceptions and adaptive capacity. *Environmental Management* **58**, 946–957.

Tanveer A, Tahir M, Nadeem MA, Younis M, Aziz A and Yaseen M (2008) Allelopathic effects of *Xanthium strumarium* L. on seed germination and seedling growth of crops. *Allelopathy Journal* **21**, 318–328.

Thi Lan Huong N, Shun Bo Y and Fahad S (2017) Farmers' perception, awareness and adaptation to climate change: evidence from northwest Vietnam. *International Journal of Climate Change Strategies and Management* **9**, 555–576.

Travlos IS (2013) Responses of invasive silverleaf nightshade (*Solanum elaeagnifolium*) populations to varying soil water availability. *Phytoparasitica* **41**, 41–48.

Trenberth KE (2018) Climate change caused by human activities is happening and it already has major consequences. *Journal of Energy and Natural Resources Law* **36**, 463–481.

Tungate KD, Israel DW, Watson DM and Rufty TW (2007) Potential changes in weed competitiveness in an agroecological system with elevated temperatures. *Environmental and Experimental Botany* **60**, 42–49.

Valerio M, Lovelli S, Perniola M, Di Tommaso T and Ziska L (2013) The role of water availability on weed-crop interactions in processing tomato for southern Italy. *Acta Agriculturae Scandinavica, Section B: Soil & Plant Science* **63**, 62–68.

Ventrella D, Charfeddine M, Moriondo M, Rinaldi M and Bindi M (2012) Agronomic adaptation strategies under climate change for winter durum wheat and tomato in southern Italy: irrigation and nitrogen fertilization. *Regional Environmental Change* **12**, 407–419.

Volis S (2009) Plasticity, its cost, and phenotypic selection under water and nutrient stress in two annual grasses. *Biological Journal of the Linnean Society* **97**, 581–593.

Volis S, Verhoeven KJF, Mendlinger S and Ward D (2004) Phenotypic selection and regulation of reproduction in different environments in wild barley. *Journal of Evolutionary Biology* **17**, 1121–1131.

Wang H, Liu X, Wu J, Huang P, Xu J and Tang C (2007) Impact of soil moisture on metsulfuron-methyl residues in Chinese paddy soils. *Geoderma* **142**, 325–333.

Ward JK, Tissue DT, Thomas RB and Strain BR (1999) Comparative responses of model C3 and C4 plants to drought in low and elevated CO_2. *Global Change Biology* **5**, 857–867.

Weiß M, Flörke M, Menzel L and Alcamo J (2007) Model-based scenarios of Mediterranean droughts. *Advances in Geosciences* **12**, 145–151.

Wheeler T and Von Braun J (2013) Climate change impacts on global food security. *Science* **341**, 508–513.

Wiréhn L (2018) Nordic agriculture under climate change: a systematic review of challenges, opportunities and adaptation strategies for crop production. *Land Use Policy* **77**, 63–74.

Wolfe DW, DeGaetano AT, Peck GM, Carey M, Ziska LH, Lea-Cox J, Kemanian AR, Hoffmann MP and Hollinger DY (2018) Unique challenges and opportunities for northeastern US crop production in a changing climate. *Climatic Change* **146**, 231–247.

Wright KJ, Seavers GP, Peters NCB and Marshall MA (1999) Influence of soil moisture on the competitive ability and seed dormancy of *Sinapis arvensis* in spring wheat. *Weed Research* **39**, 309–317.

Xu B, Li F, Shan L, Ma Y, Ichizen N and Huang J (2006) Gas exchange, biomass partition, and water relationships of three grass seedlings under water stress. *Weed Biology and Management* **6**, 79–88.

Xu W, Cui K, Xu A, Nie L, Huang J and Peng S (2015) Drought stress condition increases root to shoot ratio via alteration of carbohydrate partitioning and enzymatic activity in rice seedlings. *Acta Physiologiae Plantarum* **37**, article no. 9, 1–11. doi:10.1007/s11738-014-1760-0.

Yamashita M, Iwamoto M, Maruyama K, Ichihara M and Sawada H (2010) Contrasting infection frequencies of *Neotyphodium endophyte* in naturalized Italian ryegrass populations in Japanese farmlands. *Grassland Science* **56**, 71–76.

Ye T, Shi H, Wang Y and Chan Z (2015) Contrasting changes caused by drought and submergence stresses in bermudagrass (*Cynodon dactylon*). *Frontiers in Plant Science* **6**, article no. 951, 1–14. doi: 10.3389/fpls.2015.00951.

Zand E, Soufizadeh S and Eskandari A (2006) Water stress and nitrogen limitation effects on corn (*Zea mays* L.) competition with a C3 and a C4 weed. *Communications in Agricultural and Applied Biological Sciences* **71**, 753–760.

Zhu XC, Wu HW, Stanton R, Burrows GE, Lemerle D and Raman H (2013) Morphological variation of *Solanum elaeagnifolium* in south-eastern Australia. *Weed Research* **53**, 344–354.

Ziska LH and Dukes JS (2011) *Weed Biology and Climate Change*. Ames, IA, USA: Blackwell Publishing Ltd.