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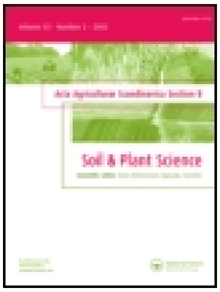

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ORIGINAL ARTICLE

The role of water availability on weed–crop interactions in processing tomato for southern Italy

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Abstract

Anthropogenic climate change is projected to increase the occurrence of drought for the Mediterranean region. The aim of this study was to quantify the role of increasing drought on weed-induced crop losses and crop–weed interactions for processing tomato grown in southern Italy. Field experiments were carried out during 2008 and 2009. Two levels of water availability were imposed to compare weed competitive effects under irrigated and rainfed conditions on tomato as a means to quantify weed–crop interactions and associated crop losses when water is limited. In this study, the absolute decline in tomato yields by weed interference was a direct function of water applied (rain + irrigation); however, the relative effect of weed biomass on crop loss appeared to increase under drought when compared to irrigated conditions. Overall, these data indicate that the relative decline in tomato fresh weight from weeds was actually greater under drought, and that the relative crop losses (per unit of weed biomass) actually declined as water availability increased. From a management standpoint, these data suggest that if drought occurrences do increase in the Mediterranean region with climate change, there may be a greater need for complete and thorough weed control for this production system.

Keywords: *Climate change, gas exchange, leaf water potential,* Lycopersicon esculentum*, stomatal control, water competition.*

Introduction

Anthropogenic climate change is likely to alter weed-crop competition and production losses either directly, through differential responses between crops and weeds to rising carbon dioxide concentration [CO_2] (Ziska, 2010), or indirectly, due to climatic extremes, particularly with respect to precipitation (Ziska & Goins, 2006; IPCC, 2007). Patterson (1995) has suggested that an increase in water availability per se may, if weeds are not managed, increase crop losses, whereas, if water is limited, weed-induced losses would decline. That is, when the crop is limited by water, competition for other resources diminishes and weed-crop competition is reduced. However, recent data on weed competition in wheat (Naidu & Varshney, 2011) has indicated that as CO_2 rises, weed induced crop losses could actually increase if drought occurs. In general, as emphasised by Zimdahl (2004), given the importance of irrigation in crop production and that water availability is likely to be a finite and increasing cost resource in the future, knowing how drought may influence weed induced crop losses is essential, so that land managers can better estimate the need and benefits of appropriate weed management strategies.

Given that the degree and extent of projected anthropogenic changes in temperature and precipitation could have unforeseen consequences for crop production and economic losses (IPCC, 2007), additional information regarding the effect of drought on weed populations is necessary to assess weed limitations on productivity. Projecting climatic outcomes, particularly at regional scales, is difficult; however, the most recent Intergovernmental Panel on Climate Change (IPCC) assessment predicts an

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increase in the occurrence and/or severity of drought as well as rising temperatures for the Mediterranean region (Olesen & Bindi, 2002; IPCC, 2007; Vitale et al., 2010).

Processing tomato (*Lycopersicon esculentum* Miller) is a very significant economic crop in southern Italy, representing approximately 18% of total production (World Processing Tomato Council, 2006) and water availability is recognized as a major restriction to its production (Friesen, 1979; Rinaldi et al., 2007; Favati et al., 2009). For the semi-arid Mediterranean area, the occurrence and severity of droughts may increase with future anthropogenic climatic change, particularly for southern Italy (see Figure 18 in, Giorgi & Lionello, 2008).

Any occurrence and/or increase in drought severity associated with climate change could also influence weed-induced production losses and subsequent weed management for processing tomato. Weed limitations on tomato production are generally recognized as important, but the interaction of weeds and water availability has not been well quantified for this region. Consequently, assessing changing water availability and subsequent impact of weeds on tomato yield is necessary to assess potential crop losses and changes in weed management. Given the degree of climatic uncertainty and the probability of increased droughts for the Mediterranean region (Giorgi & Lionello, 2008), the goal of this study was to quantify the role of water availability on crop–weed interactions and weed-induced crop losses for processing tomato grown in southern Italy. The null hypothesis being no change in weed induced loss as a function of water availability under current cultivation practices.

Materials and methods

The experiment was conducted at the University of Basilicata from May until September in 2008 and again in 2009. The experimental plots were located in southern Italy at latitude 40°00′ N, longitude 16°00′ E and 397 m.a.s.l. The regional climate is typical of the Mediterranean region with hot and dry summers and mild and rainy winters (Giorgi & Lionello, 2008).

The field soil is classified as sandy-clay soil (52.3% sand, 10.6% silt, 37.1% clay) with a moderate chemical fertility. Soil moisture content was 24.2% at field capacity and 17.2% at the theoretical wilting point (determined in the laboratory at -0.03 and -1.5 MPa, respectively). The previous crop was wheat as part of a wheat tomato crop rotation for this region. Herbicides were not used in the previous wheat crop. The tillage operation for processing tomato consisted of land levelling, ploughing and disking according to standard cultural practices.

Tomato (cv. Lungo UG 9233) was used as the experimental crop and is one of the main cultivars grown in southern Italy. Tomato seedlings, approximately 5 weeks old were transplanted into rows at 40 cm intervals with rows 1 m apart on 19 May 2008 and 7 May 2009. The experimental plots were fertilised with a total of 150 kg ha^{-1} of N, 150 kg ha^{-1} of P_2O_5 and 180 kg ha^{-1} of K_2O before sowing and during crop growth by fertigation, for both years. Nutrient distribution by fertigation was made monthly (from May to June), and successively (July) every 10 days. Main plots consisted of six 30 m rows, spaced 1 m apart and were either rainfed (V0) or fully irrigated treatments (V100) (i.e., each main plot was six 15 m rows). Subplot treatments consisted of the presence (weedy) or absence (weed-free) of weed interference, such that weed presence has a random effect over time. Subplots measured 15 m in length by 3 rows wide (3 m). In weed-free plots all emerging weeds were removed by hand or hoe.

For irrigation scheduling, evapotranspiration of the crop (ETc) was calculated as Etc = ETo × Kc, where ETo (reference evapotranspiration) was calculated according to Hargreaves and Samani (1985) and Kc was the crop coefficient of tomato as reported by Allen et al. (1998), adjusted for the environmental conditions as follows: Kc initial = 0.5; Kc midpoint = 1.15; Kc end = 0.8. In the irrigated treatment (V100), 100% of ETc was restored when 40% of total available water was depleted according to the evapotranspiration method of Doorenbos and Pruitt (1977).

A surface drip irrigation system was selected as the irrigation method, with dripping wings placed on each row and "on line" drippers spaced every 20 cm delivering 3 l h^{-1}. Soil water content was measured 68 and 81 days after transplanting tomatoes for 2008 and 2009, respectively, in order to sample at the same phenological stage and determined using the gravimetric method. The soil samples were taken at depths of 0–30 cm and 30–60 cm during each growing season and samples were weighed before and after drying at 105°C for 24 h.

For each year of the study, meteorological data were measured at a weather station placed in a meadow adjacent to the experimental plot. The recorded variables were: rainfall, maximum and minimum air temperature ($T_{\max}$, $T_{\min}$), air humidity, and wind speed; data were acquired every 10 min, averaged and recorded every 30 min by a data logger (Model Sky DataHog2, type SDL5400; Skye, Powys, UK). These data were downloaded from the data logger at regular weekly intervals to a laptop computer and processed to obtain the daily means. Long-term temperature and precipitation averages (1980–2009) were obtained from the weather station at Potenza, Basilicata, Italy (15° 48′ 0″ S, 40°, 37′, 38″ N).

Weed species identification, density, and above ground biomass were estimated at crop maturity. Among all treatment plots, *Amaranthus retroflexus* L. (redroot pigweed) was the dominant weed, comprising over 90% of weed biomass present among all experimental plots. Amaranthus species are common for this part of the Mediterranean (Holm et al., 1977). To determine the extent of water stress for tomato, leaf water potentials were measured in each treatment 68 days after transplantation on the first or second uppermost fully expanded leaf and taken at two hourly intervals from sunrise to sunset in 2008; this was repeated in 2009, but between 12:00 and 13:00 leaf water potential was measured using a pressure chamber technique. Gas exchange parameters, that is, net assimilation rate (A), stomatal resistance (r_s), and transpiration rate (T), were measured on tomato for fully expanded leaves on four plants in each treatment 68 days after transplantation. Measurements were made at two hour intervals from sunrise to sunset in 2008 and at midday (between 12.00 and 13.00 pm) in 2009 at a constant vapour pressure (~2 kPa) using a Photosynthetic Photon Flux Density of 1800 μmol m^{-2} s^{-1} (Infrared Gas Analyzer, Model LiCor-6400; Li Corporation, Lincoln, NE, USA). Water use efficiency at leaf level (WUE) was calculated as the ratio between CO_2 assimilated and H_2O transpired (μmol CO_2 $mmol^{-1}$ H_2O).

At maturity, maximum Leaf Area Index (LAI) was measured using an electronic area meter (Leaf area meter, Model Li-Cor 3100, Lincoln, NE, USA) within a 1.2 m^2 section of each treatment plot. At commercial harvest, plant parts, including above-ground biomass and reproductive yield, were dried in a thermo-ventilated oven at 75°C until constant weight was achieved (about 3 days), for dry matter recording. Harvest dates were August 12–26 and August 16–30, for 2008 and 2009, respectively.

Yield loss of tomato (as a percentage) was calculated as:

$$\frac{\text{Weed-free yield-yield with weeds}}{\text{weed-free yield}}$$

The statistical design was three complete randomised blocks for each year of the study with three replicates of rainfed/irrigated (including weed/no weed subplots) with each replicate allocated to a different field, but with all fields being contiguous. However, in each year of the study, insect infestation (Tomato russet mite, *Aculops lycopersici*) resulted in leaf and flower damage and the loss of one replicated block. Insecticide (fenbutatin oxide) was used to control this outbreak and none of the other blocks were affected. The data obtained from the remaining two blocks were subjected to a three way analysis of variance (ANOVA) with Year, Irrigation and Weeds/No Weeds as fixed effects. Mean discrimination was performed using the Fisher's least protected difference at the 1 and 5% levels of significance using the Sigmaplot 11.0 for windows (Systat Software Inc., San Jose, CA, USA).

Results

Each year of the study differed with respect to rainfall and climate. For 2008, overall precipitation was below average, with a drier than normal July and August, with warmer temperatures and a greater number of cumulative degree days above the minimum temperature, Conversely, 2009 had a very wet June and approximately twice the rainfall of 2008, with temperatures closer to the long-term average (Table I).

Supplemental irrigation had a significant effect on both above-ground dry biomass, and fresh weight of processing tomato for both years of the study (Table II). However, the relative effect of irrigation was greater for a weed-free condition, than if weeds were present, with a significant irrigation * weed interaction; in addition, significant interactions were noted for Year * Weed, Year * Irrigation, and Year * Irrigation * Weed for above ground biomass and for Year * Irrigation for yield (Table II).

A "best-fit" quadratic equation approach was used to compare changes in tomato fresh weight between the weedy and no-weed treatments as a function of water applied and weed biomass. The percent decline in tomato weight (relative to the weed free

Table I. Average monthly rainfall, irrigation volume, daily mean temperature and cumulative degree days (average minimum daily temperature above 32°C for a given month) for tomato in 2008 and 2009.

Year/ month	Rainfall (mm)	Irrigation (mm)	Daily mean temperature (°C)	Cumulative (degree days)
2008				
May	18	24.1	17.2	657
June	68	85.7	22.3	817
July	4	167.4	25.9	1072
August	5	128.0	26.3	1040
2009				
May	4	54.2	18.9	701
June	149	8.4	21.6	783
July	32	144.1	25.5	1030
August	29	107.0	25.4	998

Table II. Above-ground dry matter and yield of tomato (g m^{-2} fresh weight) (±SE) measured at harvest in 2008 and 2009, with (V100) and without (V0) supplemental irrigation, with and without weeds.

	V0	V100	V0	V100
	Weed-free	Weed-free	Weeds	Weeds
Dry matter				
2008	57.7±3.0	132.4±7.1	40.1±1.1	63.9±2.8
2009	151.0±5.2	345.6±7.2	139.4±0.8	221.7±5.5
Yield				
2008	780±78	7670±760	730±73	3080±300
2009	1330±179	10881±460	1124±78	6195±200

Significant differences (<0.05) were observed as a function of Irrigation, Weeds, Year * Irrigation, Year * Weeds, Irrigation * Weeds, and Year * Irrigation * Weeds for above ground dry matter and Year, Irrigation, Weeds, Year * Irrigation and Irrigation * weeds for yield.

condition) increased significantly as a function of water applied (Figure 1A). However, if the percent decline in tomato fresh weight is expressed as a function of weed biomass, the results indicate a greater relative effect of smaller amounts of weed biomass on tomato yields (Figure 1B). With no preciable changes in tomato yield above a weed biomass of ~800 g m^{-2}.

Diurnal comparisons of leaf assimilation and leaf water potential were taken at 68 days after transplanting in 2008, when soil water content (0–30 cm depth) was at the greatest measured difference between irrigated and rainfed tomato during the two year study (20.3 and 22.3% dry weight for the weed-free and weedy rainfed plots, and 29.1 and 28.2% for the weed-free and weedy irrigated plots, respectively). Diurnal assimilation data were significantly different for both the rainfed and irrigated treatments as a

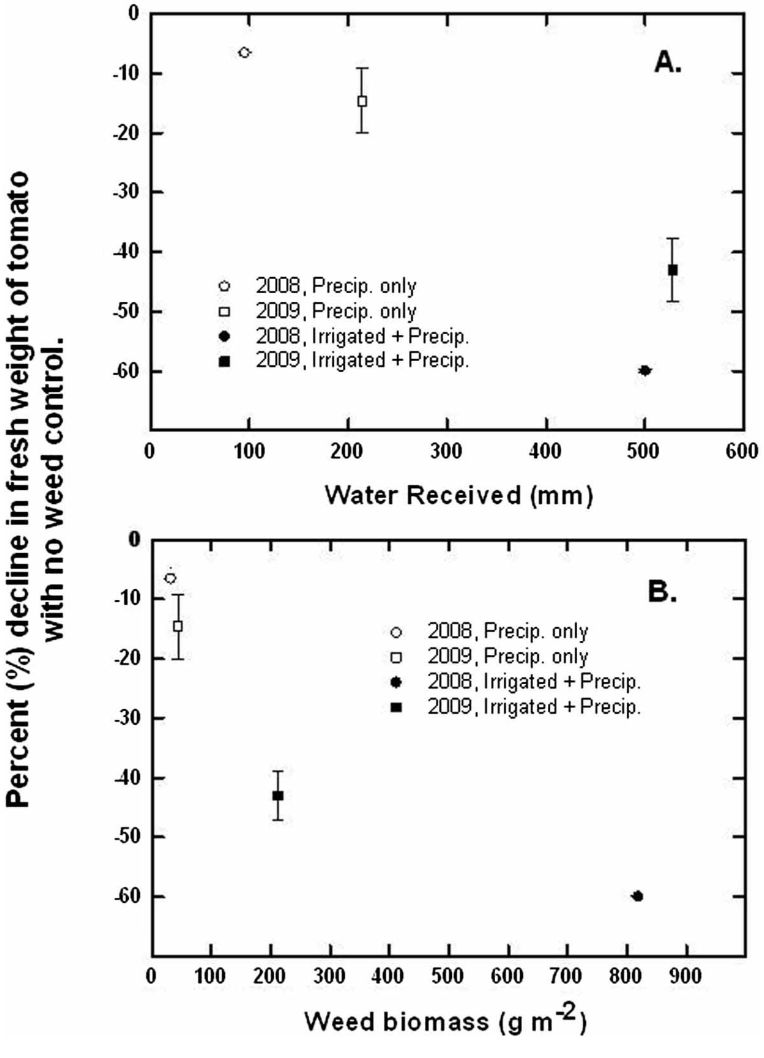

Figure 1. (A) Average percentage decline (±SE) in the fresh weight of processed tomato with no weed control (relative to 100% weed control) as a function of water added (either from precipitation or precipitation and irrigation) for 2008 and 2009. (B) Same as A, but as a function of weed biomass (g m^{-2}).

function of weeds, with the relative decline being greater for the rainfed treatment (Figure 2). For leaf water potential, no differences were observed between the weed free and weedy plots with irrigation. However, significant differences were observed during the afternoon under rainfed conditions for the weedy plot (Figure 2).

In 2009, differences in soil water content between rainfed and irrigated plots were much smaller (26% in rainfed for both weed-free and weedy treatments; 28.0 and 26.9% for irrigated weed-free and weedy treatments, respectively), than in 2008 because of the additional rainfall. Water stress did develop during 2009, but only during the latter part of the growing season prior to harvest. A seasonal comparison of leaf assimilation in 2008 and 2009, taken during the maximum dry period as determined by soil water content (~68 DAT in 2008, ~81 DAT in 2009), showed a greater relative negative effect of leaf assimilation for the weedy treatment, relative to the weed-free control in 2008, but only under rainfed (V0) conditions (Table III).

Discussion

The response of crops and weeds to water availability depends upon edaphic and management conditions as well as species characteristics. Consequently, it is difficult to generalise the impact of water availability on weed–crop interactions. Patterson (1995), in a survey of weed/crop competition studies in which soil water availability varied, suggested a trend for decreased water availability favouring the crop by reducing weed competition. That is, drought will limit both crop and weed growth to such an extent that competition for other resources will be reduced. This is consistent with studies for *Cirsium arvense* (L.) Scop. and wheat (Donald & Khan, 1992) as well as *Xanthium strumarium* L. and peanut (Royal et al., 1997). However, there is a great deal of uncertainty associated with concurrent changes in drought and other climatic variables with respect to weed-crop competitive outcomes (Zimdahl, 2004). Interestingly, recent data have suggested that a combination of rising CO_2 plus drought may actually exacerbate

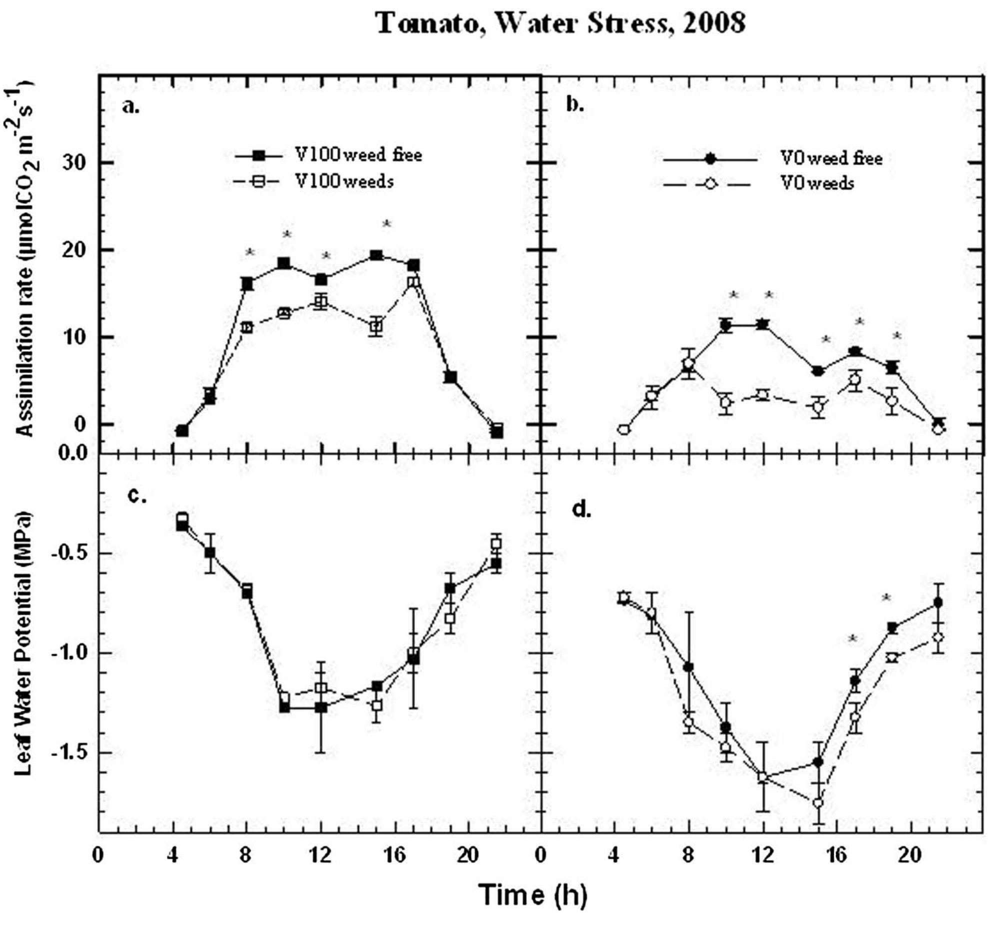

Figure 2. Assimilation rate and leaf water potential with and without weeds at 68 days after transplanting when soil water deficits were at a maximum (rainfed 2008) during the two years of the experiment. Bars are ±SE, Asterisk (*) indicates a significant difference at the $P < 0.05$ level relative to the control, at a given time. Fisher's protected LSD. V0, no supplemental water; V100, irrigated.

Table III. Average mid-day leaf assimilation (μmol m^{-2} s^{-1}), and leaf water potential (MPa), ±SE for 2008 and 2009, with (V100) and without (V0) supplemental irrigation, with and without weeds.

	V0	V100	V0	V100
	Weed-free	Weed-free	Weeds	Weeds
Assimilation				
2008	11.3 ± 0.6	16.5 ± 0.5	3.3 ± 0.7	14.0 ± 2.4
2009	11.8 ± 0.6	13.8 ± 0.7	11.7 ± 0.6	14.7 ± 2.3
Leaf water potential				
2008	−1.35 ± 0.03	−1.20 ± 0.08	−1.56 ± 0.08	−1.21 ± 0.23
2009	−1.48 ± 0.08	−1.03 ± 0.03	−1.43 ± 0.08	−1.20 ± 0.01

Data were taken ~68 days after transplanting (DAT) in 2008 and ~89 DAT in 2009. Significant differences (<0.05) were observed as a function of Irrigation, Weeds, Year * Irrigation, Year * Weeds for assimilation; and, Irrigation for leaf water potential.

crop losses in wheat from both C_3 and C_4 weeds (Naidu & Varshney, 2011).

Global accumulation of anthropogenic gases is likely to exert variation in climatic patterns, particularly for precipitation (IPCC, 2007). Agricultural water availability and deliverability can pose problems in the next decades for southern Italy (Rossi, 2003). Given that this region is the main producer of processing tomatoes for Europe (World Processing Tomato Council, 2006), projected climatic changes associated with increased drought are likely to have significant economic implications. As such, the role of water availability in weed-induced crop losses in processing tomato should be assessed, to determine the potential vulnerability of this system, and to potentially derive appropriate weed management strategies.

The present study shows the necessity for additional irrigation to maintain high tomato yields and that tomato yields decrease with increased weed growth as a function of water applied if weeds are not managed. Similarly, for processing tomato grown in California, weed-crop competition was reduced by limiting water availability to weeds via sub-surface drip irrigation relative to standard furrow irrigation (Sutton et al., 2006). Overall, these results are consistent with the observation of Patterson (1995) and others (e.g. Patterson & Highsmith, 1989; Oerke & Dehne, 2004), that weed–crop interactions can intensify with resource availability.

However, it should not be assumed that any competitive interactions between weeds and crops are proportional to the amount of water applied. In the current study, the percent decline in tomato fresh weight was not directly proportional to weed biomass per se. Rather, the relative effect of weed biomass was, in fact, greater during drought (i.e., rainfed) than under well-watered conditions, even though the amount of weed biomass present was small. In fact, relative crop losses (per unit weed biomass) actually declined as water availability increased.

The basis for this observation is not entirely clear. In both years, *Amaranthus retroflexus* was the dominant field weed (>90% of the weeds and >90% of the weed biomass), regardless of experimental treatment. While the extent of drought varied between years, the greatest observed decline in soil water status was at 68 DAT in 2008, and showed a greater effect (relative to the weed-free condition) under rainfed rather than irrigated conditions for leaf assimilation and leaf water potential. This would suggest greater relative competition with limited water resources and is consistent with a greater competitive effect of weed biomass under water-limited conditions. The association of the competitive effect with reduced water applications, in turn, may reflect the nature of a C_4 weed species (*A. retroflexus*), with a greater water-use-efficiency, relative to tomato, a C_3 crop. However, differential competitive effects between belowground nutrient and water utilization and above-ground shading were not quantified.

A single field trial is, of course, insufficient to elucidate the complex basis for weed competition and production losses *in toto*. Germination rates, stage of growth, soil water availability, weed management, and so on, all have important implications with respect to both below and above-ground competition. However, the present data indicate that competition for water between tomato and weeds may increase under drought conditions, even though the general effect of water is to enhance weed-induced production losses. These data are consistent with the suggestion of Rajcan and Swanton (2001) that crop-weed competitions regarding water should be viewed as an outcome of two dynamic systems, the abiotic interaction of soil–plant–atmosphere and the biotic interface of crop-weed resource exploitation. Both interactions are likely to be altered by anthropogenic climate change.

Overall, given that water availability depends on climate, and that anthropogenic climate change may exacerbate the occurrence of drought, water is likely to be heightened in significance in tomato production for the Mediterranean region (Pervez et al., 2009). At present, there are very few published studies about the impact of climate change and enhanced drought conditions on weed control in tomatoes *in situ*. The current study illustrates that while increasing water will exacerbate crop losses in unmanaged conditions, relative crop losses as a function of weed biomass may actually be greater when water is restricted. Given that water is a limited and increasingly costly resource, efficiency of water application, especially to minimise losses caused by weeds, should be a significant aspect in assessing the need for, and advantages of, weed control for land managers. The current study emphasises that a weed-free system, even in a drought condition, may be necessary to maximise production. However, additional information is needed to amplify and/or confirm these results.

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