Water stress may decelerate purple nutsedge (Cyperus rotundus) invasion in arid environments

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Research Article

Keywords: Drought stress, purple nutsedge, rhizome, tuber

Posted Date: May 5th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2828533/v1

Abstract

Cyperus rotundus L. causes high yield losses in fruiting vegetables and cucurbits in eastern and southeastern parts of Iran. Greenhouse studies were conducted to evaluate the effects of degree and duration of water stress on growth, fecundity and biomass partitioning of purple nutsedge. The degree of water stress study included five treatments, where the amount of water applied to each pot at 3-day interval was equivalent to 100, 75, 50, 25, and 12.5% of pot water content. The study of water stress duration included six durations of water stress: 3-, 6-, 9-, 12-, 15- and 18-day intervals, where the amount of water applied to each pot was equivalent to 100% of pot water content. The greatest values for plant height, leaf area, shoot and tuber number and below- and aboveground biomass were recorded at 100% of pot water content and also at 3-day water stress duration, whereas they were reduced as degree and duration of water stress increased. This study shows that although *C. rotundus* is susceptible to water stress, it allocates greater biomass to underground organs under a higher degree and duration of water stress. This necessitates strategies that minimize water availability to purple nutsedge plants and inhibit new shoot and tuber production.

Introduction

Water is a major factor affecting plant growth and its availability is going to reduce over the last decades. Insufficient water availability will become more important in the future due to climate change (Rudack et al. 2017). For much of the South Khorasan province in Eastern part of Iran, extreme drought was observed in recent years and aridity is a major threat to crop production in this region (Esmaeilnejad 2017). In the near future, aridity is expected to increase in many agronomically important areas and a variation in rainfall pattern and increased aridity consistent with a warming climate, could alter weeds distribution and their impact on crop production (Ramesh et al. 2017). Drought stress might accelerate or even decelerate the invasion of some noxious weed species. Patterson (1995) has suggested that decreased water availability may favor the crop by reducing the competitive impact of the weed. The sensitivity of weed species to the degree and duration of water stress, however, varies amongst different weed species. For example, itchgrass (*Rottboellia cochinchinensis* Lour.) produced similar biomass at field capacity ranging from 50 to 100% (Chauhan 2013). Rodenburg et al. (2010) found that under prolonged drought spells, C4 and parasitic weeds like *Striga hermonthica* will thrive better, whereas, it has been found that the growth of sedges is best under high soil moisture conditions (Kaur et al. 2018). Lima et al. (2016) also found various responses to water deficit amongst different weed species. Therefore, depending on the species sensitivity to water stress, a drought may create a window of opportunity for invasion or even decelerate the invasive ability of noxious weeds like *C. rotundus*.

Holm et al. (1977) listed *Cyperus rotundus* L. (purple nutsedge) as the world's worst weed based on its worldwide distribution (92 countries) and interference with over 50 crops. Interference of *C. rotundus* is a major threat to vegetable production around the world (Wallace et al. 2013), including Eastern and Southeastern parts of Iran. This invasive noxious weed has a remarkable ability to survive adverse conditions and can grow explosively when the land is planted to irrigated crops (Masiunas et al. 1997). It

is an invasive and difficult to control weed in row crops, lawns, and orchards in Eastern and Southeastern areas of Iran, where most farmers practice surface irrigation (flood or furrow irrigation) to grow their crops. Purple nutsedge tubers are the main means of reproduction as seed viability is so low (Wallace et al. 2013). Tuber production starts as early as 6 to 8 weeks after foliar emergence from rhizomes in a chain-like manner of up to eight individuals (Webster 2003). The longevity of the tubers, the ability to sprout several times, and the lack of herbicides that can kill dormant tubers make *C. rotundus* difficult to control (Bryson et al. 2003). Therefore, successful management of purple nutsedge must eliminate tuber viability or inhibit new shoot and tuber production (Webster 2003). Dhima et al. (2016) reported 81–94% losses in the total fruit number and 86–96% reductions in fruit yield of tomato (*Solanum lycopersicum* L.), eggplant (*Solanum melongena* L.) and pepper (*Capsicum annuum* L.) due to the presence of 160 plants m^{-2} of purple nutsedge.

The interference and yield losses from purple nutsedge in fruiting vegetables and cucurbits in Iran are so high, so that some farmers are forced to abandon their fields or till the whole area. The greater intense competition of *C. rotundus* under wet conditions has been observed in previous field studies (Cinco-Castro and McCloskey 1997). Similarly, massive expansions of purple nutsedge patches were observed with farms employing flood irrigation in South Khorasan, while its expansion was remarkably reduced where drip irrigation systems were utilized (unpublished data). There is paucity of information on the response of *C. rotundus* growth traits to water stress and it seems a necessity to study the growth responses of this invasive weed species to severity and duration of water stress, as crucial elements influencing the effect of drought on plants. Such information would help in developing integrated weed management options for drought-prone areas. The objectives of the work presented here were: (i) to study the effects of degree and duration of water stress on the growth and tuber production of purple nutsedge, (ii) to evaluate the sensitivity of different organs of this noxious species to water stress, and (iii) to determine the *C. rotundus* biomass partitioning to above- and belowground parts under water stress conditions.

Materials and methods

In order to study the growth responses of purple nutsedge plants to degree and duration of water stress, two separate greenhouse experiments were conducted at the Faculty of Agriculture, University of Birjand. This facility is located at lat. 32°56' N and long. 59°13' E, 1,480 m above sea level, with 20-year average annual rainfall < 150 mm. Purple nutsedge tubers were collected from natural infested vegetable farms at Birjand in South Khorasan Province, where flood irrigation is commonly practiced for growing vegetable crops, on 15 January 2018. As it was previously found that 99% of *C. rotundus* tubers were distributed within 16 cm of the soil surface (Siriwardana and Nishimoto 1987), tubers were collected from the depths of 15–20 cm and stored wrapped in paper bags at 4°C until use. To exclude the effect of tuber weight on plant growth characteristics, only tubers weighing 0.7 ± 0.15 g were used. A preliminary germination test was conducted at a light/dark temperature range of $^{25}/_{15}$°C and the photoperiod was set at 16 h. This test confirmed that there was no tuber dormancy and all tubers produced at least one

sprout after 5 days. Pot experiments were carried out in a greenhouse set at a light/dark temperature of $^{25}/_{15}$°C and the photoperiod was set at 16 h with high-pressure sodium vapor lamps (VIALOX NAV-T 400 W, OSRAM, Germany). In both experiments, cylinder pots (20 cm deep and 20 cm in diameter) were filled using a loam soil comprising 43% sand, 32% silt, and 25% clay with 0.44% total organic matter and a pH of 7.4. This soil was collected from a wheat field with no history of *C. rotundus* infestation. Before filling pots, the whole soil was passed through 2-mm sieves. A presprouted tuber with a single shoot was transplanted at 2.5 cm depth, in the middle of each pot. Water stress treatments were initiated 7 days after planting in either experiment. The first experiment was conducted to study the effect of water stress degree on *C. rotundus* growth traits and included five water stress degrees: 12.5, 25, 50, 75, and 100% of soil field capacity (pot water content). The field capacity (1.0 L water) of pots was determined in the manner described by Steadman et al. (2004). In this experiment, the volume of water was applied at 3-days intervals. The second experiment, in which the effect of water duration on *C. rotundus* growth traits was studied, included six durations of water stress: 3-, 6-, 9-, 12-, 15- and 18-days intervals. In each level of water stress duration, 100% of field capacity of water was applied. The pots were arranged in both experiments as a randomized complete block design with four replications and either experiment was repeated once. Shoots were clipped at the soil surface at 60 days after planting. Leaf areas were determined with a Delta-T leaf area meter (WinDIAS, Delta-T Devices Ltd., 128 Low Road, Burwell, Cambridge, CB5 OEJ, U.K.). Then, the pot soil was passed through a 0.1-mm mesh metal sieve to separate the tubers and underground organs from the soil. These plant parts were placed in separate paper bags and dried in an oven at 70°C for 72 hours. Shoot number, aboveground biomass, tuber number, and belowground biomass (tuber + rhizome + root) were recorded for each treatment.

Transformation of data did not improve homogeneity; therefore, ANOVA and regression analysis were performed on non-transformed data. The data of the experiments were pooled for analysis, as there was no time-by-treatment interaction. Means were separated using SED (standard error of difference). A functional three-parameter logistic model (Chauhan et al. 2006) of the form:

$$Y = D_{max} / [1 + (x/x_{50})^{Drate}] \quad [1]$$

was fitted to the relationship between the dependant variables and different water stress durations (second experiment), where, D_{max} is the maximum response, x_{50} is the duration of water stress required for 50% inhibition of the response and D_{rate} indicates the slope.

Results

Degree of water stress

Increased degrees of water stress remarkably reduced the growth of aerial and subterranean organs of *C. rotundus* plants, so that plants under high (25% of pot water content) and severe (12.5% of pot water content) water stress treatments did not survive after 20 DAT (days after treatment). The maximum *C. rotundus* height (70 cm) was observed with plants grew at no water stress (100% of pot water content),

while intensifying the water stress degree to 75% (light water stress) and 50% (moderate water stress) of pot water content considerably reduced the plant height to 40 and 20 cm, respectively (Fig. 1A). The greatest number of shoots per pot (7 shoots pot^{-1}) was recorded with 100% of pot water content treatment (no water stress), which was significantly reduced to 3 and 1 shoots per pot with 75% and 50% of pot water content, respectively (Fig. 1B). The total leaf area of plants grown at no water stress reached to 116.33 cm^2, whereas compared to no water stress treatment, total leaf area was reduced by 68 and 92% at light and moderate water stress degrees, respectively (Fig. 1C). The greatest aboveground biomass was observed in plants receiving 100% of pot water content (no water stress), while increased degrees of water stress remarkably reduced the aboveground biomass production (Fig. 1D). 52 and 88% reductions in aboveground biomass were observed with light and moderate water stress degrees, respectively, compared with 100% of pot water content.

Purple nutsedge plants produced the greatest number of tubers where received 100% of pot water content (7.7 tubers pot^{-1}), whereas increasing water stress degrees significantly reduced the production of tubers (Fig. 1E). Compared to 100% of pot water content (no water stress), tubers pot^{-1} were reduced by > 60% where the amount of applied water was equivalent to ≤ 75% of pot water content (light to severe water stress). Degree of water stress also significantly affected the total belowground biomass (tuber + rhizome + root biomass) (Fig. 1F). The greatest belowground biomass was observed with plants received 100% of pot water content (no water stress), whereas reducing the amount of applied water to ≤ 75% of pot water content reduced the total aboveground biomass by ≥ 50%. Belowground biomass (BGB) to aboveground biomass (AGB) ratio was affected by water stress degree, so that the lowest BGB/AGB ratio (0.95) was observed under no water stress situation (Fig. 2A). The application of light and moderate degrees of water stress (75 and 50% of pot water content), however, remarkably enhanced this ratio to 1.27 and 1.66, respectively, which accounts for 34 and 74% increase in this ratio.

Duration of water stress

Duration of water stress also had a significant impact on the growth and fecundity of *C. rotundus* plants. The three-parameter logistic model provided a satisfactory fit for the response of aerial and subterranean growth traits of *C. rotundus* to the duration of water stress (Table 1). The tallest plants (70 cm) were observed with 3-day interval of water stress (Fig. 3A). Increasing the duration of water stress noticeably reduced the plant height, so that compared to 3-day water stress interval, there was a 60% reduction of plant height with 18-day water stress interval. The water stress interval required for 50% reduction of maximum *C. rotundus* height (x_{50}), determined from the fitted model was 16.4 days (Table 1). The greatest shoots pot^{-1} (4.7 pot^{-1}) was recorded at 3-day water stress interval, while further prolongation of water stress duration resulted in significant decreases in shoots pot^{-1}, so that only one shoot was produced when plants received water every 18 days (Fig. 3B). Based on model estimation, the water stress duration required for 50% decrease in shoot number was 12.8 days (Table 1). *Cyperus rotundus* plants had the greatest leaf area at 3-day water stress interval (110 cm^2 pot^{-1}) (Fig. 3C). Intensifying the water stress, however, considerably reduced plants leaf area and the greatest reduction (90%) compared to 3-day water stress interval was observed with plants receiving water every 18 days.

The estimated water stress duration required for 50% reduction in leaf area (x_{50}) was 8.8 days (Table 1). Irrigating *C. rotundus* plants every 3 days also resulted in the greatest aboveground biomass, while further increasing of water stress duration significantly reduced plant aboveground biomass (Fig. 3D). Compared to 3-day water stress interval, 98% reduction was observed when irrigation was applied every 18 days. As the three-parameter logistic model estimated, irrigating plants every 7.8 days resulted in 50% reduction in aboveground biomass (Table 1).

Table 1
Parameter estimates (± SE) of logistic model predicting *C. rotundus* growth traits as affected by duration of water stress.

Growth trait	D_{max}	D_{rate}	x_{50}	R^2
Aboveground biomass (g pot^{-1})	4.5 ± 0.84	2.2 ± 0.75	7.8 ± 1.87	0.93
Belowground biomass (g pot^{-1})	3.9 ± 0.33	2.9 ± 0.78	11.8 ± 1.12	0.94
Shoot no. pot^{-1}	4.7 ± 0.22	3.0 ± 0.49	12.8 ± 0.66	0.98
Tuber no. pot^{-1}	6.8 ± 0.68	3.5 ± 1.02	10.2 ± 1.08	0.93
Leaf area pot^{-1}	117.1 ± 4.24	2.7 ± 0.22	8.8 ± 0.37	0.99
Plant height (cm)	69.1 ± 1.30	3.2 ± 0.31	16.4 ± 0.34	0.99

The greatest number of tubers (7 pot^{-1}) was produced when plants were irrigated every 3 days, while lengthening the duration of water stress caused great reductions in tuber production capability (Fig. 3E). Tuber production was ceased when water stress duration increased to 18-day interval. The estimated water stress duration required for 50% reduction in tuber production (x_{50}) was 10.2 days (Table 1). Total belowground biomass (tuber + rhizome + root biomass) was noticeably reduced by increasing the duration of water stress (Fig. 3F). The heaviest belowground organs were produced when plants were irrigated at 3-day interval. Compared with 3-day water stress interval, increasing water stress duration resulted in an 88% reduction when plants were irrigated at 18-day interval. The estimated x_{50} parameter for belowground biomass was 11.8 days, indicating that if plants were irrigated at almost 12-day interval, a 50% reduction in the maximum belowground biomass would be observed (Table 1). Belowground biomass (BGB) to aboveground biomass (AGB) ratio was also affected by water stress duration, so that the lowest and highest BGB/AGB ratios were observed with plants irrigated at 3-day (0.97) and 18-day (5.12) intervals, respectively (Fig. 2B). Increased durations of water stress enhanced this ratio in a consistent manner up to 15-day water stress duration, while there was an extraordinary increase in BGB/AGB ratio for plants irrigated every 18-day.

Discussion

Degree of water stress

Our study indicated a low tolerance of *C. rotundus* to water stress compared to many other weed species (Chauhan 2013; Sarangi et al. 2015; Tavizi 2016). In the water stress degree study, *C. rotundus* seedlings died under high and severe water stress conditions (25 and 12.5% of pot water content, respectively) at 20 DAT. In similar studies, Chauhan and Abugho (2013) found that rice plants did not survive at 25 and 12.5% of pot water content, whereas common waterhemp, and itchgrass could thrive under these conditions over 90- and 63- day study periods, respectively (Chauhan 2013; Sarangi et al. 2015). Chauhan and Johnson (2010) also found that junglerice (*Echinolcloa colona* L.) plants could survive severe water stress conditions (12.5% of pot water content) up to the anthesis growth stage. Our results showed remarkable negative impact of water stress degree on *C. rotundus* height compared to other weed species. The rates of reductions in *C. rotundus* plants height under light and moderate water stress degrees (42 and 71%, respectively) were surprisingly identical with those observed with common waterhemp shoot height under high and severe water stress conditions (Sarangi et al. 2015), indicating a greater sensitivity of *C. rotundus* compared to common waterhemp. Palmer amaranth also showed 31% reduction in shoot height under high water stress (25% of pot water content) (Moran and Showler 2005). Tavizi (2016) reported a 40% reduction in mouse barley (*Hordeum murinum* L.) plant height at 30% of pot water content compared with no stress conditions. Chauhan (2013) reported that plant height of itchgrass was reduced by 49 and 63% at high and severe water stress, respectively. Junglerice plants height was only reduced by about 5 and 12% at high and severe water stress conditions, respectively (Chauhan and Johnson 2010). Plant height has been documented amongst the best predictors of competitive success of perennial weed species as it is an important parameter for light utilization in vegetation stands (Holt and Orcutt 1991). Under water stress conditions, especially where *C. rotundus* competes with drought tolerant plant species, it is expected that this noxious weed, as a C_4 plant, may not take advantage of higher light intensities, since it experiences a huge height reduction. This problem might be exacerbated with the sensitivity of this species to shading. Santos et al. (1997) found that 60% shade cut aboveground dry weight by 80% and tuber dry weight by 97%. The potential of shoot production of *C. rotundus* was also considerably declined by the degrees of water stress, so that even applying a light water stress degree resulted in a 57% reduction in shoot number. This suggests that the shoot density of this weed species would be remarkably declined even under light water stress degrees. Leaf area of *C. rotundus* was severely impacted by water stress degree, so that it lost a great portion of its leaf expansion (> 90%) even under moderate water stress degree compared with no stress conditions. Lecoeur and Sinclair (1996) stated plant processes that depend on increases in cell volume, such as leaf area, are particularly sensitive to water deficits. Inhibition of these processes under drought can result in substantial losses in plant biomass production. The reduction of dry matter production under water stress conditions was reported to be mainly due to the reduction of leaf area (Younis et al. 2000). Neumann (1995) stated that stress-induced reductions in the leaf area available for transpiration may help plants in decreasing maximum (per plant) rates of soil water depletion. Regulated reductions in growth rate and plant size could therefore represent an adaptive feed-forward mechanism. This would prolong the period of availability of the finite soil water reserves that regulate plant survival and ability to

complete the reproductive stage of development under terminal drought environments. Lovelli et al. (2010) reported a 98% reduction in LAI of redroot pigweed (*Amaranthus retroflexus* L.) in a field experiment under water stress conditions compared to no water stress. In contrast to *C. rotundus*, Sarangi et al. (2015) found that the rate of leaf area reduction of common waterhemp was half of *C. rotundus* under moderate degrees of water stress. Paudel et al. (2016) also found no effect of water stress on leaf area of stressed Palmer amaranth (*Amaranthus palmeri* S. Wats.) plants compared with well-watered ones. This suggests that *C. rotundus* loses a greater amount of its photosynthetic ability under water stress conditions compared to abovementioned species. Water stress degree remarkably reduced the total aboveground biomass of *C. rotundus*, so that exposing *C. rotundus* plants to moderate water stress could reduce aboveground biomass production by almost 90%, which was greater than that of common waterhemp (Sarangi et al. 2015), itchgrass (Chauhan 2013), junglerice (Chauhan and Johnson 2010), spiny amaranth (*Amaranthus spinosus* L.) and Chinese sprangletop (*Leptochloa chinensis* L.) (Chauhan and Abugho 2013) even at severe water stress (12.5% of pot water stress). Tavizi (2016) also found 42% reduction in aboveground biomass of mouse barley where plants were exposed to 30% of pot water content. The great reduction of aboveground biomass under moderate water stress degree indicates that *C. rotundus* plants might lose their competitive advantage over associated species where soil water is in short supply.

The tuber production of *C. rotundus* was significantly reduced by water stress degree, so that it lost more than 85% of its tuber density under moderate water stress degree, which is an important component used to reduce the long-term population density of *C. rotundus*. The biomass production of subterranean parts of *C. rotundus* (tuber + rhizome + root biomass) was also severely reduced by water stress degree, so that plants grown under moderate water stress showed greater than 80% reduction in their total belowground biomass compared with no stress conditions, which seems much greater than corresponding values for other plant species in previous studies. For instance, total belowground biomass of itchgrass plants under moderate and no water stress conditions were similar and plants lost 69% of their belowground biomass under severe water stress degree (12.5% of pot water content) (Chauhan 2013). Tavizi (2016) also reported that mouse barley plants showed 30 and 65% reductions in belowground biomass under 60 and 30% of pot water content, respectively. In our study, belowground to aboveground biomass ratio (BGB/AGB) of *C. rotundus* even at no water stress degree was much greater than those previously recorded for common waterhemp (Sarangi et al. 2015), itchgrass (Chauhan 2013), and mouse barley (Tavizi 2016). BGB/AGB values greater than 1.5 were also previously reported for *C. rotundus* under pot (Chauhan and Opena 2012; Webster et al. 2017) and field (Miles 1991; Schonbeck 2015) trials. This difference is not surprising, since in perennial plant species belowground biomass should exceed aboveground biomass because roots and rhizomes tend to be laterally more wide-spread than aboveground plant parts (Casper et al. 2003; Pärtel et al. 2012). *Cyperus rotundus* has been described as a "geophilous" plant, because very early in its life cycle it begins partitioning a large portion of its energy to underground reproductive organs. In our study, the BGB/AGB ratio of *C. rotundus* was enhanced by water stress degrees, so that the greatest ratio (1.66) was observed with moderate water stress (50% of pot water content). In line with our study results, an increase in resource allocation to

roots was observed in *Rumex obtusifolius* L. under drought conditions (Gilgen and Feller 2013). In contrast, Sarangi et al. (2015) found that this ratio (0.42) at severe water stress was reduced to half (0.22) compared to no stress conditions. Moore and Franklin (2011), also unlike our results, found that BGB/AGB ratio of Palmer amaranth (*Amaranthus palmeri* S. Wats.) was reduced under water stress compared with no stress conditions. Although *C. rotundus* total biomass was reduced by water stress degree, there was greater biomass partitioning in subterranean parts under water stress conditions. This implies that *C. rotundus* partitioned more energy to the growth of its belowground and perennating organs under water stress conditions. Given the fact that *C. rotundus* regeneration is accomplished through its subterranean parts (tubers and rhizomes), it is well justified why this weed species tries to augment its belowground parts and allocate most of its photosynthates to belowground organs under water stress conditions. Most perennial plants have persistent belowground storage organs and meristems that allow short- or long-term dormancy for up to decades in the absence of aboveground biomass (Reintal et al. 2010). Researchers have noted increased partitioning to underground structures, particularly tubers, in response to stresses such as crowding or insufficient moisture and/or nutrients (Miles et al. 1991).

Duration of water stress

Cyperus rotundus growth traits were adversely influenced by the duration of water stress. Although plants survived to the end of this study (water stress duration) under all irrigation intervals, compared to 3-day irrigation interval, there were ≥ 88% reductions in plants leaf area, tuber production as well as above- and belowground biomass where plants were irrigated every 18 days. It is worth noting that no tuber propagation was occurred under the 18-day irrigation interval. The 3-parameter logistic model provided satisfactory fits to the data of *C. rotundus* growth parameters. The order of x_{50} values (irrigation interval required for 50% reduction in the growth trait) for different growth characteristics were as plant height > shoot no > belowground biomass > tuber no > leaf area > aboveground biomass. This indicates that the sensitivity of aboveground biomass was much greater than belowground biomass. Root growth is less sensitive to a decrease in soil water potential than stem growth and this leads to the increase in the root:shoot ratio that is commonly observed in plants exposed to a water deficit (Dhanda et al. 2004; Younis et al. 2000). Lima et al. (2016) in a greenhouse experiment observed that four different weed species (*Waltheria indica*, *Crotalaria retusa*, *Cleome affinis* and *Commelina benghalensis*) allocated a greater percentage of dry matter to their roots under water restriction, in relation to the respective control treatment. Other authors also concluded that plants under water deficit accumulated photoassimilates on the root system to the detriment of the shoot growth, indicating an attempt to make up for the water deficiency through a larger absorption area on the soil (Grzesiak et al. 2015; Martinez-Fernandez et al. 2012). It appears that plants exposed to water stress attempt to increase their capacity to extract water from greater depths through allocating a greater fraction of photosynthates to their roots (Grieu et al. 2001).

The other interesting result is the greater estimated x_{50} values for tuber production compared to leaf area and aboveground biomass, suggesting that plants might considerably lose their aboveground

growth potential under long periods of water stress, yet maintaining their tuber production ability which allows *C. rotundus* plants to persist in the soil under drought stress. The low x_{50} value for leaf area also indicates the great sensitivity of leaf area expansion to water stress. Leaf expansion is the first reaction declining under water stress. Previous research studies have confirmed that an early symptom of water stress is a reduction in the rate of leaf expansion. Water stress is known to induce loss of turgor which affects the rate of cell expansion and ultimately cell size and consequently it decreases growth rate, stem elongation, leaf expansion and stomatal aperture (Younis et al. 2000). Prolonging the water stress duration consistently increased the BGB/AGB ratio, while this increase was much greater at 18-day water stress duration compared to other water stress durations. It appears that at 18-day irrigation regime plants produced very light aboveground parts (0.1 g pot^{-1}), whereas their belowground biomass was still 5 times greater (0.5 g pot^{-1}) than that of aboveground organs. Although plants produced no tuber at this irrigation regime, they still allocated more biomass to belowground parts. Zeng et al. (2012) suggested that the plasticity of root morphology and higher root to shoot ratio (R:S) were two important strategies for *Alhagi sparsifolia* Shap. to capture water and adapt to a hyper-arid environment. Under higher soil moisture conditions, plants may have less demand to develop roots and so allocate more biomass to shoot growth, thus resulting in a lower R:S (Gui et al. 2013). Biomass partitioning pattern strongly influences plant productivity under water stress conditions (Li et al. 2008). In our study, water stress decreased leaf area, shoot number, tuber number as well as total above- and belowground biomass, and an altered biomass allocation to subterranean organs resulted in higher BGB/AGB ratio in stressed plants.

Conclusions

Our study with newly established *C. rotundus* plants may not represent field situations, where there is more soil volume and hence water availability and also many established plants with an extensive chain of rhizomes and tubers produced over several years. The information gained from our study, however, may allow the development of hypotheses for testing possible approaches for the management of this invasive weed under arid and semi arid agroecosystems. The present study indicated that *C. rotundus* plants were vulnerable and died under high and severe water stress degrees (12.5 and 25% of pot water content, respectively). Therefore, this species may not generate vigorous seedlings under severe drought events commonly occur on South Khorasan farms and may not be able to compete with crop species tolerating water stress conditions, such as sorghum and barley. This drought sensitivity indicates that this weed species may become an even less invasive in cropping systems in future climate change scenarios which imply an increase in the occurrence of drought stress. The stressed plants with shorter height and lower leaf area and shoot number are expected to be less competitive because of their lower canopy coverage to shade shorter associated species, and also might be impacted by the shade exerted by taller plants (Momayyezi and Upadhyaya 2017). The sensitivity of this invasive weed species to shade (like most C4 plants) and its suppression by a closed crop canopy has been previously substantiated (Schonbeck 2015). Our study showed that water stress may have the potential to reduce tuber production and cause a decline in *C. rotundus* tuber density in the soil propagule bank. Smaller plants

produced under moderate water stress conditions (50% of pot water content) produce a lesser number of tubers, which may impact the survival, distribution and persistence of this weed in orchards and vegetable crop farms. It seems that employment of more effective irrigation systems such as SDI (subsurface drip irrigation) rather than surface irrigation systems commonly practiced in the study region, especially for high-value vegetable crops, might limit the growth and expansion of *C. rotundus* populations through restricting the moisture to the area around the drip line near the crop root zone. The great efficiency of SDI in reducing weeds pressure in several field and vegetable crops as well as in orchards has been previously documented (Dastorani et al. 2010). Since *C. rotundus* is susceptible to both shading and water stress (Masiunas et al. 1997; Schonbeck 2015), the inclusion of competitive cereal crops, such as barley, wheat and sudangrass that quickly form a dense canopy and also have a greater drought tolerance (McKersie and Leshem 1994), in rotation with vegetable crops in highly infested farms might be a promising strategy.

Although our research indicates the susceptibility of *C. rotundus* to drought, it should not be assumed that this invasive plant is an easy to control weed under drought stress. Our results indicated that this invasive weed allocated more biomass to underground organs under drought conditions and it has been previously reported that tuber dormancy was enhanced under drought conditions (Miles et al. 1991). Therefore, *C. rotundus* persistence might be even further augmented under water stress conditions. Moreover, our study clearly showed a lower leaf expansion of water- stressed *C. rotundus* plants which might results in reduced efficacy of post-emergence herbicides under water stress situations due to less retention and uptake of herbicides by the target plants (Kudsk and Kristensen 1992). The hypotheses presented here require further investigations under greenhouse and field conditions in future studies.

Declarations

Acknowledgements

We would like to acknowledge the University of Birjand for financial support of this work.

Declarations

Hereby, the authors of the manuscript "**Water stress may decelerate purple nutsedge (*Cyperus rotundus*) invasion in arid environments**" declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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Authors contribution

The author Seyed Vahid Eslami raised the idea and planned the experiment and author Nosratollah Karimi Arpanahi has accomplished all practical jobs and wrote the first draft of the manuscript. Seyed

Vahid Eslami analysed the data and edited the first draft of the manuscript and developed the discussion of the manuscript.

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Figures

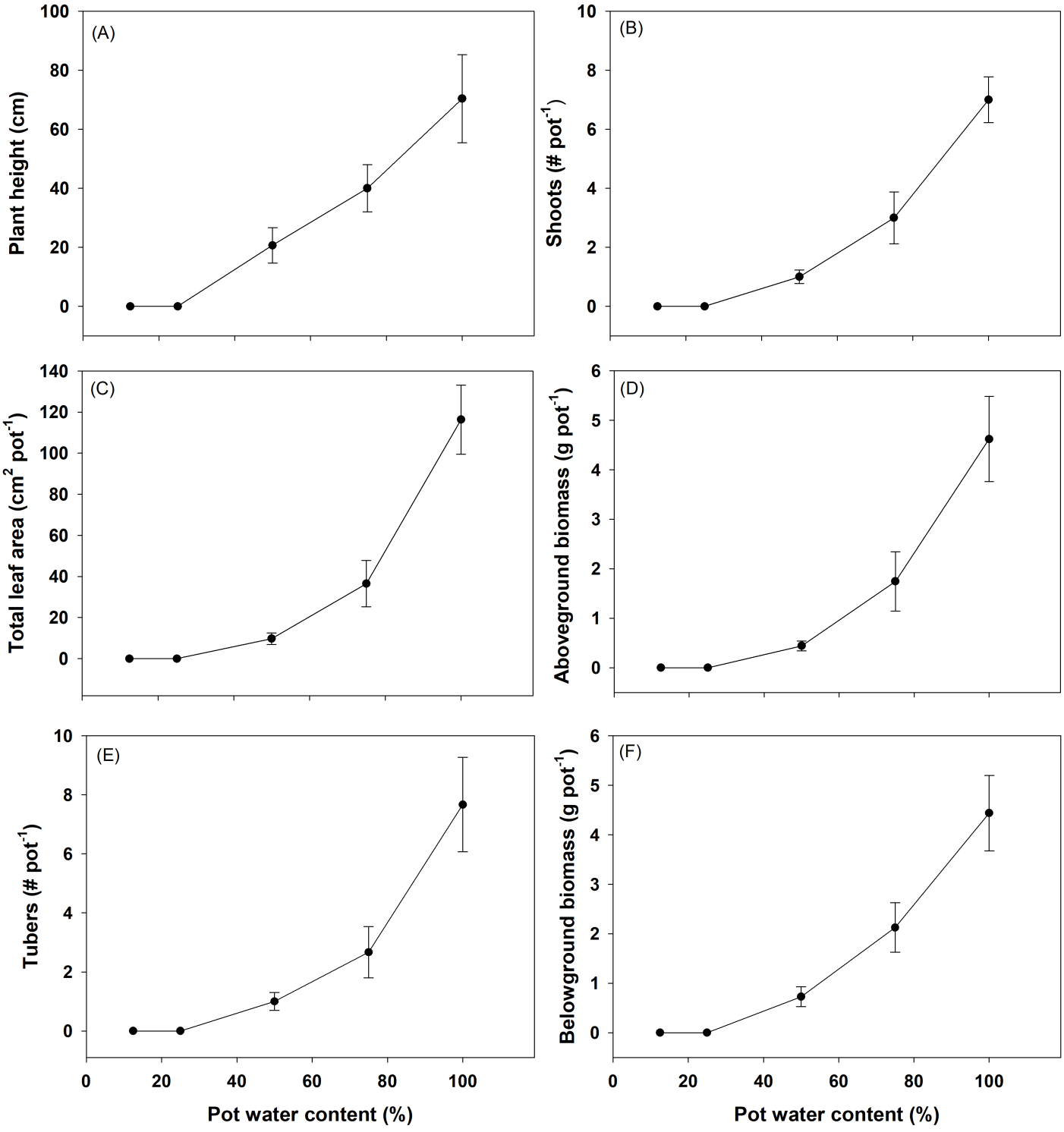

Figure 1

(A) Plant height, (B) shoots pot^{-1}, (C) leaf area pot^{-1}, (D) aboveground biomass, (E) tubers pot $^{-1}$ and (F) belowground biomass of *C. rotundus* plants grown under different pot water contents. 100, 75, 50, 25, and 12.5% pot water content treatments were considered as no, light, moderate, high, and severe water stress, respectively. Vertical bars represent SED

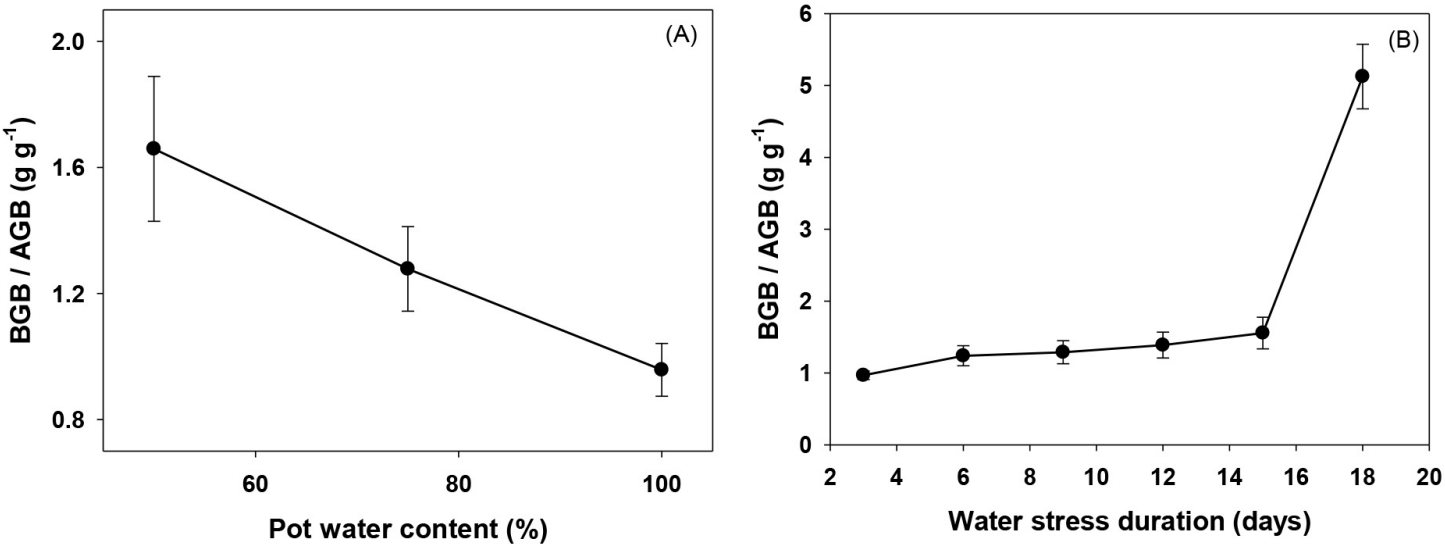

Figure 2

Belowground biomass (BGB) to aboveground biomass (AGB) ratio at different pot water contents (A) and durations of water stress (B). Vertical bars represent SED

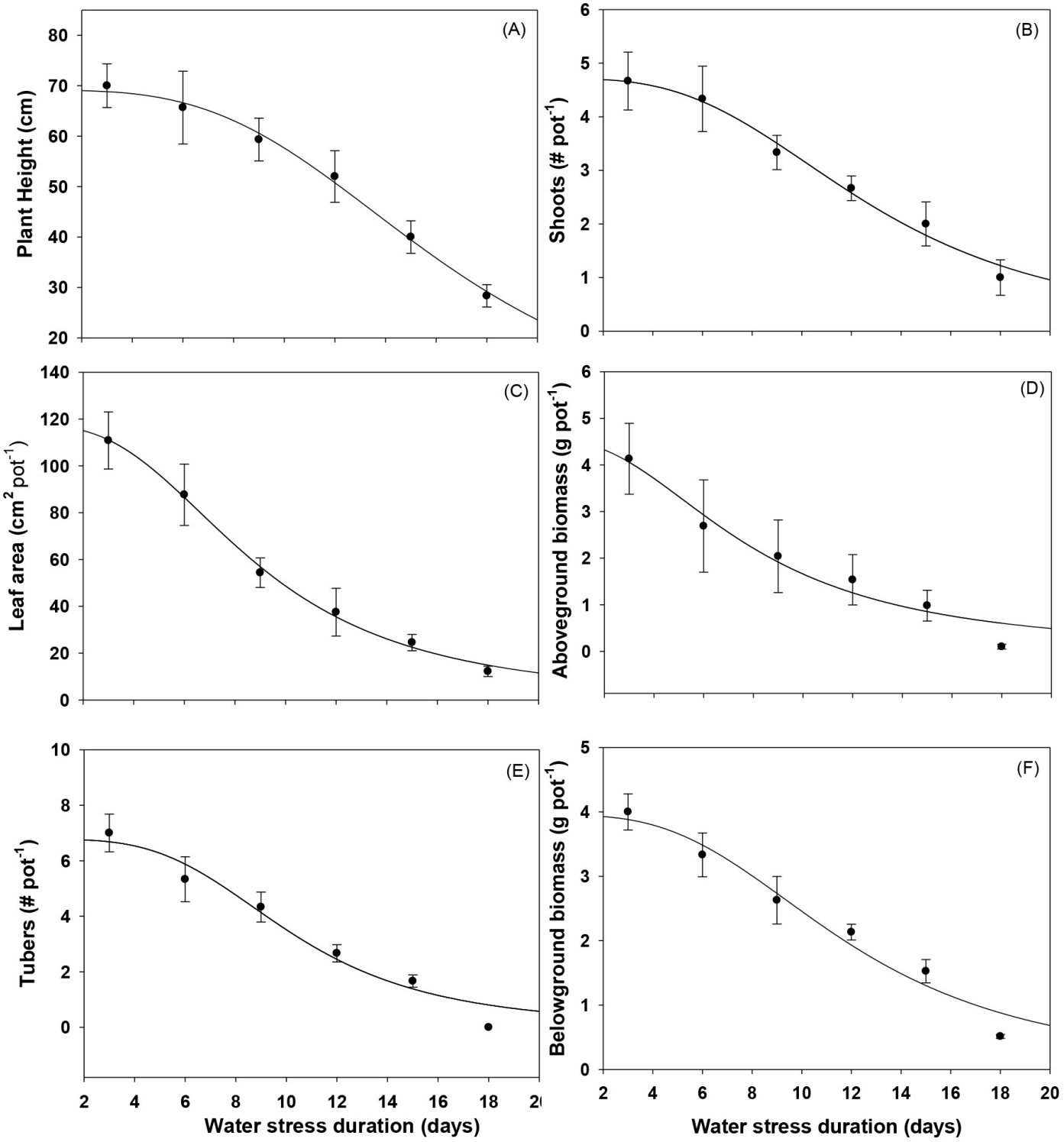

Figure 3

(A) Plant height, (B) shoots pot^{-1}, (C) leaf area pot^{-1}, (D) aboveground biomass, (E) tubers pot $^{-1}$ and (F) belowground biomass of *C. rotundus* plants grown under different durations of water stress. Vertical bars represent SED