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Allelopathic effects of Canada goldenrod leaf extracts on the seed germination and seedling growth of lettuce reinforced under salt stress

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Abstract

Allelopathic effects on the seed germination and seedling growth of the natives play a crucial role in the successful invasion of numerous invaders. Meanwhile, soil salinity is an emerging driver of the spread of many invaders, especially in the colonization of saline habitats. Thus, the allelopathic effects of the invaders on the seed germination and seedling growth of the natives may be altered or even reinforced under salt stress. This study aims to address the allelopathic effects of the notorious invader Canada goldenrod (*Solidago canadensis* L.; goldenrod hereafter) on the seed germination and seedling growth of the native lettuce (*Lactuca sativa* L.; lettuce hereafter) under a gradient of salt stress. Goldenrod leaf extracts with high concentration significantly decreased root length, leaf shape index, germination percentage, germination potential, germination index, germination vigor index, and germination rate index of lettuce. However, goldenrod leaf extracts with low concentration significantly increased root length and leaf width of lettuce. Goldenrod leaf extracts with high concentration display more serious allelopathic effects on the seed germination and seedling growth of lettuce than those with low concentration. Salt stress regardless of concentration significantly decreased seedling height, root length, leaf shape index, and seedling biomass (fresh weight) of lettuce. The combined goldenrod leaf extracts and salt stress have a synergistic effect on seedling height, root length, leaf shape index, germination percentage, germination potential, germination index, and germination rate index of lettuce. Thus, the allelopathic effects of the invaders on the seed germination and seedling growth of the natives may be reinforced under salt stress. Accordingly, salt stress may be beneficial to the further invasion of the invaders mainly via the reduced growth performance of the natives.

Keywords Allelopathic effects · Growth performance · Invasive plant species · Seed germination and seedling growth · Salt stress · *Solidago canadensis*

Introduction

At present, as one of the most global environmental problems, ever-increasing biological invasion trigger a severe threat to the structure and/or functions of the ecosystems in which the invasion process occur (Abhilasha et al. 2008; Yuan et al. 2013; Wang et al. 2017a, 2017b, 2018a, 2018b, 2018c). Accordingly, the mechanism underlying the successful invasion is a topic of long-standing interest to ecologists. In particular, the concept of allelopathy, i.e., numerous invasive plant species (invaders hereafter) can inhabit the growth and/or establishment of their competitors via the released allelochemicals, has become widely recognized as a major driving force of the successful invasion in the past decades (Callaway and Ridenour 2004; Yang et al. 2007; Yuan et al. 2013; Svensson et al. 2013). More importantly, the allelochemicals released by the invaders can recruit obviously allelopathic effects on the seed germination and seedling growth of the co-occurring native plant species (natives hereafter) (Abhilasha et al. 2008; Hu and Zhang 2013; Yuan et al. 2013; Wang et al.

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Table 1 The climate summaries of the sampling area

	Values	
	Maximum (month)	Minimum (month)
The annual mean temperature (°C)	16.1	
The monthly mean temperature (°C)	28.2 (July)	3.1 (January)
The annual precipitation (mm)	1150.6	
The monthly mean precipitation (mm)	213.8 (July)	35.1 (December)
The annual sunshine (h)	1986.9	
The monthly mean sunshine (h)	195.5 (May)	129.4 (February)

2016a, 2017c, 2017d, 2017e, 2017f). The seed germination and seedling growth is generally supposed as the critical process of the population recruitment and ecological expansion of plant species (Turk and Tawaha 2003; Hu and Zhang 2013; Svensson et al. 2013). According, the strongly allelopathic effects raised by the disgusting invaders have led to a reduction in the growth performance of the co-occurring natives (Yang et al. 2007; Abhilasha et al. 2008; Yuan et al. 2013; Wang et al. 2016a, 2017c).

Meanwhile, numerous plant species may often suffer salt stress (Parida and Das 2005; Morais et al. 2012; Rouifed et al. 2012; Chaugool et al. 2013). The salt stress can cause a significant shift in their growth performance (Parida and Das 2005; Rouifed et al. 2012; Chaugool et al. 2013; Li et al. 2017) mainly through water deficit, ion toxicity, ion imbalance, and/or a combination of these undesirable factors (Parida and Das 2005; Li et al. 2012; Hu et al. 2015). More importantly, soil salinity plays an important role in favoring or limiting the spread of many invaders, especially in the colonization of saline habits (Kuhn and Zedler 1997; Vasquez et al. 2006; Rouifed et al. 2012). In addition, some invaders, including the notorious invader Canada goldenrod (*Solidago canadensis* L.; goldenrod hereafter), were shown to be tolerant to salinity and to have invaded saline habits with a significant salt content (Xu et al. 2011; Li et al. 2012, 2017; Morais et al. 2012). Consequently, the allelopathic effects of the invaders on the seed germination and seedling growth of the co-occurring natives may be changed or even reinforced under the progressive shifts in the salt stress. Hence, it is important to address the allelopathic effects of the invaders on the seed germination and growth of the co-occurring natives across a gradient of salt stress in order to better understand the mechanism facilitate the successful invasion, especially under the condition with salt stress.

The present study focuses on the issue of the allelopathic effects of the notorious invader goldenrod (by using leaf extracts) on the seed germination and seedling growth of the native lettuce (*Lactuca sativa* L.; lettuce hereafter) under a gradient of salt stress. The results of the present study would offer a platform for further prying into the mechanism driving the success of goldenrod and build an important theoretical foundation and practical significance for effective invasion prevention and control, especially under the condition with salt stress.

This study tested the following hypotheses: (1) the allelopathic effects of goldenrod on the seed germination and seedling growth of lettuce significantly increases with increasing concentration of leaf extracts; (2) the effects of salt stress on the seed germination and seedling growth of lettuce also significantly increases with increasing concentration; (3) the combined goldenrod leaf extracts and salt stress contribute synergistically to the seed germination and seedling growth of lettuce compared with the independent goldenrod leaf extracts.

Materials and methods

Materials

In this study, we chose goldenrod as the targeted invader. Goldenrod is a herbaceous perennial species. The species was introduced to Shanghai in China in the 1930s as a horticultural plant in the early 1930s. The species has been distributed in most areas of China and this species poses a great threat to numerous ecosystems (mainly including meadows and pastures, along roads, upland forests, ditches, and savannas, etc.). Thus, goldenrod has been classified as one of the most noxious and destructive invaders in China (Dong et al. 2006; Abhilasha et al. 2008; Zhao et al. 2015). More important, the notably allelopathic effects of goldenrod on the co-occurring natives have been generally supposed as one of the main drives of its successful invasion in numerous habitats (Abhilasha et al. 2008; Yuan et al. 2013; Wang et al. 2016a, 2017c, 2018d).

Fully expanded, mature, and undamaged leaves samples of goldenrod were randomly collected from Zhenjiang (32.21°N, 119.52°E), China in late September 2017. The sampling area has a north subtropical monsoon humid climate. Table 1 shows the climate summaries of the sampling area. The climate summaries were taken from local records (Hang and Wu 2017). The leaves samples of goldenrod were thoroughly washed and completely air dried at room temperature for 72 h prior to take the post-processing steps.

Table 2 Summary of the bioassay design in this study

Treatment	Name	Concentration
CK	Control (distilled water)	$0\ g\ L^{-1}$
LE1	Goldenrod leaf extracts with low concentration	$10\ g\ L^{-1}$
LE2	Goldenrod leaf extracts with high concentration	$20\ g\ L^{-1}$
SalL	Salt stress (NaCl) with low concentration	$20\ mg\ L^{-1}$
SalH	Salt stress (NaCl) with high concentration	$40\ mg\ L^{-1}$
GolLSalL	The combined treatment of goldenrod leaf extracts and salt stress both with low concentration	The former with $10\ g\ L^{-1}$ and the latter with $20\ mg\ L^{-1}$, respectively
GolLSalH	The combined treatment of goldenrod leaf extracts with low concentration and salt stress with high concentration	The former with $10\ g\ L^{-1}$ and the latter with $40\ mg\ L^{-1}$, respectively
GolHSalL	The combined treatment of goldenrod leaf extracts with high concentration and salt stress with low concentration	The former with $20\ g\ L^{-1}$ and the latter with $20\ mg\ L^{-1}$, respectively
GolHSalH	The combined treatment of goldenrod leaf extracts and salt stress both with high concentration	The former with $20\ g\ L^{-1}$ and the latter with $40\ mg\ L^{-1}$, respectively

We chose lettuce seeds as the targeted native seeds. The lettuce seeds were bought in the local vegetable market. In particular, plenty of studies have demonstrated that lettuce seeds are sensitive to allelochemicals (Wang et al. 2016a, 2017d, 2017f, 2018d). Meanwhile, the two species (i.e., goldenrod and lettuce) can coexist in the same ecosystem, especially in farmland and wildland. In addition, the two plant species all belong to the Compositae family, which forms the maximum number of the invaders in China at the family level (Yan et al. 2014; Wang et al. 2016b).

Goldenrod leaf extracts preparation

Air-dried leaves of goldenrod (80 g) were placed in flasks containing 800 mL distilled water and were soaked for 48 h at room temperature. Then the next step is to filter the impurities (such as solid material) in the goldenrod leaf extracts by using cheese cloth and two layers of filter paper. The manufactured solution of goldenrod leaf extracts ($100\ g\ L^{-1}$) is placed in the refrigerator at 4 °C for subsequent processing. Dilutions were made with distilled water prior to use to create a series with gradient contents, namely, CK (control, $0\ g\ L^{-1}$; mimicked uninvaded condition), GolL (goldenrod leaf extracts with low concentration: $10\ g\ L^{-1}$; mimicked the light invasion degree), and GolH (goldenrod leaf extracts with high concentration: $20\ g\ L^{-1}$; mimicked the heavy invasion degree).

Salt solutions preparation

The salt solution was produced by using Sodium chloride (NaCl; Manufacturer: Sinopharm Chemical Reagent Co., Ltd., Shanghai, China; Reagent grade: AR, Purity: ≧ 99.5%). The salt solution were set with a gradient concentration, namely, CK (control, $0\ mg\ L^{-1}$; mimicked no salt stress condition), SalL (salt stress with low concentration, $20\ mg\ L^{-1}$; mimicked the light salt stress); SalH, (salt stress with high concentration, $40\ mg\ L^{-1}$; mimicked the heavy salt stress).

Bioassay design

The bioassay included nine treatments: control with distilled water, two different concentrations of goldenrod leaf extracts ($10\ g\ L^{-1}$, LE1; and $20\ g\ L^{-1}$, LE2) applied, two different concentrations of salt stress ($20\ mg\ L^{-1}$, SalL; and $40\ mg\ L^{-1}$, SalH) applied, and 2*2 combinations of goldenrod leaf extracts with salt stress applied. Each bioassay was performed in five replicates. A summary of the bioassay design is shown in Table 2.

Seed germination and seedling growth experiment

Seed germination and seedling growth experiments were carried out by using the incubation method in Petri dishes in the mid-May 2018 (Wang et al. 2016a, 2017c, 2017d, 2017e, 2017f, 2018d). The surface of the lettuce seeds were sterilized with 1% Sodium hypochlorite (NaClO; Manufacturer: Sinopharm Chemical Reagent Co., Ltd., Shanghai, China; Reagent grade: CP, Active chlorine content: 7–8% for Cl^-; Free alkali content: ≧ 5.2% for NaOH) for approximately 15 min and then rinsed thoroughly with deionized water. Thirty healthy seeds of lettuce were carefully move to the Petri dish (diameter: 9 cm) and carpeted with two layers of filter paper. The Petri dishes were placed in a climate-controlled incubator (Manufacturer: Taihong Medical Instrument Co., Ltd., Shaoguan, China; Instrument model: LRH-250-G; Instrument volume: 250 L; Temperature range: 5–75 °C; Instrument power: 600 W for normal light; Light intensity: 0–8000 Lux for normal light; Internal dimension: 50*48*103 cm; External dimension: 70*65*155 cm) in Jiangsu University at 25 °C for 10 d with

12 h light per day (the light intensity was set at 2200 Lux for normal light). 0.5 mL of deionized water, salt solutions, and/or goldenrod leaf extracts was applied in each Petri dish per day. The amount of germinated seeds was counted every day after incubation, and each lettuce seed was adjudged as germinated if the radicle has emerged (Wang et al. 2016a, 2017c, 2017d, 2017e, 2017f).

Determination of the seed germination and seedling growth indices of lettuce

Ten seedlings per Petri dish were randomly selected to estimate the values of the seed germination and seedling growth indices of lettuce on the same day.

Seedling height (SH), root length (RL), leaf length (LL), and leaf width (LW) were measured by using a ruler (Wang et al. 2016a, 2017c, 2017d, 2017e, 2017f). Leaf shape index (LSI) was calculated as the ratio of leaf length to the corresponding leaf width (Jeong et al. 2011; Wang and Zhang 2012).

Seedling biomass (fresh weight, SFW; dry weight, SDW) were determined by using an electronic balance with an accuracy of 0.001 g (Wang et al. 2016a, 2017c, 2017d, 2017e, 2017f). Moisture content (MC) was counted as the ratio of the absolute difference between fresh weight and dry weight to fresh weight (Wang et al. 2017d, 2018d).

Germination percentage (GPe) was determined using the ratio of the final number of germinated seeds to the total number of the subjects' seeds when no new germination occurred after 10 d of incubation (Hou et al. 2014, Wang et al. 2016a, 2017c, 2017d, 2017e, 2017f, 2018d).

Germination potential (GPo) was calculated using the ratio of the number of germinated seeds on the third day (i.e., the germination peak period) to the total number of the subjects' seeds (Wang et al. 2016a, 2017c, 2017d, 2017e, 2017f, 2018d).

Germination index (GI) was calculated as $\sum G_i/I$, where G_i indicative of the number of germinated seeds and I indicative of the time after cultivation (day) (Schmer et al. 2012; Hou et al. 2014).

Germination vigor index (GVI) was calculated in terms of the arithmetic product of GI and SFW (Lin et al. 2000).

Germination rate index (GRI) was measured by multiplying the two values of GPe and GI (Steinmaus et al. 2000).

The indices of allelopathic effects (*RIs*) for the all present indices of seed germination and seedling growth of lettuce were determined to assess the allelopathic effects of goldenrod leaf extracts with or without salt stress on the seed germination and seedling growth of lettuce. *RI* was defined as $1-C/T$ if T equal to or greater than C and as $T/C-1$ if T less than C; where C is the control value and T is the treatment value (Williamson and Richardson 1988).

Statistical analysis

Deviations from normality and homogeneity of variances were determined before data analysis. Differences among the seed germination and seedling growth indices of lettuce were assessed with an analysis of variance (ANOVA) among treatment groups followed by the Student–Newman–Keuls test for multiple comparisons. Statistically significant differences were set at P values equal to or lower than 0.05. All statistical analyses were performed using IBM SPSS Statistics (version 22.0; IBM Corp., Armonk, NY, USA).

Results

Effects of goldenrod leaf extracts on the seed germination and seedling growth indices of lettuce

Goldenrod leaf extracts regardless of concentration significantly decreased LSI (15.35 and 15.60% lower under low and high concentration, respectively), GPe (12.64 and 14.94% lower under low and high concentration, respectively), GPo (22.08 and 58.44% lower under low and high concentration, respectively), GI (15.62 and 36.73% lower under low and high concentration, respectively), and GRI (26.05 and 46.10% lower under low and high concentration, respectively) of lettuce compared with the control ($P < 0.05$; Fig. 1). Goldenrod leaf extracts with high concentration also significantly decreased RL (49.92% lower) and GVI (38.91% lower) of lettuce compared with the control ($P < 0.05$; Fig. 1). But, goldenrod leaf extracts with low concentration significantly increased RL (10.48% higher) and LW (14.44% higher) of lettuce compared with the control ($P < 0.05$; Fig. 1).

RL (54.67% lower), LW (11.65% lower), SFW (15.00% lower), GPo (46.67% lower), GI (25.02% lower), GVI (36.48% lower), and GRI (27.11% lower) under goldenrod leaf extracts with high concentration were significantly lower than those under goldenrod leaf extracts with low concentration ($P < 0.05$; Fig. 1).

Effects of salt stress on the seed germination and seedling growth indices of lettuce

Salt stress regardless of concentration significantly decreased SH (37.70 and 44.50% lower under low and high concentration, respectively), RL (66.59 and 68.81% lower under low and high concentration, respectively), LSI (10.61 and 12.77% lower under low and high concentration, respectively), and SFW (17.59 and 18.49% lower under low and high concentration, respectively) of lettuce compared with the control ($P < 0.05$; Fig. 1). Salt stress with high

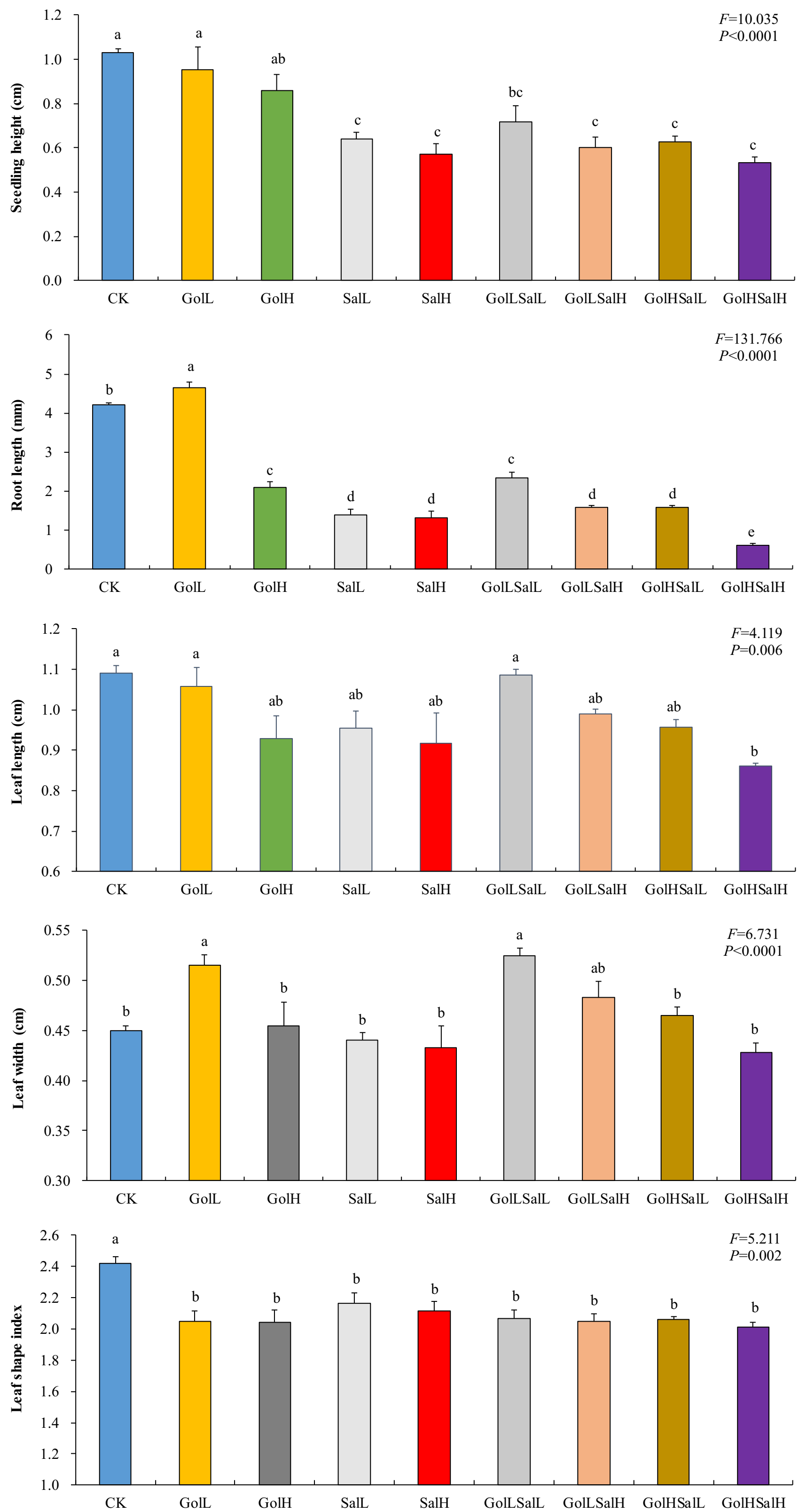
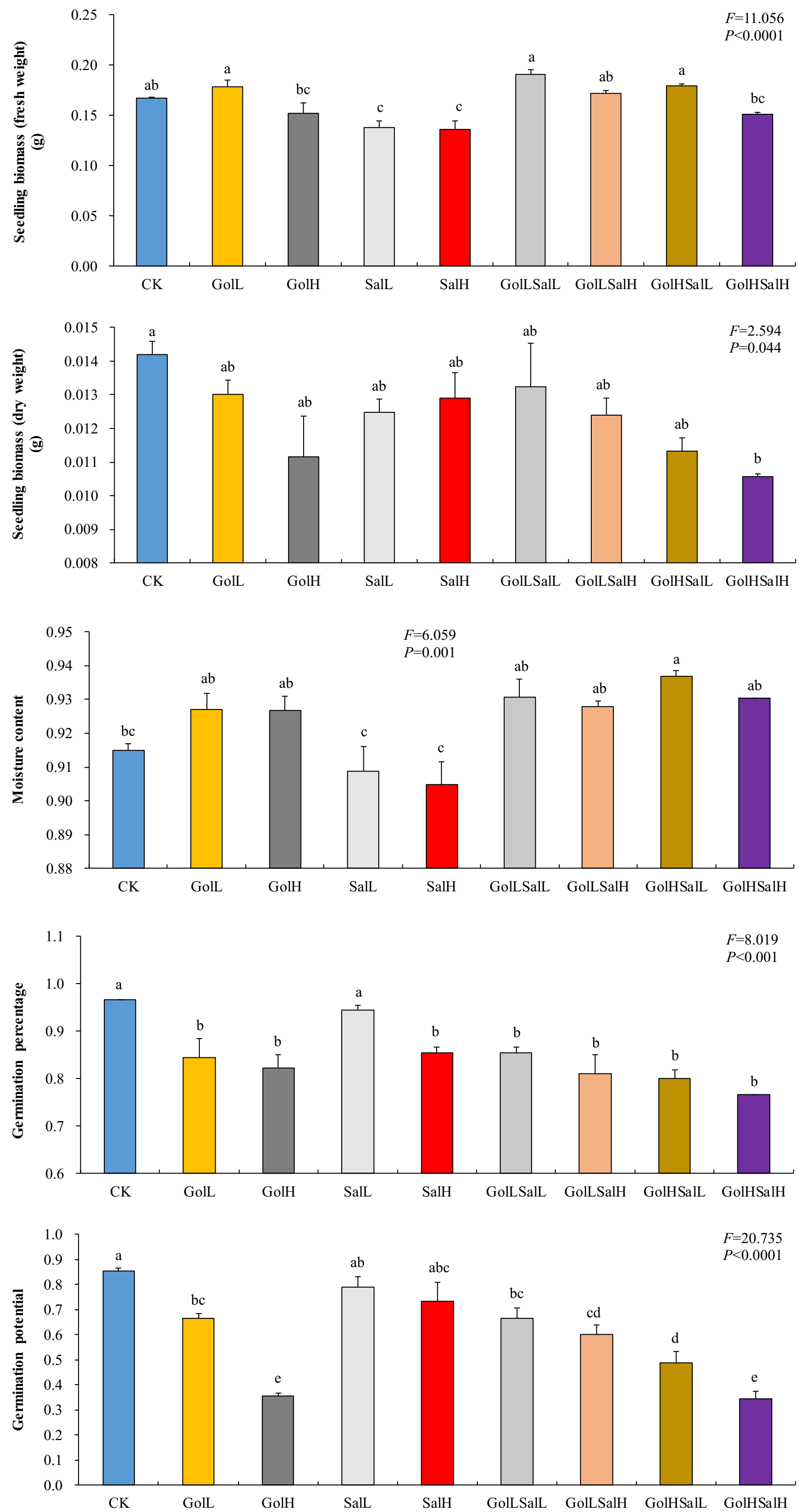


Fig. 1 The seed germination and seedling growth indices of lettuce with different treatments. Data (means and standard error) with different lowercase letters indicate a significant difference ($P < 0.05$) assessed by one-way analysis of variance followed by the Student–Newman–Keuls test for multiple comparisons. Abbreviations have the same meanings as described above (Table 2)

Fig. 1 (Continued)



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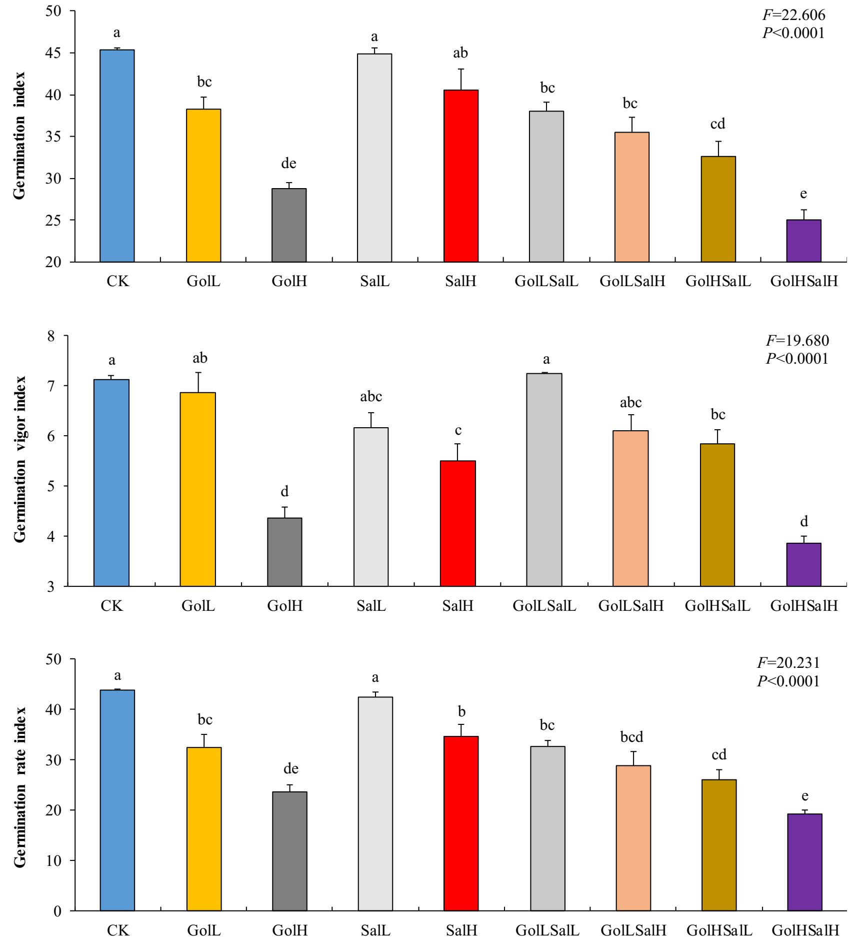


concentration also significantly decreased GPe (11.49% lower), GVI (22.82% lower), and GRI (20.90% lower) of lettuce compared with the control ($P < 0.05$; Fig. 1).

GPe (9.41% lower) and GRI (18.05% lower) under salt stress with high concentration of lettuce were significantly lower than those under salt stress with low concentration ($P < 0.05$; Fig. 1).

Effects of goldenrod leaf extracts on the seed germination and seedling growth indices of lettuce under salt stress

SH of lettuce was approximately 30.42, 41.75, 39.00, and 48.38% lower under the combined goldenrod leaf extracts and salt stress both with low concentration, the combined goldenrod leaf extracts with low concentration and salt stress with high concentration, the combined goldenrod leaf extracts with high concentration and salt stress with low concentration, and the combined goldenrod leaf extracts and salt stress both with high concentration compared with the control, respectively ($P < 0.05$; Fig. 1). RL of lettuce was approximately 44.56, 62.26, 61.98, and 85.28% lower under the combined goldenrod leaf extracts and salt stress both with low concentration, the combined goldenrod leaf extracts with low concentration and salt stress with high concentration, the combined goldenrod leaf extracts with high concentration and salt stress with low concentration, and the combined goldenrod leaf extracts and salt stress both with high concentration compared with the control, respectively ($P < 0.05$; Fig. 1). LSI of lettuce was approximately 14.62, 15.32, 15.05, and 16.91% lower under the combined goldenrod leaf extracts and salt stress both with low concentration, the combined goldenrod leaf extracts with low concentration and salt stress with high concentration, the combined goldenrod leaf extracts with high concentration and salt stress with low concentration, and the combined goldenrod leaf extracts and salt stress both with high concentration compared with the control, respectively ($P < 0.05$; Fig. 1). GPe of lettuce was approximately 11.49, 16.09, 17.24, and 20.69% lower under the combined goldenrod leaf extracts and salt stress both with low concentration, the combined goldenrod leaf extracts with low concentration and salt stress with high concentration, the combined goldenrod leaf extracts with high concentration and salt stress with low concentration, and the combined goldenrod leaf extracts and salt stress both with high concentration compared with the control, respectively ($P < 0.05$; Fig. 1). GI of lettuce was approximately 16.21, 21.78, 28.15, and 44.96% lower under the combined goldenrod leaf extracts and salt stress both with low concentration, the combined goldenrod leaf extracts with low concentration and salt stress with high concentration, the combined goldenrod leaf extracts with high concentration and salt stress with low concentration, and the combined goldenrod leaf extracts and salt stress both with high concentration compared with the control, respectively ($P < 0.05$; Fig. 1). GRI of lettuce was approximately 25.81, 34.09, 40.45, and 56.35% lower under the combined goldenrod leaf extracts and salt stress both with low concentration, the combined goldenrod leaf extracts with low concentration and salt stress with high concentration, the combined goldenrod leaf extracts with high concentration and salt stress with low concentration, and the combined goldenrod leaf extracts and salt stress both with high concentration compared with the control, respectively ($P <$ 0.05; Fig. 1). Meanwhile, LL (20.95% lower), SDW (25.59% lower), and GVI (45.82% lower) of lettuce also significantly decreased under the combined goldenrod leaf extracts and salt stress both with high concentration compared with the control ($P < 0.05$; Fig. 1).

Salt stress regardless of concentration significantly affected the allelopathic effects caused by goldenrod leaf extracts on the seed germination and seedling growth of lettuce (Fig. 1). In particular, SH of lettuce was approximately 24.69 and 36.95% lower under the combined goldenrod leaf extracts and salt stress both with low concentration and the combined goldenrod leaf extracts with low concentration and salt stress with high concentration compared with goldenrod leaf extracts with low concentration ($P < 0.05$; Fig. 1). SH of lettuce was also approximately 26.94 and 38.18% lower under the combined goldenrod leaf extracts with high concentration and salt stress with low concentration and the combined goldenrod leaf extracts and salt stress both with high concentration compared with goldenrod leaf extracts with high concentration ($P < 0.05$; Fig. 1). RL of lettuce was approximately 49.82 and 65.84% lower under the combined goldenrod leaf extracts and salt stress both with low concentration and the combined goldenrod leaf extracts with low concentration and salt stress with high concentration compared with goldenrod leaf extracts with low concentration ($P < 0.05$; Fig. 1). RL of lettuce was also approximately 24.09 and 70.60% lower under the combined goldenrod leaf extracts with high concentration and salt stress with low concentration and the combined goldenrod leaf extracts and salt stress both with high concentration compared with goldenrod leaf extracts with high concentration ($P < 0.05$; Fig. 1).

RL (60.99% lower), GPo (42.59% lower), GI (29.64% lower), GVI (36.72% lower), and GRI (33.77% lower) of lettuce under the combined goldenrod leaf extracts and salt stress both with high concentration were significantly lower than those under the combined goldenrod leaf extracts with low concentration and salt stress with high concentration ($P < 0.05$; Fig. 1). RL (31.42% lower), LW (11.43% lower), GPo (26.67% lower), and GVI (19.15% lower) of lettuce under the combined goldenrod leaf extracts with high concentration and salt stress with low concentration were significantly lower than those under the combined goldenrod leaf extracts and salt stress both with low concentration ($P < 0.05$; Fig. 1).

The index of allelopathic effect for the seed germination and seedling growth indices of lettuce under goldenrod leaf extracts and/or salt stress

The indices of allelopathic effects for SH, LL, LSI, SFW, GPe, GPo, GI, and GRI of lettuce were less than zero under all treatments (Fig. 2). Meanwhile, the indices of allelopathic effects for RL and GVI of lettuce were also less than zero under most treatments (Fig. 2). However, the indices of allelopathic effects for RL, LW, SFW, and MC of lettuce were greater than zero under goldenrod leaf extracts with low concentration (Fig. 2).

Discussion

Numerous studies have documented that the allelochemicals released by the invaders can lead to a significant reduction in the seed germination, seedling growth, or both of the co-occurring natives (Prati and Bossdorf 2004, Wang et al. 2016a, 2017c, 2017d, 2017e). The results of this study revealed that goldenrod leaf extracts with high concentration significantly decreased RL, LSI, GPe, GPo, GI, GVI, and GRI of lettuce compared with the control. Accordingly, goldenrod leaf extracts with high concentration triggered notably allelopathic effects on the growth of the underground part as well as the competitive ability for soil nutritious, leaf shape and variation, germination capacity and uniformity, and germination speed and vitality of lettuce seedling. Many previous studies have documented such similar phenomena (Yang et al. 2007; Abhilasha et al. 2008; Yuan et al. 2013; Wang et al. 2016a, 2017c, 2018d). Consequently, the growth performance of the co-occurring natives may be significantly suppressed under the allelopathic effects mediated by goldenrod with heavy invasion degree. It is interesting to mention that goldenrod leaf extracts with low concentration significantly increased RL

Fig. 2 The indices of allelopathic effects for the seed germination and seedling growth indices of lettuce with different treatments. The index indicates a simulative effect when the value greater than zero, while an inhibitory effect when it less than zero. Abbreviations have the same meanings as described above (Table 2)

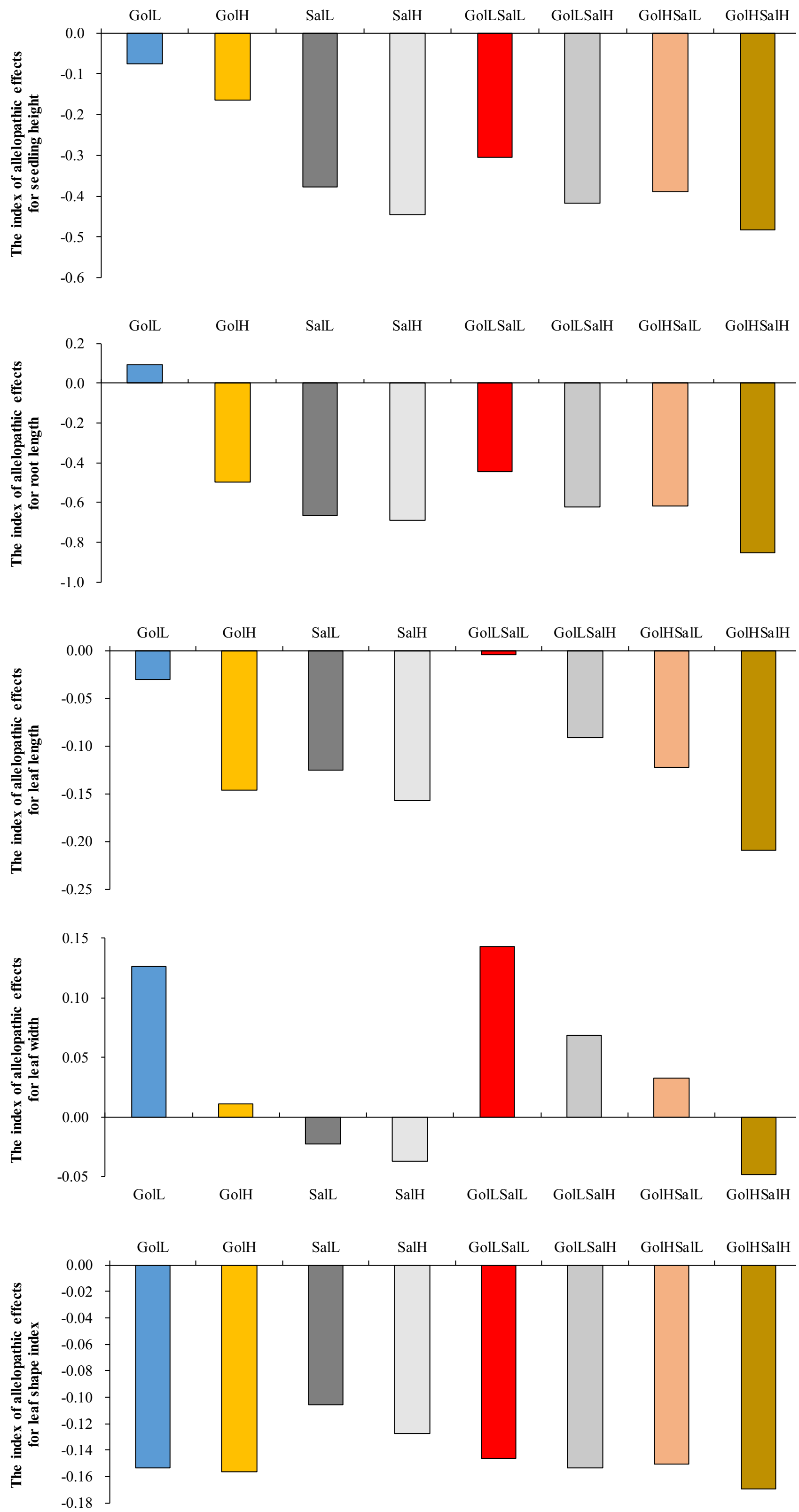
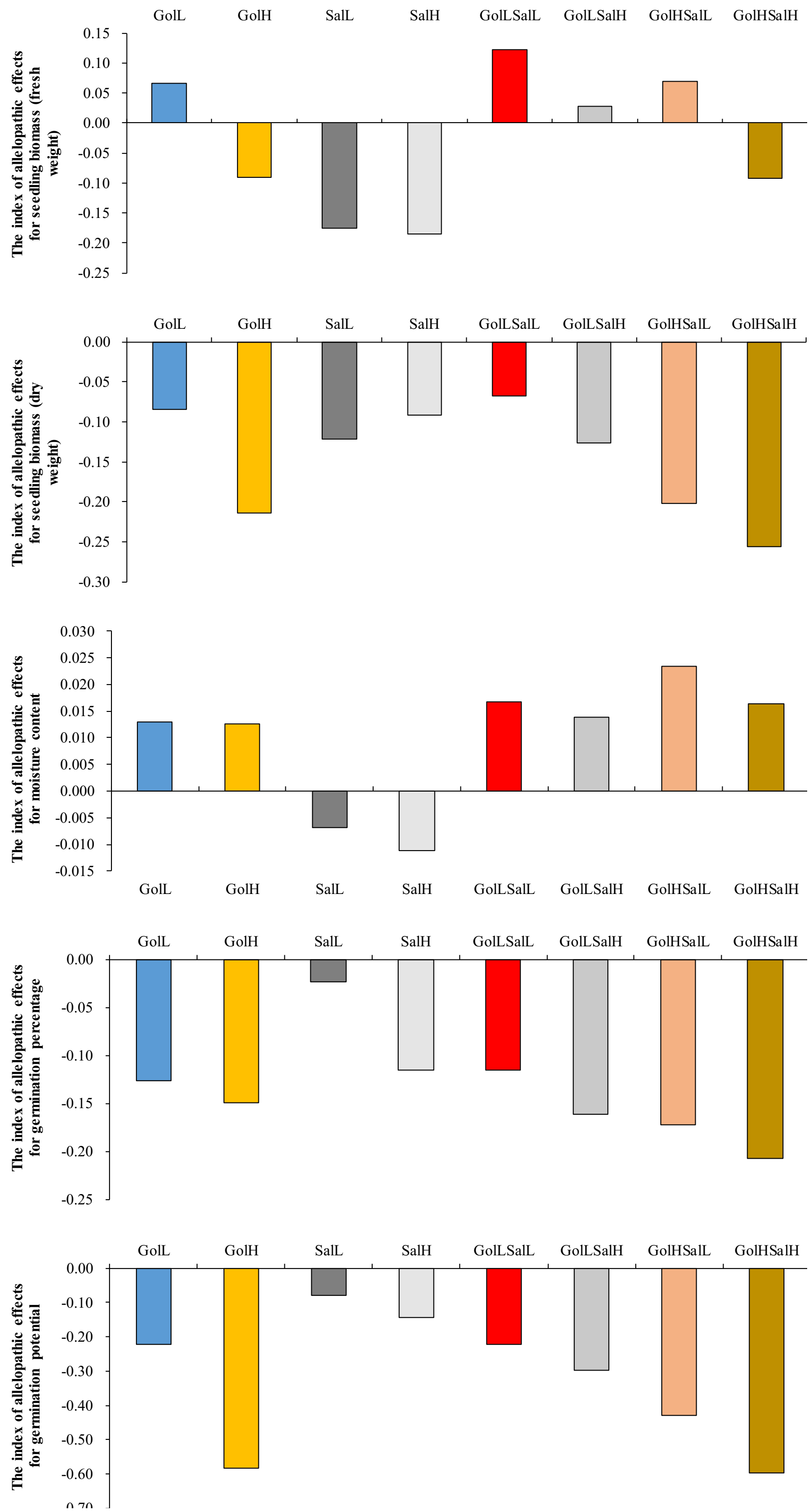
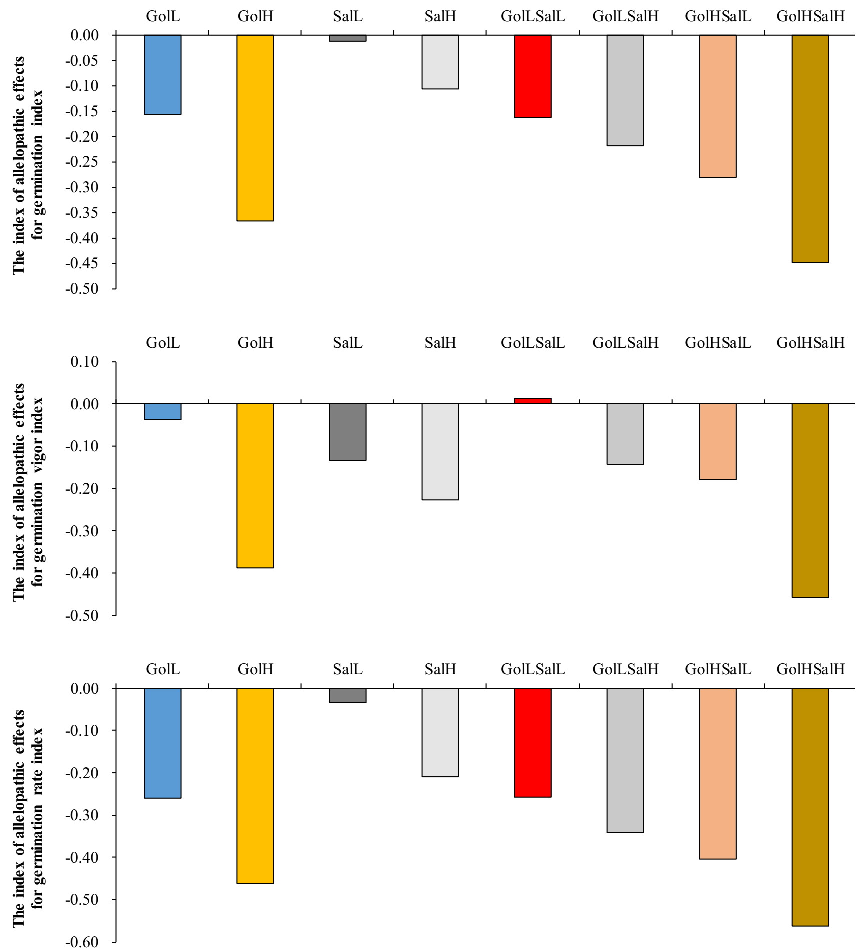


Fig. 2 (Continued)



and LW of lettuce compared with the control. In addition, the indices of allelopathic effects for RL, LW, SFW, and MC of lettuce were greater than zero under goldenrod leaf extracts with low concentration. Accordingly, goldenrod leaf extracts with low concentration can present a positive effect on the growth of the underground part as well as the

Fig. 2 (Continued)



competitive ability for soil nutritious, competitive ability for sunlight, growth competitiveness, and the degree of moisture of lettuce seedling. Thus, goldenrod with light invasion degree can enhance the growth performance of the co-occurring natives. A possible explanation is that the allelochemicals released by goldenrod leaf extracts with low concentration can generate the reactive oxygen molecules in plant cell extension and then produce a positive effect on the seed germination and seedling growth of lettuce (Duke et al. 2006; Prithiviraj et al. 2007). It can be said that the invader with light invasion degree can pose light stress on the co-occurring natives and then give a positive force for their seed germination and seedling growth (Ye et al. 2014; Hossain et al. 2016; Wang et al. 2017c, 2017e, 2018d). This kind of situation may be attributed in part to hormonal effects which is generally considered as the main driver of the ecological strategies for plant species response to external pressure (An 2005; Viator et al. 2006, Takao et al. 2011). Accordingly, the invaders with light invasion degree did not show an allelopathic effect on the seed germination and seedling growth of the co-occurring natives.

While, the result of this study also revealed that goldenrod leaf extracts with high concentration display more serious allelopathic effects on RL, LW, SFW, GPo, GI, GVI, and GRI of lettuce than those with low concentration. Based on this, the growth of the underground part as well as the competitive ability both for soil nutritious and sunlight, growth competitiveness, germination capacity and uniformity, and germination speed and vitality of lettuce seedling may be significantly restrained with increasing concentration of goldenrod leaf extracts. Thus, the allelopathic effects of goldenrod on the seed germination and seedling growth of lettuce significantly improved with increasing invasion degree of goldenrod which can facilitate its further invasion process. The phenomenon largely from the fact that more allelochemicals may be released into the colonized ecosystems with increasing invasion degree of the invaders and then pose more seriously allelopathic effects on the seed germination and seedling growth of the co-occurring natives (Wang et al. 2016a, 2017c, 2017d). A previous study also showed an accumulation for the allelochemicals in the invaded ecosystem with increasing invasion degree of goldenrod (Zhang et al. 2011). As a consequence, the results were consistent with the study's first hypothesis.

The results of this study showed that salt stress regardless of concentration pose a significant negative effect on SH, RL, LSI, and SFW of lettuce compared with the control. Salt stress with high concentration also has a significantly negative effect on GPe, GVI, and GRI of lettuce compared with the control. Therefore, salt stress can agitate a significant inhibition on the growth both of the underground and aboveground parts as well as the competitive ability both for sunlight and soil nutritious, leaf shape and variation, growth competitiveness, germination ability, and germination speed and vitality of lettuce seedling. The reduced growth performance of lettuce mediated by salt stress may be mainly due to the water deficit, ion toxicity, ion imbalance and/or a combination of these factors (Parida and Das 2005; Li et al. 2012; Hu et al. 2015). Meanwhile, GPe and GRI of lettuce seedling under salt stress with high concentration were significantly lower than those under salt stress with low concentration. Accordingly, salt stress with high concentration may be more toxic on the germination ability and germination speed and vitality of lettuce than that with low concentration. The possible reason for this is that salt stress with high concentration can release more degrees of water deficit, ion toxicity, ion imbalance and/or a combination of these factors than salt stress with low concentration and thus exert more toxicity (Parida and Das 2005; Li et al. 2012; Hu et al. 2015). Thus, the effects of salt stress on the seed germination and seedling growth of lettuce significantly increases with increasing concentration. Consequently, the results were consistent with the study's second hypothesis.

The results of this study revealed that the combined goldenrod leaf extracts and salt stress have a synergistic effect on SH, RL, LSI, GPe, GI, and GRI of lettuce compared with the control. Thus, the growth both of the underground and aboveground parts as well as the competitive ability both for sunlight and soil nutritious, leaf shape and variation, germination ability, and germination speed and vitality of lettuce seedling may be significantly reduced under the combined goldenrod leaf extracts (particularly with high concentration) and salt stress. This phenomenon could be explained by the fact that the goldenrod leaf extracts (particularly with high concentration) and salt stress restrain the seed germination and growth of lettuce, thereby create a synergistic effect when they interact. The results of this study also showed that the combined goldenrod leaf extracts and salt stress regardless of concentration significantly decreased SH and RL of lettuce compared with goldenrod leaf extracts with the same concentration alone. In addition, the absolute value for the indices of allelopathic effects for the most of the seed germination and seedling growth indices of lettuce under the combined goldenrod leaf extracts and salt stress were lower than those under goldenrod leaf extracts alone. Thus, salt stress regardless of concentration significantly improved the allelopathic effects caused by goldenrod leaf extracts on the growth both of the underground and aboveground parts as well as the competitive ability both for sunlight and soil nutritious of lettuce seedling. As a consequence, the allelopathic effects of the invaders on the seed germination and seedling growth of the co-occurring natives may be reinforced under the condition with salt stress. Thus, the results were consistent with the study's third hypothesis. Accordingly, salt stress may be beneficial to the invasion process of the invaders mainly via the reduced growth performance of the co-occurring natives.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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