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Impact of an alien invasive plant *Amaranthus retroflexus* on wetland sediment properties under two growth stages

Xiang Bai ^a and Li-Xia Shang ^b

^aDepartment of Ecology, Hebei University of Environmental Engineering, Qinhuangdao, P. R. China; ^bKey Laboratory of Marine Ecology and Environmental Sciences, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, P. R. China

ABSTRACT

It is meaningful to investigate the impact of alien invasive plants on wetland sediment. Field experiments were conducted to study the impact of the alien invasive plant, *Amaranthus retroflexus*, on wetland sediment properties under two growth stages. The results showed that growth of *A. retroflexus* tended to increase moisture content, porosity, and could significantly decrease total nitrogen (TN) and nitrate (N-NO_3^-) concentrations in sediment and ammonium (N-NH_4^+) concentration in interstitial water ($p < 0.05$). However, no obvious impact was observed on total phosphorus (TP) nor on N-NH_4^+ concentrations in sediment. There was a difference in impact of *A. retroflexus* on sediment properties under two growth stages. The plants with a longer growth stage significantly decreased loss on ignition in sediment and P-PO_4^{3-} concentration in interstitial water. There were also significant differences in N-NH_4^+ concentration in both sediment and interstitial water over the vertical profile of the plant. In the plant treatment with a longer growth stage, P-PO_4^{3-} concentration also showed significant differences over the vertical profile. Therefore, the growth of *A. retroflexus* can improve sediment physical and chemical properties, reducing N-NH_4^+ and P-PO_4^{3-} release from sediment to overlying water to some extent, thereby decreasing sediment nutrient loading.

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Introduction

In today's world, biological invasions are severe ecological and environmental problems that happen worldwide. Invasion results in a series of impacts to the invaded habitat, including changed distribution patterns of available resources, altered community structure, decreased biodiversity, etc. (Bai et al. 2016). As an important component of biological invasion, alien plants can increase or decrease the rate of nutrient cycling in the soil (Ehrenfeld 2003; Corbin and D'Antonio 2004; Dassonville et al. 2008) or increase soil nutrient content (Qin et al. 2014), these have direct and indirect effects on the composition and function of soil communities which may create a feedback that influences aboveground communities (Wolfe and Klironomos 2005).

Amaranthus retroflexus is an important alien invasive plant belonging to the family of Amaranthaceae. It is an erect, annual broadleaf herb with taproot system. Its plant height is from 20 to 80 cm (maximum of 100 cm) in China. *A. retroflexus* has strong adaptive ability and can invade different communities for settlement (Gao et al. 2011), such as farmland, orchard, park, road sides,

intertidal zone and wasteland, and has a negative impact on them. Due to its strong invasiveness, *A. retroflexus* is ranked third in the list of alien invasive plants in China. However, as an alien plant, it has a high utilization value which needs to be developed. As one of the three ecosystems (wetland, forest, and ocean) in the world, wetlands can also be invaded by *A. retroflexus*. The plant has resulted in moderate damage to Dongting Lake wetland in Hunan province, China (Hou et al. 2011). Another study shows that the allelopathy effect of *A. retroflexus* is the strongest when this plant is a seedling (Liu and Ma 2009; Zhao et al. 2013), so the impact of *A. retroflexus* is different under different growth stages. Recently, research on the impact of *A. retroflexus* mainly focused on agricultural production in terrestrial ecosystems (Saberli et al. 2012; Gholamhoseini et al. 2013; Amini et al. 2014). So far, there is little information about the impact of *A. retroflexus* invasion on sediment biogeochemistry of wetlands, resulting in a lack of systematic understanding of the impact of this plant on wetland ecosystems. *A. retroflexus* has been verified to have the ability for nitrate enrichment (Bischoff and Smith 2011). Is there any positive impact of this plant on sediment in wetlands? In order to answer this question, field experiments were conducted with the objective of investigating the impact of alien invasive plant *A. retroflexus* on sediment physicochemical properties as well as nitrogen and phosphorus concentrations in interstitial water. The results can provide useful information for understanding the impact of *A. retroflexus* on sediment nutrient loading, providing further scientific references for the management of alien invasive plants and wetland ecosystem protection.

Materials and methods

Materials and experimental design

Seeds of *A. retroflexus* were collected in autumn of the past year from the campus of Hebei University of Environmental Engineering (HUEE), Qinhuangdao, Hebei province, China. In early June, about 30 seeds were sown in a plant slot (S1) which was 40 and 15 cm in length and width, respectively. Ten days later, another 30 seeds were sown in another plant slot (S2) with the same soil. After 14 days, due to different germination periods, plants in the two plant slots were in different growth stages with different plant heights. The plant height was about 24 cm (PH24) from S1, and 11 cm (PH11) from S2. Five plants with about the same plant height in each plant slot were selected and planted in five pots (20 cm in height and 15 cm in upper diameter). One pot contained one experimental plant and 20 cm sediment in depth. The sediment was collected from the Xinhe River on the campus of HUEE (39°51'55"N, 119°26'47"E). The sediment type is clay, and its principal properties are listed in Table 1. The treatment with the same sediment and without plant was used as a contrast (CK). The sediment was well mixed before it was added to the pots one by one. Therefore, there were three treatments including PH24, PH11, and CK, with five replicates for each treatment. After letting the seedlings recover for five days, the pots were put into 15 buckets which were about 30 cm in height and 20 cm in upper diameter (one bucket contained one pot). The buckets were filled with river water collected from Xinhe River and filtered by a 25# plankton net. Due to the weaker adaptability of *A. retroflexus* to flooding and the comparability of this experiment, water depth was controlled at 5 cm above the surface sediment. Total nitrogen (TN), total phosphorus (TP), ammonium (N-NH₄⁺) and phosphate (P-PO₄³⁻) concentrations of the river water were 0.448 ± 0.097, 0.029 ±

Table 1. Principal properties of the sediment and N-NH₄⁺ and P-PO₄³⁻ in interstitial water. MC, moisture content. φ , porosity. LOI, loss on ignition. TN, total nitrogen. TP, total phosphorus. N-NH₄⁺, ammonium. N-NO₃⁻, nitrate. P-PO₄³⁻, phosphate. The same as below.

Sediment					Interstitial water				
MC (%)	φ (%)	LOI (%)	TN (mg/g)	TP (mg/g)	N-NH ₄ ⁺ (mg/g)	N-NO ₃ ⁻ (mg/g)	N-NH ₄ ⁺ (mg/L)	P-PO ₄ ³⁻ (mg/L)	
52.03	73.32	10.44	0.717	0.362	0.018	0.013	0.103	0.013	

0.009, 0.101 ± 0.022 , and 0.013 ± 0.002 mg/L, respectively. Due to the weak growth potential of the plant in PH11 and for comparability among the treatments, the experiment ran for 21 days (from 1 July to 21 July 2016).

Sampling and analysis

At the end of the experiment, 50 ml of the overlying water was first collected using syringes. Sediment was then divided into five layers from top down (0 ~ 2, 2 ~ 5, 5 ~ 10, 10 ~ 15, and 15 ~ 20 cm) and sampled carefully according to sediment depth. Sediment samples were divided into two parts, one was used for the determination of physicochemical properties, another part was used for the determination of N-NH_4^+ and P-PO_4^{3-} concentrations in interstitial water after centrifugation (5000 r/min for 15 min) and filtering through $0.45\text{-}\mu\text{m}$ fiber membranes. Moisture content (MC) and porosity (φ) were determined by the dispersion method. Loss on ignition (LOI) was determined by calculating weight loss after combusting dry sediment samples at $550\text{ }^\circ\text{C}$ for 4 h. TN and TP were measured by titration after $\text{K}_2\text{Cr}_2\text{O}_7\text{-H}_2\text{SO}_4$ digestion and by molybdenum blue method after combustion at $450\text{ }^\circ\text{C}$ for 3 h and 3.5 mol/L HCl extraction, respectively. Sediment N-NH_4^+ and nitrate (N-NO_3^-) were determined using the Nessler's reagent colorimetric and ultraviolet spectrophotometry screening, respectively. N-NH_4^+ and P-PO_4^{3-} in interstitial water were measured using Nessler's reagent colorimetric method and molybdenum blue method, respectively (Jin and Tu 1990).

Statistical analysis

Statistical analysis was performed with SPSS 16.0. After performing the homogeneity of variances test, one-way ANOVA was performed to determine the differences among the experimental treatments and the vertical profiles of each treatment. LSD-test was used to determine the significant difference among means. t -test was also used to determine the plant differences between the two growth stages. All statistically significant differences were tested at $p < 0.05$.

Results

Plant differences

There were morphological differences of *A. retroflexus* under different growth stages (Table 2). Plant height, basic stem diameter, root length, and total biomass of the plant in PH24 were 4.69, 1.63, 1.49, and 3.74 times higher than that in PH11, respectively, while root to shoot ratio in PH24 was 51.73% to PH11. The results of t -test showed that the plant differences between PH24 and PH11 were significant ($p < 0.01$), indicating that there were significant differences of *A. retroflexus* under two growth stages after growing for 21 days at 5 cm water depth.

Table 2. Morphological differences of *A. retroflexus* under two growth stages ($n = 5$). PH24 and PH11 were the experimental plants with early and late germination period, and plant height was 24 and 11 cm at the beginning of experiment, respectively. The same as below.

	PH24	PH11	t -value	p
Plant height (cm)	29.18 ± 2.30	17.30 ± 2.25	8.262	<0.000
Basic stem diameter (mm)	1.92 ± 0.18	1.18 ± 0.13	7.475	<0.000
Root length (cm)	13.62 ± 1.16	9.16 ± 1.43	5.429	0.001
Total biomass (g)	1.538 ± 0.092	0.411 ± 0.036	25.640	<0.000
Root-to-shoot ratio	0.195 ± 0.007	0.376 ± 0.014	-26.500	<0.000

Table 3. Sediment physicochemical properties over the vertical profile among treatments ($n = 5$).

Treatments	Profile (cm)	MC (%)	φ (%)	LOI (%)	TN (mg/g)	TP (mg/g)	N-NH ₄ ⁺ (mg/g)	N-NO ₃ ⁻ (mg/g)
PH24	0 ~ 2	55.64	75.80	12.57	0.512	0.283	0.010	0.003
	2 ~ 5	54.50	74.87	11.92	0.544	0.321	0.011	0.003
	5 ~ 10	54.48	74.92	11.65	0.571	0.345	0.012	0.004
	10 ~ 15	53.73	74.35	10.85	0.430	0.294	0.013	0.003
	15 ~ 20	54.77	75.17	10.50	0.463	0.302	0.018	0.003
PH11	0 ~ 2	54.84	75.07	11.67	0.524	0.334	0.011	0.003
	2 ~ 5	53.71	74.30	12.69	0.417	0.297	0.011	0.003
	5 ~ 10	52.92	73.75	14.15	0.503	0.340	0.009	0.004
	10 ~ 15	52.64	73.53	14.90	0.461	0.310	0.012	0.003
	15 ~ 20	50.57	71.87	14.55	0.553	0.358	0.017	0.004
CK	0 ~ 2	51.40	72.53	16.27	0.839	0.280	0.011	0.009
	2 ~ 5	53.23	73.99	16.23	0.703	0.321	0.012	0.008
	5 ~ 10	51.76	72.83	15.33	0.598	0.355	0.012	0.008
	10 ~ 15	52.74	73.47	13.48	0.788	0.244	0.013	0.008
	15 ~ 20	52.42	73.36	10.47	0.631	0.290	0.015	0.009

Sediment properties

There was different impact of *A. retroflexus* on sediment moisture content, porosity, LOI, TN, TP, N-NH₄⁺, and nitrate (N-NO₃⁻) concentrations under two growth stages, resulting in the differences among the treatments and over the vertical profile (Table 3). Compared to CK, growth of *A. retroflexus* resulted in higher moisture content, porosity, and lower LOI, TN and N-NO₃⁻ concentrations in the sediment (Table 4). Sediment properties of *A. retroflexus* also showed differences under two growth stages. Sediment in PH24 had higher moisture content, porosity, TN, and N-NH₄⁺ concentrations, and lower LOI and TP concentration. Results of one-way ANOVA showed that there were significant differences in LOI, TN and N-NO₃⁻ concentrations among different treatments (Table 5, $p < 0.01$), in which LOI of PH24 was significantly lower than other two treatments, while TN and N-NO₃⁻ of plant treatments were significantly lower than CK, indicating that growth of *A. retroflexus* altered the physical properties and decreased nitrogen loading of sediment. Although there were no significant differences in TN and N-NO₃⁻ concentrations between the two plant treatments,

Table 4. The mean values of sediment properties over the vertical profile ($n = 5$).

Treatments	Sediment							Interstitial water	
	MC (%)	φ (%)	LOI (%)	TN (mg/g)	TP (mg/g)	N-NH ₄ ⁺ (mg/g)	N-NO ₃ ⁻ (mg/g)	N-NH ₄ ⁺ (mg/L)	P-PO ₄ ³⁻ (mg/L)
PH24	54.62	75.02	11.50 a	0.504 a	0.309	0.013	0.003 a	0.112 a	0.011 a
PH11	52.94	73.70	12.99 b	0.492 a	0.328	0.012	0.003 a	0.120 a	0.013 b
CK	52.31	73.24	14.35 b	0.712 b	0.298	0.013	0.008 b	0.152 b	0.013 b

Table 5. Results of F -values and significance from one-way ANOVA among treatments of plant and sediment profile ($n = 5$). Plant: F -values and significance among the three treatments; Sediment profile: F -values and significance over the vertical profile.

Dependent variable	Plant	Sediment profile		
		PH24	PH11	CK
Sediment				
MC	2.740 ns	0.166 ns	0.617 ns	0.198 ns
φ	2.759 ns	0.176 ns	0.587 ns	0.188 ns
LOI	7.641**	10.139**	43.793***	56.86***
TN	11.324***	2.279 ns	0.562 ns	0.679 ns
TP	1.041 ns	2.473 ns	0.304 ns	1.385 ns
N-NH ₄ ⁺	0.355 ns	19.073***	19.935***	1.973 ns
N-NO ₃ ⁻	7.868**	0.213 ns	0.641 ns	1.387 ns
Interstitial water				
N-NH ₄ ⁺	4.770*	8.082**	16.481***	2.154 ns
P-PO ₄ ³⁻	3.411*	5.040*	1.234 ns	0.338 ns

ns, $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 6. N-NH₄⁺ and P-PO₄³⁻ distribution in interstitial water (*n* = 5).

	PH24		PH11		CK	
	N-NH ₄ ⁺ (mg/L)	P-PO ₄ ³⁻ (mg/L)	N-NH ₄ ⁺ (mg/L)	P-PO ₄ ³⁻ (mg/L)	N-NH ₄ ⁺ (mg/L)	P-PO ₄ ³⁻ (mg/L)
OW	0.013 ± 0.001	0.002 ± 0.001	0.021 ± 0.001	0.003 ± 0.001	0.035 ± 0.003	0.005 ± 0.001
0~2	0.096 ± 0.030	0.007 ± 0.002	0.098 ± 0.020	0.011 ± 0.002	0.119 ± 0.011	0.012 ± 0.002
2~5	0.089 ± 0.015	0.007 ± 0.001	0.099 ± 0.014	0.013 ± 0.002	0.156 ± 0.039	0.014 ± 0.002
5~10	0.112 ± 0.018	0.011 ± 0.004	0.093 ± 0.006	0.016 ± 0.004	0.148 ± 0.004	0.013 ± 0.003
10~15	0.111 ± 0.009	0.016 ± 0.002	0.114 ± 0.024	0.013 ± 0.002	0.150 ± 0.039	0.013 ± 0.004
15~20	0.168 ± 0.039	0.011 ± 0.003	0.196 ± 0.022	0.015 ± 0.006	0.185 ± 0.025	0.015 ± 0.002

N-NO₃⁻ concentration, compared to PH11, decreased by 13.56% while TN increased by 2.49% in the plant treatment of PH24. Furthermore, there were significant differences of LOI and N-NH₄⁺ concentration over the vertical profile in two plant treatments (*p* < 0.05). LOI in CK also showed significant differences over the vertical profile. These indicated that N-NH₄⁺ concentration in plant treatments, and LOI in all treatments varied significantly over the vertical profile.

N-NH₄⁺ and P-PO₄³⁻ distribution in interstitial water

There were differences of N-NH₄⁺ and P-PO₄³⁻ concentrations in overlying water and interstitial water (Table 6). Due to the lower concentration in overlying water, they could release from sediment to overlying water. According to the mean concentration over the sediment vertical profile (Table 4), N-NH₄⁺ concentration was lower in interstitial water in plant treatments, while treatment of PH24 had lower P-PO₄³⁻ concentration than other two treatments. Statistical analysis showed that plant growth significantly decreased N-NH₄⁺ concentration in interstitial water (Table 5, *p* < 0.05). No significant differences were observed between the two plant treatments, however, N-NH₄⁺ concentration in interstitial water in treatment of PH24 was 6.67% lower than PH11. Meanwhile, P-PO₄³⁻ concentration in PH24 was significantly lower in interstitial water than other two treatments due to which there was no significant difference between them. The differences of N-NH₄⁺ and P-PO₄³⁻ concentrations over the vertical profile were also significant in the plant treatment of PH24 (*p* < 0.05), as well as N-NH₄⁺ concentration in plant treatment of PH11 (*p* < 0.05). However, there were no significant differences in CK.

Discussion

Wetland sediment plays an important role in the function of wetland ecosystem. Among the influencing factors of freshwater eutrophication, nitrogen (N) and phosphorus (P) are considered to be the main nutrient elements. The sources of N and P can be divided into exogenous and endogenous sources. When exogenous pollution is controlled, endogenous N and P loading in sediment will emerge (Bai et al. 2012). Under proper conditions, N and P can release from sediment to overlying water by diffusion, convection, and sediment resuspension (Ignatieva 1996; Golosov and Ignatieva 1999; Chowdhury and Bakri 2006), which may be a key factor in continuing water quality deterioration and eutrophication when external nutrient loading is controlled effectively (Spears et al. 2007). Therefore, researchers are trying to find effective ways to prevent N and P releasing from sediment to overlying water by focusing on the impact of plants on sediment properties (Moore et al. 1994; Wigand et al. 1997; Sand-Jensen 1998; Templer et al. 1998; Madsen et al. 2001). The plants in these studies are mainly wetland plants, and have different functions in controlling sediment endogenous N and P release (Bai et al. 2012; Bai et al. 2013). In this experiment, results show that growth of *A. retroflexus* can decrease N in sediment and N and P in interstitial water, which reduces the possibility of N and P releasing from sediment to overlying water. However, there is different impact of *A. retroflexus* growth on sediment properties under two growth stages.

Plant growth is vital to change sediment physical properties in a variety of ways. Investigation in natural wetlands indicates that subsurface porosity of sediment (2 ~ 5 cm) with plants is 30% higher than that without plants (Gu et al. 2010). However, *A. retroflexus* under two growth stages increases sediment porosity by only 2.43% and 0.63%, which may be due to the short experimental period. LOI provides a rough estimation of organic matter content in sediment. Living roots and rhizomes in wetlands can supply organic matter to sediment by excretion of dissolved organic carbon and fermentation products from anaerobic root metabolism (Gribsholt et al. 2003), and improves LOI. Meanwhile, the decomposition of plant litter can also result in high carbon content in the sediment (Dinakaran and Krishnayya 2010). Researches have indicated that root has the ability to excrete oxygen to sediment interstitial spaces (Sand-Jensen and Prahl 1982; Smith et al. 1984), and increases rhizosphere oxidation state, resulting in the decomposition of organic matter. This may be the main reason for the lower organic matter content in sediment with *A. retroflexus* growth in this experiment. The difference in root oxygen excretion of the plant under two growth stages may result in the significant difference in organic matter content. It is needed to clarify the root oxygen excretion of *A. retroflexus* and the redox potential alteration of sediment under different growth stages in further investigation. On the other hand, plant growth can change nutrient concentration in sediment. As one of the main functions, roots can acquire nutrient elements such as N and P for plant growth and reduce their concentration in sediment (Rattray et al. 1991). Similarly, oxygen excretion from roots can promote organic N mineralization and increase inorganic N concentrations in sediment. Nitrification process can also be promoted to increase N-NO₃⁻ concentration (Bai et al. 2013). However, *A. retroflexus* has the ability for N-NO₃⁻ enrichment (Bischoff and Smith 2011). Its roots can absorb much N-NO₃⁻ from soil/sediment, resulting in significantly lower N-NO₃⁻ concentration in plant treatments. However, there are no obvious differences in N-NH₄⁺ concentration in sediment among the treatments, which may be due to the high TN concentration in the experimental sediment resulting in a stable level of N-NH₄⁺ concentration. Oxygen excretion from roots can also promote organic P mineralization and increase sediment redox potential to oxidizing condition. Ferric and manganic oxyhydroxide precipitate on or around plant roots can adsorb P and make it less available for plant uptake or diffusion to overlying water (Jaynes and Carpenter 1986). Furthermore, sediment in different treatments may have different microfloras that impact P conversion directly or indirectly. P retention by sediment may be promoted by plant growth with a corresponding increase in P concentration of sediment (Bai et al. 2012), which may explain the results that sediment has a higher TP concentration in *A. retroflexus* growth treatments. The differences in sediment properties over the vertical profile may be related to root distribution patterns. As a xerophyte species, *A. retroflexus* has special characteristics for adapting to xeric environment (Liu et al. 2013). However, when facing flooding stress, its root morphology may change due to the fact that root morphological plasticity is an important mechanism for plants to adapt to changing environments (Wang et al. 2009). There are significant differences in N-NH₄⁺ concentration of sediment over the vertical profile in plant treatments, which may be due to root absorption and sediment redox condition changes. LOI shows significant differences over the vertical profile of all treatments, which may be due to the different ability of root excretion or different associated microfloras in the sediment.

Change to nutrient concentrations of interstitial water has a direct impact on sediment endogenous nutrient loading. In this experiment, N-NH₄⁺ and P-PO₄³⁻ concentrations in interstitial water show significant differences in all treatments (Table 5, $p < 0.05$), and growth of *A. retroflexus* can significantly reduce N-NH₄⁺ concentration in interstitial water. N-NH₄⁺ in sediment occurs mostly in free and adsorbed states (Lange 1992), the latter is the main source for interstitial water. As one of the products in organic N mineralization caused by oxygen excretion, N-NH₄⁺ can filter into interstitial water and increase its concentration. Meanwhile, root absorption can also decrease N-NH₄⁺ concentration. There is lower N-NH₄⁺ concentration in interstitial water in plant treatments, which may be related to root absorption. Promoted nitrification process by oxygen excretion may be another reason. Variation of P-PO₄³⁻ concentration in interstitial water is determined by organic matter content and mineralization degree (Song 1992). Root absorption is the main process for its reduction. There is no significant difference of P-PO₄³⁻ concentration in interstitial water between

the plant treatments with a shorter growth stage and CK, which may be due to root ateliosis or short experimental period. N-NH_4^+ concentration in interstitial water shows significant difference over the vertical profile in plant treatments, while P-PO_4^{3-} shows significant difference in the plant treatment with a longer growth stage, which may be due to the root distribution pattern. On the other hand, N-NH_4^+ and P-PO_4^{3-} concentrations in interstitial water are higher than overlying water (Table 6), indicating that N-NH_4^+ and P-PO_4^{3-} can release from sediment to overlying water. Although diffusion fluxes are different due to the concentration differences between interstitial water and overlying water, N-NH_4^+ and P-PO_4^{3-} concentrations in overlying water decrease with the extension of growth stage, which indicates that growth of *A. retroflexus* can reduce N and P concentrations in overlying water to some extent and decrease sediment nutrient loading.

Conclusion

Wetlands are widely distributed and have many habitat types, which allow them to be easily invaded by alien plants (Li and Meng 2006). *A. retroflexus* is a potential invasive plant in wetlands due to its highly selective evolution ability. Wetland sediment properties can be altered by the invasion of this plant. Results of this experiment indicate that the growth of *A. retroflexus* can improve sediment physical properties by having the trend to increase sediment moisture content and porosity. It can also significantly decrease TN, N-NO_3^- , and N-NH_4^+ concentrations in sediment and interstitial water, respectively. However, there are no obvious differences in TP and N-NH_4^+ concentrations in sediment among the treatments. There is different impact of *A. retroflexus* on sediment properties under two growth stages. The plant with a longer growth stage significantly decreases LOI in sediment and P-PO_4^{3-} concentration in interstitial water. There were also significant differences in the N-NH_4^+ concentration in both the sediment and interstitial water over the vertical profile of the plant. In the plant treatment with a longer growth stage, P-PO_4^{3-} concentration also showed significant differences over the vertical profile. Therefore, the growth of *A. retroflexus* can improve sediment physicochemical properties and reduce the possibility of N-NH_4^+ and P-PO_4^{3-} releasing from sediment to overlying water to some extent, which may decrease sediment nutrient loading. There is potential remediation impact for wetland contaminated sediment. Further investigation is needed to find out the impact of *A. retroflexus* on other aspects of wetland ecosystems, which will help in understanding its comprehensive ecological impact on wetlands.

Disclosure statement

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Notes on contributors

Xiang Bai is a lecturer and is specialized in wetland and invasion ecology.

Li-Xia Shang is a post-doctor. Her research is focused on water ecology.

ORCID

Xiang Bai  <http://orcid.org/0000-0002-5980-5888>

Li-Xia Shang  <http://orcid.org/0000-0002-6387-3373>

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