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RESEARCH ARTICLE

Decomposition of *Phragmites australis* rhizomes in artificial land-water transitional zones (ALWTZs) and management implications

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Abstract Rhizomes are essential organs for growth and expansion of *Phragmites australis*. They function as an important source of organic matter and as a nutrient source, especially in the artificial land-water transitional zones (ALWTZs) of shallow lakes. In this study, decomposition experiments on 1- to 6-year-old *P. australis* rhizomes were conducted in the ALWTZ of Lake Baiyangdian to evaluate the contribution of the rhizomes to organic matter accumulation and nutrient release. Mass loss and changes in nutrient content were measured after 3, 7, 15, 30, 60, 90, 120, and 180 days. The decomposition process was modeled with a composite exponential model. The Pearson correlation analysis was used to analyze the relationships between mass loss and litter quality factors. A multiple stepwise regression model was utilized to determine the dominant factors that affect mass loss. Results showed that the decomposition rates in water were significantly higher than those in soil for 1- to 6-year-old rhizomes. However, the sequence of decomposition rates was identical in both water and soil. Significant relationships between mass loss and litter quality factors were observed at a later stage, and P-related factors proved to have a more significant impact than N-related factors on mass loss. According to multiple stepwise models, the C/P ratio was found to be the dominant factor affecting the mass loss in water, and the C/N and C/P ratios were the main factors affecting the mass loss in soil. The combined effects of harvesting, ditch broadening, and control of water depth should be considered for lake administrators.

Keywords *Phragmites australis* rhizomes, mass loss, decomposition rates, nutrient contents, Pearson correlation analysis, Artificial Land-Water Transitional Zone(ALWTZ)

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1 Introduction

Shallow lakes in northern China are traditionally used to construct raised fields with different scales for plantation by dredging sediment in situ. Many ditches are left on the raised fields, and as a result, artificial land-water transitional zones (ALWTZs) are formed between the raised fields and the ditches. In recent years, ALWTZs have been recognized for the direct and important role they play in the removal of nutrients by soil through adsorption and plant assimilation. The ALWTZs have predominantly been used for nitrogen loads from agricultural runoff and domestic sewage (Bai et al., 2004; Wang et al., 2010b). The amphibious characteristics and abundant nutrient content of ALWTZs can promote the growth of the species with strong ecological suitability, such as *P. australis* (Papastergiadou et al., 2007; Eid et al., 2010).

P. australis has a broad ecological amplitude and grows on soils with different pH, salinity, fertility, and inundation levels (Eid et al., 2014). The dominance of *P. australis* significantly affects the physicochemical characteristics of ALWTZs through their production and decomposition (Gessner, 2001). The high primary production of *P. australis* has been reported in many studies around the world (Dinka et al., 2004; Papastergiadou et al., 2007). In lake ecosystems, a considerable part of organic material production is formed by *P. australis*, which plays an important role in the detritus food chain (Hietz, 1992). *P. australis* absorbs large amounts of nutrients from the ambient environment and thus reduces the nutrient content of domestic and agricultural wastewater (Wang and Yin, 2008). The growth and proliferation of *P. australis* in ALWTZs is mainly dependent on its rhizomes, which are modified subterranean stems that often send out roots and shoots from their nodes (Jang et al., 2006). Rhizomes are considered as important organs for carbon and nutrient storage. They continually serve as a large pool of biomass and nutrients, and can affect the primary production of above-ground components (Bart and Hartman, 2003).

During the annual dormant period of *P. australis* (December–March), the leaves and culms die, and the dead matter is returned to the lake sediments. The organic matter and nutrients within tissues can potentially be released back into the environment and can provide a short-term sink for available nutrients in ALWTZs. The change of sediment quality is primarily due to anthropogenic activities, such as industrial discharged wastewater (Lei et al., 2013). Similarly, the residues after decomposition can accumulate in the sediments and thus change the properties of the lake sediment. Therefore, the decomposition of *P. australis* is considered an important metabolic process in the ALWTZ ecosystem (Bedford, 2005), and significantly affecting the ecosystem service by supplying organic matter and nutrient sources (van Dokkum et al., 2002; Dinka et al., 2004). In this regard, the decomposition and nutrient dynamics of *P. australis* should be clearly understood to maintain the health of the ALWTZ ecosystem.

The decomposition dynamics of *P. australis*, particularly its above-ground components, have been examined by some researchers during the past decades. These studies mainly focused on the dynamics of mass loss and change in nutrient contents during the decomposition process (Hietz, 1992; Gessner, 2000; Villar et al., 2001; van Dokkum et al., 2002). Factors that affected decomposition have also been studied, such as environmental conditions (Wrubleski et al., 1997; Du Laing et al., 2006), patterns of microbial respiration (Gessner, 2001; Eid, 2012), and dynamics of bacteria and fungi associated with *P. australis* litters (Schultz and Urban, 2008). Among these factors, litter quality, defined as the chemical composition of decomposing litter, has been considered as the main factor for decomposition. High decomposition rates are generally associated with high initial N and P contents and low C/N and C/P ratios (Chimney and Pietro, 2006; Shilla et al., 2006). In addition, external environmental conditions, such as temperature, pH, moisture, and nutrient levels have been considered as factors affecting the decomposition of *P. australis* (Royer and Minshall, 2001; Rejmánková and Houdková, 2006).The decomposition rates and nutrient dynamics of *P. australis* rhizomes in soil or in water are the primary topics currently being examined by some scholars (Wrubleski et al., 1997; Ágoston-Szabó et al., 2006; Eid et al., 2014). These studies have provided useful information. However, two issues yet to be addressed are the comparison of *P. australis* decomposition rates in water and in soil, and the determination of the age-specific characteristics on decomposition rates as a result of different nutrient contents. Although Asaeda and Nam (2002) reported on the different decomposition rates and changes in nutrient content for 1- to 4-year-old rhizomes in soil, these are in fact applicable to 1- to 6-year-old rhizomes according to the method developed by Karunaratne et al. (2004).

The ALWTZs in Lake Baiyangdian occupy approximately 26% of the total lake area (94 km^2) and has a high annual primary production of *P. australis* (4,000 t/km^2). *P. australis* rhizomes in ALWTZs can be easily damaged by manual and mechanical harvesting, grazing of waterfowl, strong storms and winds, and waves caused by boating activity. The dead rhizomes often float on the water surface or remain in a standing position in soil, and then become a part of the lake sediments and soil as organic detritus (Hietz, 1992). The nutrient release from rhizome litters can also lead to eutrophication in ALWTZs. The decomposition rates and change in nutrient concentrations of dominant macrophytes in Lake Baiyangdian, such as *Ceratophyllum demersum*, *Potamogeton pectinatus*, *Typha angustifolia*, and stems and leaves of *Phragmites australis*, have been studied by Li et al. (2013) and Lan et al. (2012). However, the decomposition of *P. australis* rhizomes had never been investigated in this area until now. Thus, research to increase the understanding in these areas is vital for ALWTZ management in Lake Baiyangdian.

The objectives of this study are to: (1) examine the mass loss and changes in nutrient contents of *P. australis* rhizome litter with different age categories in the ALWTZs in Lake Baiyangdian, (2) determine the effects of litter quality factors on mass loss, and (3) summarize management implications on the ALWTZ.

2 Materials and methods

2.1 Study site

The study site was located at Lake Baiyangdian (38°38′N, 115°54′E), which is the largest shallow lake in the North China Plain. It has a total area of approximately 366 km^2. The ALWTZ dominated by *P. australis* spans a total area of 94 km^2, which forms a typical raised field-ditch landscape. The average water depth of the lake ranges from 2 m to 3 m, and from 1 m to 1.5 m of the ALWTZ. In recent years, the construction of dams and reservoirs upstream, nutrient input from adjacent cropland, and domestic sewage from rural areas have simultaneously contributed to the eutrophication and terrestrialisation of Lake Baiyangdian.

P. australis is the competitively dominant species and occupies most areas of ALWTZ in Lake Baiyangdian. The decreased water level and abundant nutrient availability in the lake allow for high production and excessive expansion of *P. australis*. Its rhizomes can grow up to approximately 1.5 m deep in the soil of the ALWTZ, with most being densely spread at the top 1.0 m below the soil surface. They can also spread from the soil into the water. Because of their ecomocial value, the leaves and culms of *P. australis* are often harvested manually or with the use of harvesting machines by local farmers. During this process, the rhizomes that grow in the ALWTZ are often destroyed, yet some float on the water surface, and after dying, enter the lake sediment as organic matter detritus. Additionally, other rhizomes that remain in the transitional zone become organic matter sources for the soil (Fig. 1).

2.2 Decomposition experiment

In April 2012, live *P. australis* rhizomes were collected at depths of 10 to 100 cm below the ground in the ALWTZ. Three replicate quadrats were used and rhizome biomass was recorded at each site. Several studies on the rhizome life cycle and morphology have shown the feasibility for categorizing rhizomes according to the morphological characteristics of different ages (Haslam,1970; Fiala, 1976; Weisner and Strand, 1996; Karunaratne et al., 2004). In this present study of rhizomes, the method developed by Karunaratne et al. (2004) was used. All the rhizomes were classified into 1- to 6-year-old age categories according to their branching structures, conditions of the stems attached to the vertical rhizomes, and their colors. In the laboratory, all rhizomes were cut into small pieces and dried to a constant weight of 65°C±1°C. The dry mass was also recorded. For the field experiment, the rhizome samples were placed in litterbags of 15 cm× 15 cm. Litterbags with a 1 mm mesh were used to ensure water, ion, microorganisms, and invertebrates, which exist in both water and soil, could pass through. The dried rhizomes (5 g) were then placed into different litterbags according to their ages. Five randomly selected samples from each age category were analyzed to estimate the initial C, N, and P contents.

A total of 288 litterbags were prepared, and different age categories were identified with the use of different-colored insulating tapes (Fig. 2). All litterbags were placed in both water and soil of the ALWTZ on 25, May, 2012. In the water, litterbags were bound with bamboo which was inserted into the lake sediment and placed at the lake bottom. In the soil, the litterbags were placed 50 cm below the ground. Three replicate bags from each site were retrieved after 3, 7, 15, 30, 60, 90, 120, and 180 days from each site. The samples were gently hand-washed with deionized water and were then dried in an oven at 85°C for about a week to obtain their constant weights. To obtain accurate dry mass and nutrient contents in decomposing litters, we calculated the mean value of the three replicates each time.

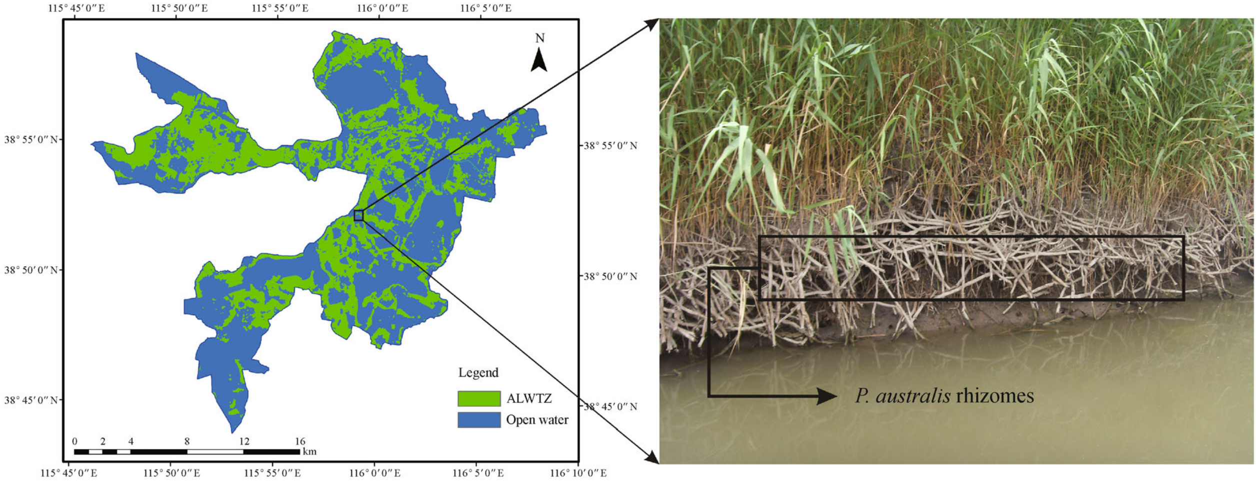
To identify the changes in nutrient contents during decomposition, the N and P contents at the different sampling times were determined in the laboratory. The release or accumulation of N and P in the rhizomes was determined by the calculating the difference between the original amount and the final amount of the two elements present in dry mass. The contents of N in the rhizomes were estimated with an Element Analyzer (Elementar, Inc., Germany). The contents of P in the litter were analyzed with the ICP-AES method.

2.3 Mass loss

Rhizome mass loss can be expressed as the proportion of the remaining mass to the initial mass at each sampling time. The decomposition process is modeled with the composite exponential model according to its mathematical and biological behaviors (Godshalk and Wetzel, 1978) .

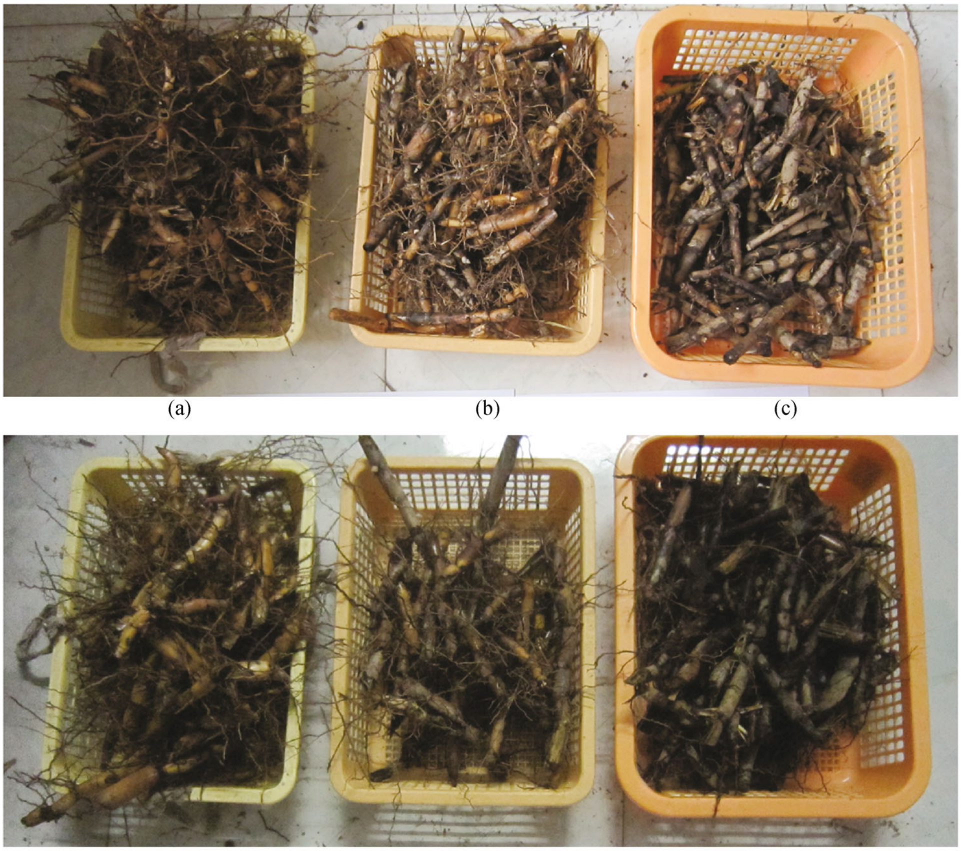
$$W_t = W_1 \exp(-k_1 t) + (1 - W_1) \exp(-k_2 t), \qquad (1)$$

where W_1 is the refractory portion of the litter mass, k_1 is the constant fraction of the refractory portion, k_2 is the



(a) (b)

Fig. 1 The location and photograph of study sites. (a) The distribution of ALWTZ in Lake Baiyangdian, and (b) the photograph of *P. australis* rhizomes in ALWTZ.


(a) (b) (c)

(d) (e) (f)

Fig. 2 The photographs *P. australis* rhizomes. The photograph (a)-(f) represents 1- to 6-year-old rhizomes, respectively.

constant fraction of the labile portion, and t is time in days (Brock, 1984).

2.4 Data analysis

The percentages of remaining mass and initial mass were compared for the different age categories using the two-way ANOVA analysis. The Pearson analysis correlation was utilized to analyze the relationships between mass loss of the *P. australis* rhizomes at each sampling time and the litter quality factors (N, P, C/N, C/P, and N/P ratios). In addition, a multiple stepwise regression model using rhizome litter quality factors (N, P, and C/N, C/P, and N/P ratios) to predict mass loss was adopted to determine the dominant litter quality factor affecting the mass loss. All variables were standardized (z-scores) before the regression analyses which were conducted with SPSS statistical software (version 16.0). Graphs were prepared with Origin 8.0 software.

3 Results

3.1 Mass loss

At the end of the experiment (180 days), approximately 45.17%±2.1% (mean±SD) of the mass of 1- to 6-year-old rhizomes remained in water, while approximately 51.17%±2.62% remained in soil. The remaining mass of the rhizomes for all age categories in soil was generally larger than that in water.

The average decomposition rates of 1- to 6-year-old rhizomes were 0.0442 d^{-1} in water and 0.0374 d^{-1} in soil. The highest decomposition rate occurred in the 1-year-old rhizomes, with the slowest rate observed in the 3-year-old rhizomes in both water and soil. The sequence of average decomposition rates in both water and soil from fastest to lowest is $1 > 6 > 5 > 2 > 4 > 3$ (the values indicate the age of rhizome).

Although the average decomposition rate in water was slightly greater than that in soil, similar stage characteristics appeared in both water and soil. In the present study, the fastest rate of mass loss was observed during the first 30 days, which accounted for approximately 58% of the total loss in water and 44% of that in soil. After the 30th day, decomposition rates began to decrease with the passage of time and then stabilized (Fig. 3). The relevant parameters of the composite exponential model are shown in Table 1.

3.2 Changes of nutrient content in the rhizomes

Obvious differences were observed in the initial nutrient

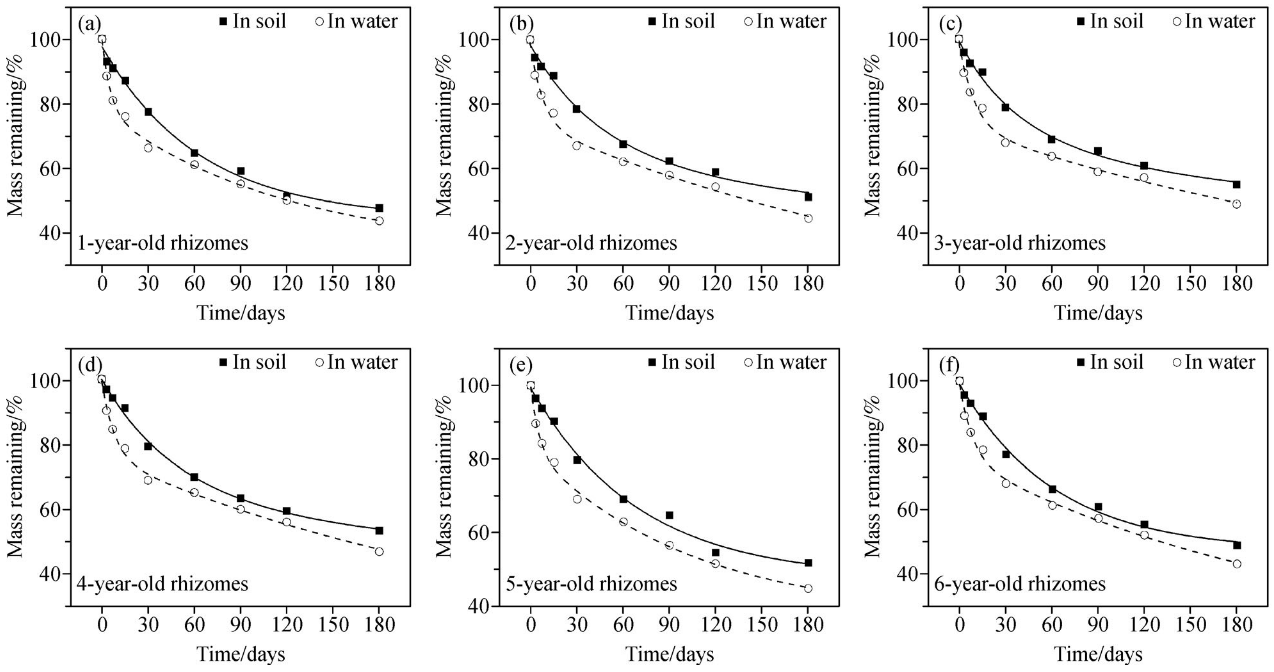


Fig. 3 Mass remaining of 1- to 6-year-old *P. australis* rhizomes in both water and in soil during the experimental period. Plots represent mean percentage of dry mass remaining of 1- to 6-year-old rhizomes (a–f) at each sampling time in both soil and water. The solid line and dot dash line are the regression line calculated via composite exponential model for decomposition.

Table 1 The relevant parameters of the composite exponential model for 1- to 6-year-old rhizomes in both water and soil.

Age	Environment	k_1	k_2	W_1/%	r^2	p
1-year-old	In water	0.00313	0.14107	26.79	0.9723	< 0.0001
	In soil	0.00178	0.02753	35.75	0.9516	< 0.0001
2-year-old	In water	0.00276	0.13029	26.07	0.9318	< 0.0001
	In soil	0.002	0.03573	26.65	0.9786	< 0.0001
3-year-old	In water	0.00219	0.10957	27.29	0.9753	< 0.0001
	In soil	0.00151	0.03242	28.05	0.9834	< 0.0001
4-year-old	In water	0.00266	0.12474	24.38	0.9712	< 0.0001
	In soil	0.0012	0.0224	35.34	0.9438	< 0.0001
5-year-old	In water	0.00309	0.11932	24.34	0.9692	< 0.0001
	In soil	0.0012	0.0197	38.73	0.9714	< 0.0001
6-year-old	In water	0.0031	0.1218	24.75	0.9851	< 0.0001
	In soil	0.0019	0.0286	31.59	0.9233	< 0.0001

contents among the *P. australis* rhizomes for six age categories. The C contents in these age categories ranged from 25.208% to 42.875%, with the highest observed in the 1-year-old rhizomes and the lowest observed in the 4-year-old rhizomes. The N contents ranged from 0.403% to 1.265%, whereas the P content ranged from 0.029% to 0.075%. The N and P contents were the highest in the 1-year-old rhizomes and the lowest in those at 6-years-old. The C/N and C/P ratios were the lowest in the 1-year-old rhizomes and were the highest in those at 6-years-old. The N/P ratio ranged from 14.053 to 18.954. The lowest N/P ratio was found in 6-year-old rhizomes, and the highest was found in those at 3-years-old (Table 2).

The N contents of water showed a decrease in 1- to 3-year-old rhizomes (decreased by 34.2%, 30.6%, and 23.9%, respectively) and an increase in 4- to 6-year-old rhizomes (increased by 12.8%, 27.8%, and 100.02%, respectively). A change in P contents demonstrated similar characteristics (decreased by 43.5%, 40.6%, and 19.5% in the 1- to 3- year-old rhizomes, and increased by 13%, 3%,

Table 2 Initial nutrient content characteristics of *P. australis* rhizomes with six age categories

Age	C%	N%	P%	C:N	C:P	N:P
1 year	42.875	1.265	0.075	33.893	568.626	16.777
2 year	39.848	0.963	0.066	41.375	607.392	14.680
3 year	36.025	0.808	0.043	44.600	845.372	18.954
4 year	25.208	0.703	0.037	35.857	674.869	18.821
5 year	27.582	0.560	0.032	49.293	856.791	17.382
6 year	27.623	0.403	0.029	68.530	963.043	14.053

and 12% in those 4- to 6-years-old, respectively). The N contents in soil for the 1- to 6-year-old rhizomes increased, while the older ones showed a large increase in amplitude. By contrast, the P contents in the 1- to 6-year-old rhizomes decreased while the younger ones showed a larger decrease in amplitude (Fig. 4).

The changes of nutrient contents also showed obvious stage characteristics during the decomposition process. Regardless of an increase or decrease in the nutrient contents, the greatest variation amplitude appeared during the first 30 days. For example, the 1- to 3-year-old rhizomes in water lost 41% to 52% of N and 54% to 62% of P during the first 30 days. After the 120th day, changes in both N and P contents, in water and in soil, stabilized until the end of the experiment (Fig. 5).

3.3 Effects of litter quality factors on mass loss

The mass loss of the rhizomes, in both water and soil, during the experiment was significantly and positively

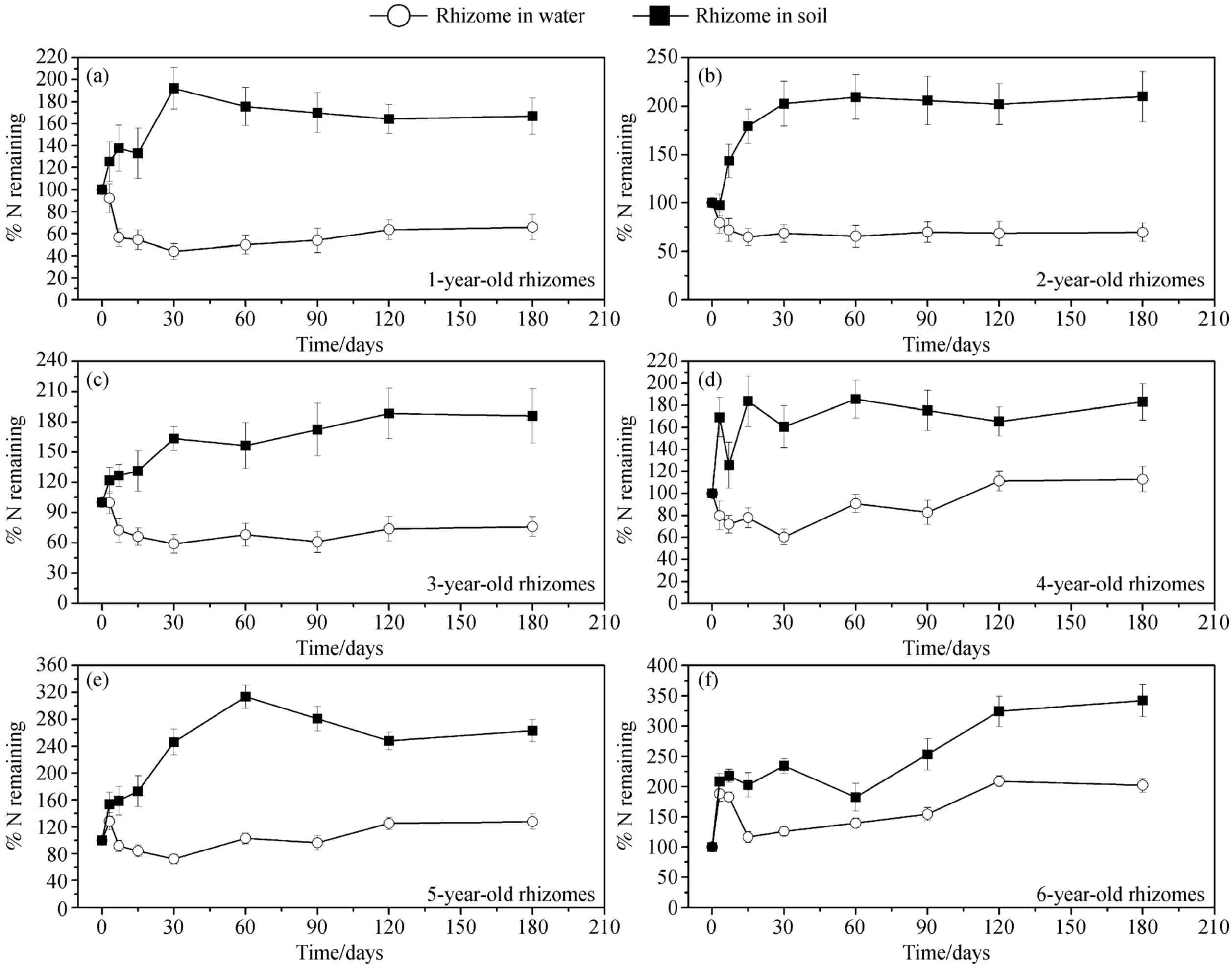


Fig. 4 Remaining N content of *P. australis* rhizomes in both soil and water during experimental period. (a)–(f) represent 1- to 6-year-old rhizomes, respectively.

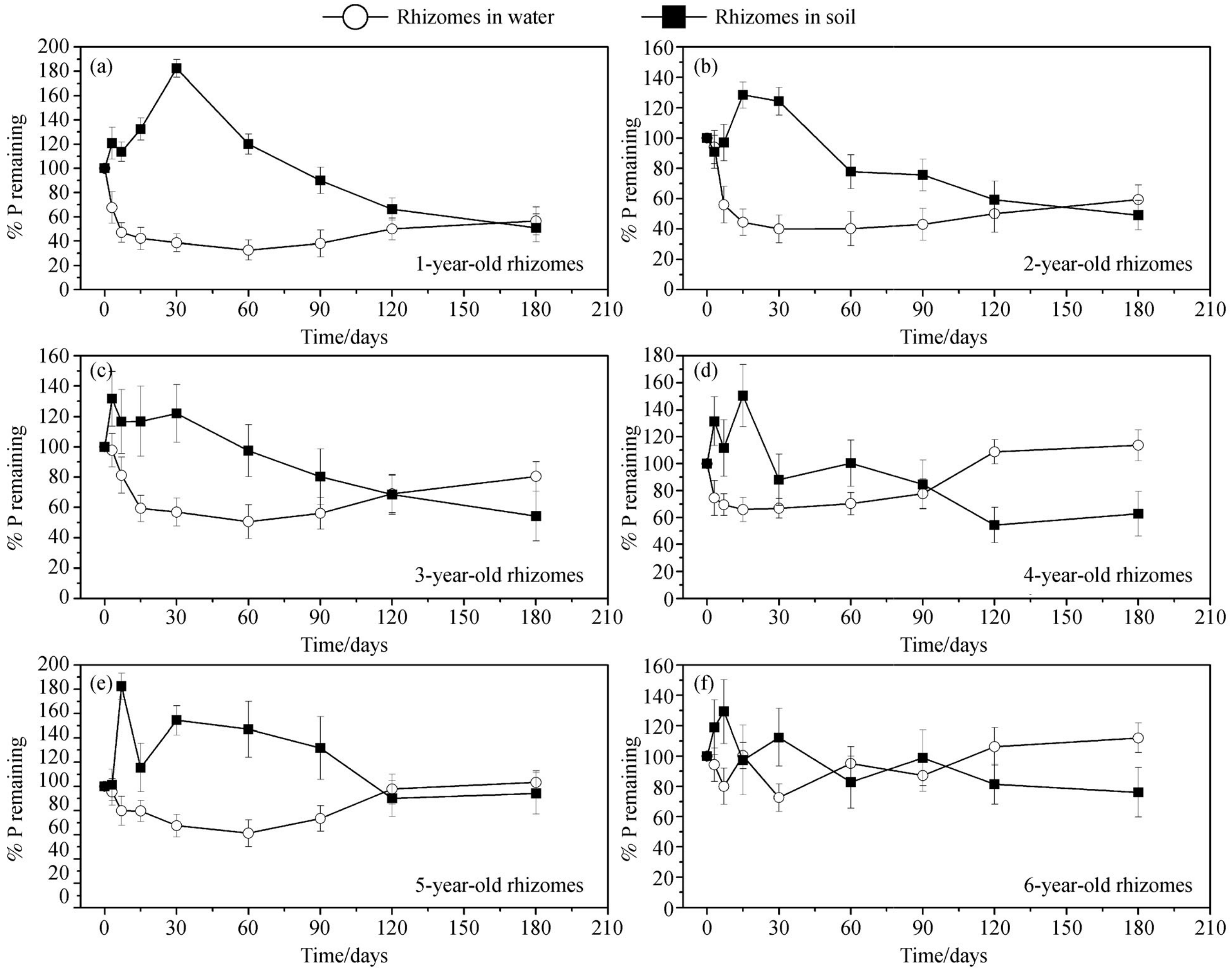


Fig. 5 Remaining P content of *P. australis* rhizomes in both soil and water during experimental period. (a)–(f) represent 1- to 6- year-old rhizomes, respectively.

Table 3 Pearson correlation coefficients (r) between mean mass losses and rhizome nutrient contents during the experimental period

Environment	Nutrient content	Percentage of mass losses at different sampling times							
		3 days	7 days	15 days	30 days	60 days	90 days	120 days	180 days
In water	N%	0.009	0.167 $^{c)}$	0.398	0.283 $^{b)}$	−0.879 $^{b)}$	0.905 $^{b)}$	0.897 $^{b)}$	0.57 $^{a)}$
	P%	0.211	0.264 $^{c)}$	0.465	0.463$^{a)}$	0.936 $^{b)}$	0.955$^{a)}$	0.926 $^{b)}$	0.716 $^{a)}$
	C:N	0.313	0.14	0.001	0.311	−0.426 $^{b)}$	−0.554	−0.466	0.022
	C:P	−0.101	−0.101	−0.182	−0.063 $^{b)}$	−0.677 $^{b)}$	−0.820$^{a)}$	−0.874$^{a)}$	−0.919 $^{b)}$
	N:P	−0.792	−0.465	−0.359	−0.77	−0.275	−0.236	−0.197 $^{b)}$	−0.624
In soil	N%	0.272	0.255 $^{c)}$	0.451	0.913 $^{c)}$	0.954 $^{b)}$	−0.008 $^{b)}$	0.938 $^{b)}$	0.919 $^{a)}$
	P%	0.424	0.294 $^{c)}$	0.563	0.950 $^{c)}$	0.887$^{a)}$	0.129 $^{a)}$	0.941$^{a)}$	0.958 $^{a)}$
	C:N	0.165	0.035	−0.047	−0.569	−0.850 $^{c)}$	0.541	−0.625	−0.512
	C:P	−0.226	−0.136	−0.431	−0.81	−0.851$^{a)}$	0.202 $^{b)}$	−0.719 $^{b)}$	−0.742 $^{a)}$
	N:P	0.684	0.293	0.548	0.181	−0.276 $^{b)}$	0.691$^{a)}$	0.734 $^{b)}$	0.875 $^{a)}$

a) $p < 0.01$, b) $p < 0.05$, c) $p < 0.1$.

correlated with the N and P contents and negatively correlated with the C/N and C/P ratios. Slightly significant relationships were found between the litter quality factors and mass loss at the early stage (< 30 days). Highly significant and strong correlations between the litter quality factors and mass loss were observed after 30 days. The litter N-related factors (N and C/N ratio) of mass loss were not as strong as the litter P-related factors (P, N/P, and C/P ratios) in both water and soil, although all of these factors showed a significant effect on mass loss (Table 3).

The mass loss was affected by almost all the litter quality factors at varying degrees. Consequently, the dominant factors in both water and soil were further examined with the multiple stepwise regression models. In water, rhizome mass loss was highly related to the C/P ratio, with the regression coefficient at 0.933. In soil, the multiple stepwise regression model indicated that the mass loss was higher when C/N and C/P ratios were considered together with the time factor and the regression coefficient increased to 0.924 (Table 4).

4 Discussion

4.1 Mass loss

The decomposition rates in water were relatively higher than those in soil for all 1- to 6-year-old rhizomes. There could be two contributing factors for this result. First, nutrient availability in water is considered to be an important factor affecting the litter decomposition (Gulis and Suberkropp, 2003; Xie et al., 2004; Rejmánková and Houdková, 2006). Lake Baiyangdian is a hyper-eutrophic lake due to sewage discharge and fertilizer use in the cropland (Li et al., 2013). High nutrient availability in water could cause an increase in decomposition rates (Gulis and Suberkropp, 2003; Breeuwer et al., 2008). The nutrient availability in soil was relatively lower than that in water because of the water quality purification by root channel of *P. australis* which lived in the ALWTZ in Lake Baiyangdian. The mean N and P contents in soil were 1.2 and 0.11 mg/L, respectively, which accounted for only 5% of that in water (Wang and Yin, 2008; Wang et al., 2010b). As a result, low nutrient contents may limit the microbial activities and fast decomposition rates may not be supported (Debusk and Reddy, 2005; Bedford, 2005). The second factor could be the effect of water movement. More than 100,000 people live in the villages surrounding Lake Baiyangdian with boats as the main mode of transportation. The average water depth of Lake Baiyangdian is no more than 2 m; thus, an increased water velocity due to the intensive boating activity could exacerbate the effects of mechanical damage on decomposing litters and accelerate decomposition.

The stage characteristics of the decomposition process were consistent with the relationship between litter quality and mass loss (Table 3). Higher significant Pearson correlation coefficients between the initial litter quality factors and mass loss were observed at a later stage, opposed to an early stage (<30 days), in both water and soil. A rapid mass loss during the early stage involved the rapid leaching of water soluble compounds, such as sugars, starches, and proteins (Aerts and de Caluwe, 1997; Gulis et al., 2006). During the later stage, the mass loss mainly involved remaining refractory materials, such as lignocellulose, cellulose, and hemicellulose, associated with the activities of the microbe and fungi (Bayo et al., 2005). These refractory materials often showed relatively slower mass losses than those involved during the early stage (Nziguheba et al., 1998; Alvarez and Guerrero, 2000; Hobbie and Vitousek, 2000). These characteristics also can be used to explain the differences in decomposition rates between 1- to 6-year-old rhizomes. Young rhizomes caused faster decomposition rates during the early stage in both water and soil because of their high initial contents (Asaeda and Nam, 2002). However, C/N and C/P ratios became more important than N and P contents with the passage of time (Cleveland et al., 2004; Güsewell, 2004; Rejmánková and Sirová , 2007), and as a result, the 3- and 4-year-old rhizomes showed slower decomposition rates than the 5- and 6- year-old rhizomes in both water and soil.

Many studies have shown that the litter initial P, C/N, and C/P ratios can be considered as good factors of decomposition rates (Rejmánková and Houdková, 2006; Rejmánková and Sirová, 2007). However, P-related factors were more significant than N-related factors in the present study (Table 3). It is reported that the C/P of 100 divides the net P mineralization ($C/P < 100$) and P immobilization ($C/P > 100$) (Hoorens et al., 2003). In addition, the C/N of 25 divides the net N mineralization ($C/N < 25$) and N immobilization ($C/N > 25$) (Geurts et al., 2010). In this study, rhizome litters showed the initial C/N ratios in the range of 30 to 70, and the initial C/P ratios in the range of 500 to 1000. The obvious discrepancy between microbial demand and litter P in this study was much higher than that for N, indicating that P immobilization might occur and that microbes demand external P to maintain their metabolism. Therefore, the relative shortage of P can

Table 4 Multiple stepwise regression model of determination and probability values of relationships between rhizome mass loss and litter quality factors during the experimental period

Environment	Equations	r^2	p
In water	$M_{\text{loss}} = 0.003t + 0.145$	0.819	<0.0001
	$M_{\text{loss}} = 0.003t - 0.0008\text{C:P} + 0.074$	0.933	<0.0001
In soil	$M_{\text{loss}} = 0.003\,t + 0.075$	0.884	<0.0001
	$M_{\text{loss}} = 0.002t - 0.136\ \text{C:N} - 0.0007\text{C:P} + 0.167$	0.924	<0.0001

limit decomposition and thus increase the significance of P-related factors and decrease the significance of N-related factors (Hobbie and Vitousek, 2000; Blanco et al., 2011).

The decomposition rates in this study are relatively higher than those in related literature (Table 5). For instance, the decomposition rate for 1- to 2-year-old rhizomes was just 0.0023 d^{-1} in water (Ágoston-Szabó et al., 2006).The litter quality can account for the relatively slow decomposition rates in such a study because the rhizomes in their study were primarily collected from die-back reed bed and were characterized by low nutrient contents. Moreover, environmental conditions, such as temperature and moisture, can also affect decomposition rates (Davidson and Janssens, 2006). The decomposition rates of older rhizomes (3- to 6-years-old) in soil in the present study were almost identical to those of the younger ones (1- to 2-years-old) in Asaeda and Nam's (2002) study. Temperature differences could be the leading cause. The temperatures in this study ranged from 28°C to 38°C, but in the Asaeda and Nam's (2002) study, temperature ranged from 8°C to 24°C. A low temperature has been considered as a cause for the low metabolic rate of the microorganisms and slow mass loss (Breeuwer et al., 2008).

Multiple stepwise regression models indicated the dominant factors on the decomposition rates. The litter C/P ratio in water was the dominant factor for mass loss; a result that was consistent with the high correlation coefficients (r^2) between C/P and mass loss. Both the C/N and C/P ratios in soil were the dominant factors for mass loss. The decomposition model did not consider the effects of fiber content on decomposition (e.g., lignin, cellulose, and hemicellulose content in rhizomes). However, the r^2 in both water and soil was high (0.933 and 0.924, respectively), which demonstrated that the multiple stepwise regression model can be used to predict mass loss.

4.2 Changes in nutrient content in the rhizomes

The N content in water decreased in the 1- to 3-year-old rhizomes. This finding can be attributed to the leaching effect during the early stage when the soluble N in decomposing litters was easily leached out along with water-soluble compounds (Villar et al., 2001). The initial increase in 4- to 6-year-old rhizomes can be attributed to their relatively lower initial N contents than those observed in the 1- to 3-year-olds. Therefore, the N from the surrounding water was taken up by microorganisms to maintain their metabolic activities (Eid et al., 2014), and the binding of some nitrogenous substances to lignin decreased the availability for nitrogen decomposition (Dinka et al., 2004). The N content in soil increased in all 1- to 6-year-old rhizomes, since the leaching effect in soil was relatively weaker than that in water, and the immobilization of N by the microbe and fungi resulted in an increase in N content (Shilla et al., 2006).

The P content decreased in 1- to 6-year-old rhizomes in both water and soil. However, a sharp decrease in the P content in water was observed primarily during the early stage (<30 days), while sharp decrease in the P content in soil was observed during the later stage (>30 days) increased. Decreases of P content in water during the early stage essentially dissolved along with the water soluble compounds due to a stronger leaching effect. The increased P content in soil, which occurred during the same time primarily due to the external P, was absorbed by the microorganisms to maintain their metabolic activities (Wrubleski et al., 1997; Asaeda and Nam, 2002). Compared to the changes of N content, the P content of all 1- to 6-year-old rhizomes showed a decrease at the end of the experiment. Lake Baiyangdian is a P-limited lake (Wang et al., 2010a), so the insufficient P from the ambient environment could have been utilized by the microorganisms. This phenomenon also proves that P-related factors are more important than N-related factors for controlling decomposition.

4.3 Implications for management

The combined effect of high production (Villar et al., 2001) and low decomposition rates resulted in a net accumulation of rhizome litter. According to the composite exponential model, we estimated that approximately 27% and 31% of dry mass remained after one year in water and in soil, respectively. According to our survey results, the average dry weight of rhizome biomass in ALWTZ is (5.82±0.38) kg/m^2, with the assumption that the rhizomes that lived in the margins of the ALWTZs (length: 30 m, width: 3 m) will completely enter the water, and approxi-

Table 5 Comparison of average *P. australis* rhizome decomposition rates in related literature and in the present study

Age categories	Mesh size/mm^2	Incubation days/d	$v/(d^{-1})$	Environment	References
1- to 6- year-old	1 × 1	180	0.0040–0.0047	In water	This study
1- to 6- year-old	1 × 1	180	0.0033–0.0041	In soil	This study
1- to 2- year-old	1 × 1	953	0.0023	In water	Ágoston-Szabó et al. (2006)
1-year-old	1 × 1	434	0.0014	In soil	Wrubleski et al. (1997)
1-year-old	1 × 1	434	0.0032	In water	Wrubleski et al. (1997)
1- to 4- year-old	1 × 1	369	0.0014–0.005	In soil	Asaeda and Nam (2002)
1- to 2- year-old	5 × 5	150	0.004	In water	Eid et al. (2014)

mately 290 kg of dry mass will remain after one year. We also assumed that with an even distribution of the rhizome litter over the entire basin between two ALWTZs, and an average bulk density of 1.072 kg/m^3 of the sediment, the in-filling rate as a result of the organic litter of rhizomes will be 3.5−4.2 mm per year. The remaining nutrient contents in the litter canaccumulate in the sediment and thus change the sediment quality. Therefore, *P. australis* rhizomes can be a major source of organic matter and the available nutrients in the ALWTZs. In addition, water between the two ALWTZs is stagnant, and with a lower dissolved oxygen content than that in the river (Akbari et al., 2013), terrestrialization and eutrophication could possibly occur. The surface area of the ALWTZs accounts for 26% of the total surface area in Lake Baiyangdian. This type of ALWTZ is very common in other macrophyte-dominated shallow lakes in Northern China. Therefore, effective measures should be taken to improve the management practices of rhizomes in ALWTZs.

Reducing the rhizome biomass in ALWTZs was accepted as an effective management practice to address litter accumulation (Güsewell, 2004). At present, the harvesting of leaves and culms is a common measure for controlling *P. australis* biomass. Harvesting primarily focused on above-ground components, however, rhizomes generally reserved sufficient nutrients that can be used for re-growth of above-ground components under suitable conditions. Therefore, the harvesting of rhizomes should be given adequate attention by local administrators. Broadening the width of ditches is another effective measure for suppressing rhizome propagation and preventing its expansion (Bart and Hartman, 2003). This also increases the width between two ALWTZs, so the in-filling rate will decrease even if rhizome biomass is constant.

Furthermore, water depth control in ALTWZ was important because it affected the survival and propagation of rhizomes. Water depth was considered to have the most profound effect on bud emergence from rhizome cuttings during the early growth stage. Some studies demonstrated that a high mortality of *P. australis* occurred when it was inundated for a four-week period or even longer (Adams and Bate, 1999; Mauchamp et al., 2001). The seeding growth of *P. australis* in ALTWZ often started in early April, when the biomass and nutrient content in above-ground components is at a minimum, whereas that in the rhizomes reaches the maximum level during the same time. If the *P. australis* rhizome was continuously inundated during this period, bud emergence from rhizomes could be suppressed and then the proliferation of *P. australis* could be prevented.

5 Conclusions

This study demonstrated that although the decomposition rate for rhizomes in water was relatively higher than that in soil, the sequence of decomposition rate among 1- to 6-year-old rhizomes was identical in both water and soil. Rhizome nutrient content showed significant effects on mass loss during the later stage of the experimental period, and the P-related factors represented higher correlations with mass loss than with the N-related factors. Although the changes in nutrient content were different, nutrient release occurred among 1- to 6-year-old rhizomes, indicating that rhizomes were important nutrient sources in ALWTZs. The multiple stepwise regression model further indicated that the C/P ratio was the main factor affecting the mass loss of the *P. australis* rhizome in water, and that the C/N and C/P ratios were the main factors affecting mass loss in soil. Overall, rhizomes served as an important source of organic matter and nutrient accumulation in ALWTZs. Therefore, for the sustainability of the ALWTZS, it is crucial that an integrated management approach, including harvesting, ditch broadening, and control of water depth be adopted by lake administrators.

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