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Research Article

Litter Decomposition of Six Macrophytes in a Eutrophic Shallow Lake (Baiyangdian Lake, China)

The decomposition of aquatic macrophytes has important consequences for wetlands because it is closely related to organic matter accumulation and nutrient cycling. A field litter bag experiment was undertaken to investigate the decomposition rates of six dominant macrophytes. And the level of nutrient transfer from plant residues to lake water was also researched in Baiyangdian Lake, a typical macrophyte-dominated lake in the Northern China Plain. Intact standing plants of *Phragmites australis*, *Typha angustifolia*, *Nelumbo nucifera*, *Potamogeton pectinatus*, *Ceratophyllum demersum*, and *Chara* sp. were collected and different plant tissues incubated near sediment traps. Litter bags were collected at days 6, 26, 60, 104, and 140 to follow biomass loss and nutrient release. Decomposition rates of different macrophytes calculated from an exponential model ranged from 0.0028 to 0.0110 day^{-1}. For the same external environmental conditions, decomposition rates were significantly affected by initial litter chemistry. The remaining biomass was positively related to the C/N and C/P ratios and negatively related to the N and P concentrations and the N/P ratio. Both stems and roots showed a lower decomposition rate than the leaves of the same species due to the higher C/N ratio. The nutrient release from plant litter to the lake water was substantial. Over the incubation period, the release of N from the litter represented 18.10–88.79% of the initial content, and the release of P from the litter represented 24.26–92.83% of the initial content.

Keywords: Aquatic macrophytes; Decomposition rate; Litter bag; Nutrient; Terrestrialization

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1 Introduction

Over the past decades, the terrestrialization of shallow freshwater lakes due to the deposition of organic matter has attracted considerable attention [1, 2]. Aquatic macrophytes are one of the most important components of the lake ecosystem and play a crucial role in the process of lake terrestrialization. Aquatic macrophytes usually contain large amounts of organic matter. After the breakdown of macrophyte tissues, the residues begin to accumulate in the sediment at the lake bottom as biological decomposition process [3]. Generally, the decomposition rate is much less than the accumulation rate, and the residual organic matter from extremely abundant aquatic macrophytes will produce a long-term accumulation of plant litter. Although the bioaccumulation from a single plant is extremely low, the relatively large biomass represented by aquatic macrophytes proves to be a significant reservoir of lake sedimentation. For this reason, a sediment layer forms and becomes increasingly thick over time. This process eventually has a direct effect by accelerating the terrestrialization of the lake [4]. Simultaneously, the nutrients released from the plant litter will increase the eutrophication level of the lake water [5], then change the aquatic plant belt, and finally create shoals in the lake and transform it into a marsh. During the entire process, hydrophytes are progressively replaced first by helophytes and then by terrestrial species [6].

In principle, the balance between the accumulation and decomposition of plant litter determines the terrestrialization rate. It has been widely recognized that litter decomposition includes two principal processes: fast leaching and slow biodegradation. Leaching, the physical process whereby leaves fall to the sediment surface and begin to release their content of soluble material, produces an immediate loss of more than 20% of the biomass during the first few days [7]. The physical leaching period is very brief. During this period, certain soluble compounds (e.g., carbohydrates, organic acids, proteins, and aldehyde acids) and minerals (e.g., K, Ca, Mg, and Mn) are dissolved. A rapid decline of the large initial amounts of organic and inorganic matter accompanies this process [8, 9]. During the following period, the decomposition of plants is controlled primarily by microbial colonization and invertebrate feeding [10–12]. This process is always slower because a certain fraction of the remaining matter dissolves only with difficulty. Changes in the types and amounts of compounds retained by plants may affect the overall decomposition rate by selectively stimulating or inhibiting colonization by aquatic microorganisms [13] and modifying the palatability of the plant material to herbivorous invertebrates. In addition, the decomposition rate is affected by the natural characteristics of the lake water, especially the temperature, pH, and dissolved oxygen (DO). The decomposition rate is also affected by the nutrient

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utilization level of each species, as expressed by the ratio of carbon to nitrogen. In general, high temperature, moderate pH, and high DO facilitate the decomposition of macrophytes because they can stimulate the growth of the microorganisms [14–16]. In addition, the C/N ratio in plant tissues determines the availability of nutrients to microorganisms and microinvertebrates. A higher rate of plant decomposition has been hypothesized to be closely correlated with a lower C/N ratio [17]. In general, the differences in decomposition rates among aquatic macrophytes can be attributed to physiological and environmental variables [18].

Abundant data are available on the decomposition of aquatic macrophytes in productive systems. Decomposition pattern and factors in controlling decomposition rates of aquatic plants have been studied intensively [19–21]. Floodplains, coastal lakes, eutrophic lakes, macrophyte-dominated lakes, and constructed wetlands are the chief research areas for these studies because large quantities of organic matter are available for accumulation [4, 14–16, 22]. Baiyangdian Lake, a plains lake and the most important lake of its type in the Northern China Plain, is simultaneously facing three major ecological problems: eutrophication, terrestrialization, and water shortage [23]. The plant biomass and the decomposition rates of the lake's principal macrophytes need further research. At the same time, little is known about the role of different plant tissues (leaves, stems, and shoots) in lake carbon accumulation and nutrient cycling. The objectives of this paper are to investigate the decomposition rates of different tissues of six dominant emergent and submerged macrophytes in Baiyangdian Lake and to determine the characteristics of nutrient release by measuring the contents of N and P in the residues of different plant tissues during the decomposition period.

2 Materials and methods

2.1 Study site

Baiyangdian Lake (115°38′–116°07′N, 38°43′–39°02′E), 39.5 km long (E–W) and 28.5 km wide (S–N), is located in the North China Plain and has a total area of 366 km^2 (Fig. 1). The lake plays an important role in adjusting the local climate, maintaining biodiversity, and supplying water resources for the human population. The principal water sources for the lake are located in the upstream areas of the Daqinghe watershed. The elevation of the lake is 5.5–6.5 m, and the lake's capacity is 10.7 billion m^3. Overall, the lake is generally high in the west and low in the east. Its annual temperature is between 7.3 and 12.8°C, and it receives an annual rainfall of 524.9 mm. A total of 39 species of aquatic macrophytes are found in the lake. These species consist primarily of emergent plants, such as *Phragmites australis*, *Typha angustifolia*, and *Nelumbo nucifera*, and submerged plants, such as *Ceratophyllum demersum*, *M. spicatum*, *Chara* sp. and *Potamogeton pectinatus* [24]. The growing season lasts 8–9 months, from March to November. Because it is covered by aquatic macrophytes, which provide an abundant source of available organic matter, Baiyangdian Lake has been negatively impacted by terrestrialization [25].

2.2 Decomposition experiment

To measure the decomposition rates of the dominant aquatic macrophytes and the release of chemical constituents from these plants, a litter bag decomposition experiment was conducted in the field at Wangjiazhai (115°59′39.9″N, 38°56′66″E). Intact standing plants were collected using plant quadrats (1 m × 1 m) at the end of July 2009. The plants collected included *P. australis*, *T. angustifolia*, *N. nucifera*, *P. pectinatus*, *C. demersum*, and *Chara* sp. Three replicate plant quadrats were used at each sampling site, and the plant biomass was also recorded at each site. The samples were transported to the laboratory within 24 h. Individual *P. australis*, *T. angustifolia*, *N. nucifera*, and *P. pectinatus* were separated into stems, leaves, and roots, whereas entire plants of *C. demersum* and *Chara* sp. were used. This approach was chosen because the roots of *C. demersum* and *Chara* sp. are rhizoid and the separation of the stems of these species from the leaves is extremely difficult. Moreover, these species are relatively fragile after being dried, and it is impossible to separate the different tissues. All plants were carefully washed to remove sediment particles and microinvertebrates. To determine the dry weight, all plants were dried to a constant weight at 65 ± 1°C. The roots and stems were cut into pieces

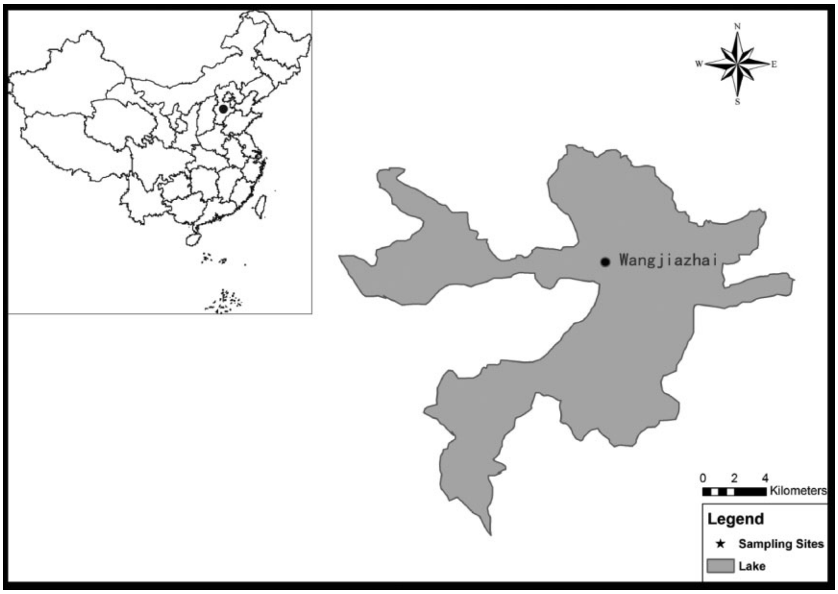

Figure 1. Location of the study site.

5 mm in length, and were placed in three replicate polyethylene bags ($10 \times 10\,\mathrm{cm}^2$) with a mesh size of 0.5 mm. This mesh size was selected to inhibit the colonization of culm material by macroinvertebrates. To ensure comparability between consecutive samples, the litter samples in all the bags were standardized to the same weight and similar shapes. These samples were then attached to sections of bamboo 5 m long positioned 0.8 m from the surface of the sediment and completely submerged.

The initial weight of each plant was 10 g, and triplicates were used for each sample and to ensure the precision of all the data. The replicate samples for each plant species were collected on five dates: day 6 (August), day 26 (August), day 60 (September), day 104 (November), and day 140 (December). These dates covered the chief periods of bioaccumulation. All material was used to determine the weight loss and to measure the total nitrogen (TN) and phosphorous (TP) content.

2.3 Sample processing and analysis

At each sampling time, each litter bag was collected by locating the fixed bamboo sections and removing the labeled bags without disturbing the other bags. The retrieved residues were packed in ice and carefully transported to the laboratory. To remove the sediment and extraneous plants and animals, these residues were washed with distilled water. The residues were then dried for 72 h to constant weight with a freeze drier. The remaining mass of each sample was measured with an electronic balance. The litter was then ground through a 60-mesh sieve to for subsequent analysis. C and N were determined with an element analytical instrument (Vario EL), while P was analyzed with the ICP method.

In situ measurements of pH, temperature (*T*), and DO of lake water were taken using YSI Pro Plus at each sampling time. Water samples were collected from about 10 cm below the water surface and stored in pre-acid washed polyethylene bottles. All the samples were analyzed within 48 h after sampling. TP was also measured with the ICP method. TN was carried out using a spectrophotometer DR2800. Nitrate nitrogen (NO_3^-–N) and ammonium nitrogen (NH_4^+–N) were determined by an Astoria Analyzer 300 system.

2.4 Data analysis

A repeated 2-way ANOVA was performed to analyze the litter dry weight and the N and P contents of the leaves, stems and roots of the retrieved materials at each sampling time. The dry weight remaining in the litter bags was plotted against time (in days) to examine the pattern shown by the breakdown of the litter. The decomposition rates were estimated using an exponential model [26], in which the decomposition rate follows the equation:

$$W_t = W_o\,e^{-kt} \qquad (1)$$

where W_o is the initial weight; W_t is the weight at time *t*; *k* is the decomposition rate; and *t* is time in days.

3 Results

3.1 Water quality

Table 1 demonstrates that the surface water of Baiyangdian Lake is alkaline (pH 8.13). DO values remained low and little changed. Temperature gradually decreased through the seasons. The average temperature dropped to 5.1°C in winter from 30.8°C in summer. Specifically, nutrients content in the studied lake exceeded the limits for eutrophication of reservoirs. The nutrient variations during the study periods are high.

Table 1. Physico-chemical features of the study site throughout the decomposition experiment

	Range	Average	Standard deviation
pH	7.04–9.75	8.13	1.07
DO ($\mathrm{mg\,L^{-1}}$)	1.02–3.54	2.11	0.93
T (°C)	5.1–30.8	19.4	10.8
TN ($\mathrm{mg\,L^{-1}}$)	1.19–3.93	2.31	1.05
NH_4^+–N ($\mathrm{mg\,L^{-1}}$)	0.21–3.48	1.92	1.43
NO_3^-–N ($\mathrm{mg\,L^{-1}}$)	0.12–1.05	0.54	0.39
TP ($\mathrm{mg\,L^{-1}}$)	0.18–0.32	0.22	0.03

3.2 Biomass of macrophytes

The annual maximum biomass and N and P content of aquatic macrophytes were observed between July and August in Baiyangdian Lake. The biomass of macrophytes had a significant effect on the accumulation of dry matter. The dry biomass of the plants ranged from 189 to 1632 $\mathrm{g\,m^{-2}}$ (Fig. 2). Most of the total plant biomass came from the stems, whereas the roots only contributed 11.11–32.61% of total *P. australis*, *T. angustifolia*, and *Chara* sp. were the main contributors to the total plant biomass. They accumulated 721.3, 965.4, and 1632.8 $\mathrm{g\,m^{-2}}$ dry biomass, respectively.

3.3 Initial detritus characteristics

The initial nutrient concentrations differed among the six macrophytes (Tab. 2). The emergent plants had a higher C content than the submerged plants. The C and N content of the leaves was higher than that of the stems and roots in *P. australis*, *T. angustifolia*, and *N. nucifera*, whereas in each species the initial C/N ratio in the leaves was all significantly lower than that in the stems and roots. The ratios of C/N and C/P were highest in the roots of *T. angustifolia*, and the lowest initial C/P and N/P ratios were found in the roots of *N. nucifera*.

3.4 Detritus decomposition

The decomposition of the leaves, stems and roots of the six emergent and submerged macrophytes was monitored 140 days. The calculated dry weight losses and decomposition rates of the six species are

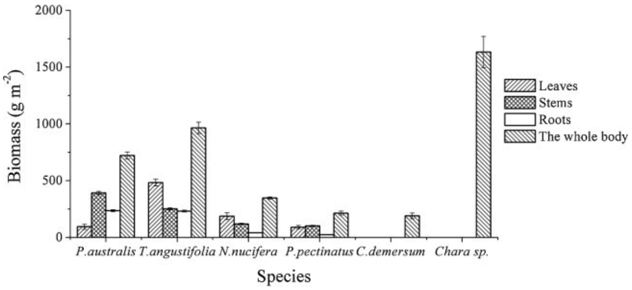

Figure 2. The biomass of the six emergent and submerged macrophytes. Values are means of three replicates.

Table 2. Initial chemical characteristics of the six emergent and submerged macrophytes

		C %	N %	P %	C/N	C/P	N/P
P. australis	Leaves	41.972 ± 1.352	1.068 ± 0.032	0.089 ± 0.031	39.3	471.6	12.0
	Stems	37.757 ± 0.987	0.733 ± 0.021	0.137 ± 0.003	51.5	275.6	5.4
	Roots	33.252 ± 1.279	0.816 ± 0.019	0.122 ± 0.003	40.8	272.6	6.7
T. angustifolia	Leaves	43.155 ± 1.532	2.968 ± 0.054	0.187 ± 0.010	14.5	230.8	15.9
	Stems	40.161 ± 0.821	0.805 ± 0.026	0.103 ± 0.015	49.9	389.9	7.8
	Roots	40.542 ± 1.110	0.439 ± 0.011	0.066 ± 0.003	92.4	614.3	6.7
N. nucifera	Leaves	41.932 ± 1.470	3.897 ± 0.058	0.264 ± 0.006	10.8	158.8	14.8
	Stems	36.382 ± 1.897	1.342 ± 0.032	0.074 ± 0.007	27.1	491.6	18.1
	Roots	27.908 ± 0.568	1.541 ± 0.072	0.368 ± 0.016	18.1	75.8	4.2
P. pectinatus	Leaves	29.259 ± 0.794	1.276 ± 0.044	0.104 ± 0.005	22.9	281.3	12.3
	Stems	32.336 ± 0.832	0.904 ± 0.023	0.083 ± 0.003	35.8	389.6	10.9
	Roots	36.509 ± 0.512	1.098 ± 0.067	0.143 ± 0.007	33.3	255.3	7.7
C. demersum	The whole body	27.529 ± 1.033	2.277 ± 0.153	0.201 ± 0.010	12.1	137.0	11.3
Chara sp.	The whole body	17.509 ± 0.760	0.612 ± 0.032	0.067 ± 0.003	28.6	261.3	9.1

Values are means of three replicates.

shown in Fig. 3 and Tab. 3. Significant differences were found among all plant species and tissues. The six species all had a significant dry weight loss in the first 6 days. The decomposition curves then became increasingly flatter, which meant that the decomposition rates were getting much slower over time. The most rapid decomposition calculated by the exponential model was showed by the leaves of *N. nucifera*, whereas the stems were the slowest to decompose. The dry weight losses of these above two species were 88.40 and 40.76%, respectively. *N. nucifera* showed the highest decomposition rate of 0.0028 day^{-1}, whereas *T. angustifolia* showed the lowest decomposition rate of 0.0110 day^{-1}. Relatively long degradation times were calculated by the exponential model for *T. angustifolia*, *C. demersum*, and *Chara* sp. In addition, the results from the exponential model expressed the general rule that decomposition rates of the leaves were always higher than those of the stems and roots for all the species.

For the same external environmental conditions, the large differences in decomposition rates of the individual plant species suggested that the initial characteristics of the litter play a primary role in the process of decomposition. The initial nutrient concentration is considered to be an effective predictor of decomposition rate. The remaining biomass (%) of all plant species on five initial

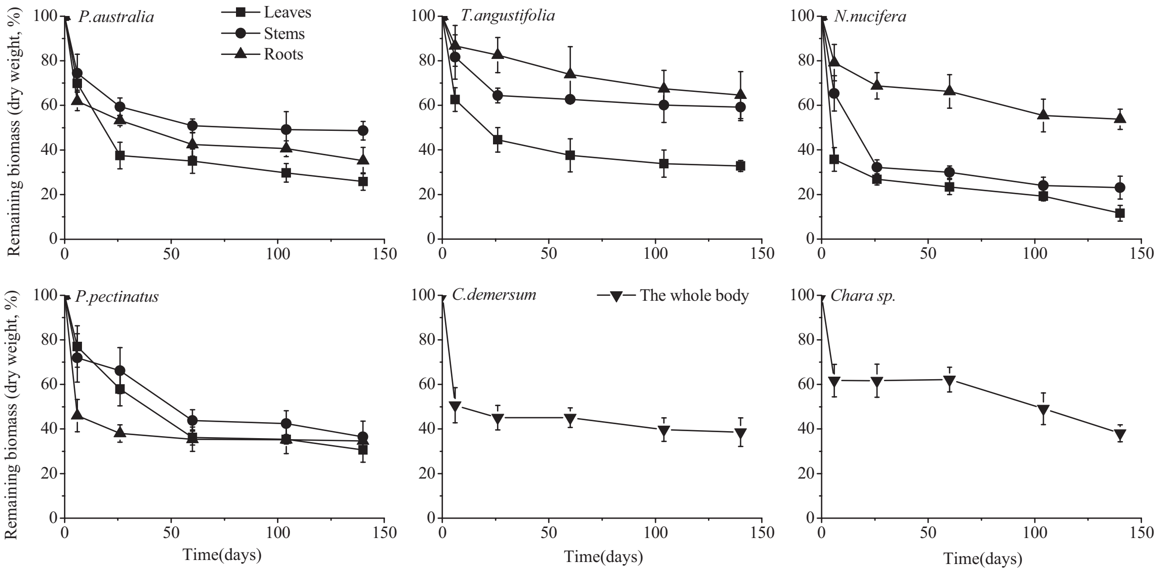

Figure 3. Dry weight loss of the litter from the six emergent and submerged macophytes during the decomposition period.

Table 3. Decomposition rate (*k*) of the six species calculated with the exponential model (day^{-1})

k	*P. australis*	*T. angustifolia*	*N. nucifera*	*P. pectinatus*	*C. demersum*	*Chara* sp.
Leaves	0.0081	0.0064	0.0110	0.0078		
Stems	0.0042	0.0028	0.0086	0.0063		
Roots	0.0057	0.0030	0.0037	0.0047		
The whole body					0.0044	0.0049

Table 4. Results of a linear regression analysis of the relationship between the remaining biomass and initial detritus quality factors

	Remaining biomass at each sampling time				
	Day 6	Day 26	Day 60	Day 104	Day 140
N %	-0.657^*	-0.619^*	-0.563^*	-0.612^*	-0.583^*
P %	-0.281	-0.145	-0.023	-0.087	-0.042
C/N	0.809^*	0.816^*	0.881^*	0.867^*	0.860^*
C/P	0.496	0.228	0.154	0.203	0.206
N/P	-0.698^*	-0.678^*	-0.726^*	-0.772^*	-0.748^*

$^*p < 0.05$.

litter quality factors at each sampling time was regressed (Tab. 4). The remaining biomass was positively related to the C/N and C/P ratios, and negatively related to the N and P concentrations and the N/P ratio. The N concentration and C/N and N/P ratios had significant effects on the remaining biomass over the entire experimental period. The C/N ratio explained approximately 80.9% of the variation in the biomass changes. This ratio showed a consistent decrease after the initial leaching times. Based on the analysis of the C/N ratio of each plant species, the results of our study support the general rule that lower C/N ratios are associated with higher decomposition rates. The initial C/P ratio and P concentration have no apparent effects on litter decomposition.

3.5 Nutrient release

Nutrients are one of the most important factors affecting the growth of aquatic macrophytes in a lake. The nutrient release during the decomposition of the vegetation was analyzed by measuring the decrease in the total mass of N and P in each sample. The N and P concentrations of the dominant macrophytes were also monitored 140 days (Tab. 5). The results of these analyses showed that the nutrient concentrations varied markedly among the six species in the experiment, especially during the first 6 days. These concentrations all rose continuously during the later incubation period. At the end of the incubation period, many of the nutrient concentrations exceeded the initial level. The result included the N concentrations of *P. australis* and *P. pectinatus* and the P concentration of *P. pectinatus* and *Chara* sp.

Despite the increase in the nutrient concentrations, the N and P content of each litter bag showed a general decrease due to the dry weight loss during the incubation period. The N and P content remaining from the initial litter content was calculated (Fig. 4). In association with the substantial decrease in dry weight over the first 6 days, the N and P content decreased sharply. The N and P content fluctuated mildly thereafter and remained at a relatively low level during the following days. The P content of the leaves of *N. nucifera* decreased by 90.84% during the initial 6 days. In general, substantial amounts of nutrients were transferred from the plants to the lake water. The release of N from the litter represented 18.10 to 88.79% of the initial value and the release of P from the litter represented 24.26 to 92.83% of the initial value. The nutrient release from the leaves was always greater than that from the roots and stems. The N and P content of the *P. pectinatus* stems were always lower than that of the leaves but higher than that of the roots until the end of the investigation. The level of nutrient release from the roots of most species was relatively higher than the level of nutrient release from the stems. This difference was observed for *P. australis*, *P. pectinatus*, the N release from *T. angustifolia*, and the P release from *N. nucifera*. The highest N and P release was found for the leaves of *N. nucifera*, and the smallest N and P release was found for the stems of *P. australis* and *P. pectinatus*.

4 Discussion

4.1 Decomposition of macrophytes

The dry weight loss during the 140 decomposition days included both the leaching and biodegradation stage. Leaching is the key process in the decomposition of macrophytes during the initial exposure period [27, 28]. A considerable proportion of the initial biomass was lost due to the dissolution of low molecular-weight substances and the effective utilization of these products by micro-consumers. The leaching rate depends primarily on the characteristics of litter and on the natural breakdown of plant litter before submersion. In this study, 13.33–64.27% of the total weight loss of

Table 5. Changes of N and P concentrations in the leaves, stems, and roots of the six species monitored throughout the decomposition experiment

		N concentration (%)							P concentration (%)				
		Day 0	Day 6	Day 26	Day 60	Day 104	Day 140	Day 0	Day 6	Day 26	Day 60	Day 104	Day 140
P. australis	Leaves	1.068	0.956	0.945	0.822	0.986	1.250	0.089	0.088	0.056	0.066	0.066	0.076
	Stems	0.733	0.679	0.734	0.941	1.083	1.104	0.137	0.066	0.067	0.080	0.102	0.109
	Roots	0.816	1.103	1.219	1.286	1.465	1.823	0.122	0.097	0.109	0.103	0.103	0.130
T. angustifolia	Leaves	2.968	2.813	1.410	1.527	1.678	1.723	0.187	0.077	0.067	0.067	0.087	0.090
	Stems	0.805	0.940	1.028	0.962	0.945	1.087	0.103	0.032	0.041	0.041	0.059	0.062
	Roots	0.439	0.469	0.406	0.408	0.411	0.445	0.066	0.055	0.043	0.048	0.061	0.068
N. nucifera	Leaves	3.897	5.126	3.281	3.230	3.242	3.765	0.264	0.068	0.098	0.121	0.149	0.163
	Stems	1.342	0.887	2.327	1.424	1.897	1.992	0.074	0.072	0.111	0.098	0.149	0.153
	Roots	1.541	1.229	1.448	1.040	1.225	1.321	0.368	0.219	0.126	0.114	0.133	0.153
P. pectinatus	Leaves	1.276	0.958	1.123	1.943	2.187	2.598	0.104	0.088	0.084	0.118	0.113	0.139
	Stems	0.904	1.103	0.989	1.469	1.573	1.693	0.083	0.082	0.092	0.115	0.160	0.173
	Roots	1.098	1.254	1.565	1.771	1.982	2.034	0.143	0.107	0.082	0.117	0.200	0.205
C. demersum	The whole body	2.277	2.753	1.812	1.306	1.724	1.765	0.201	0.123	0.106	0.094	0.120	0.130
Chara sp.	The whole body	0.612	0.516	0.244	0.268	0.352	0.598	0.067	0.044	0.045	0.046	0.054	0.068

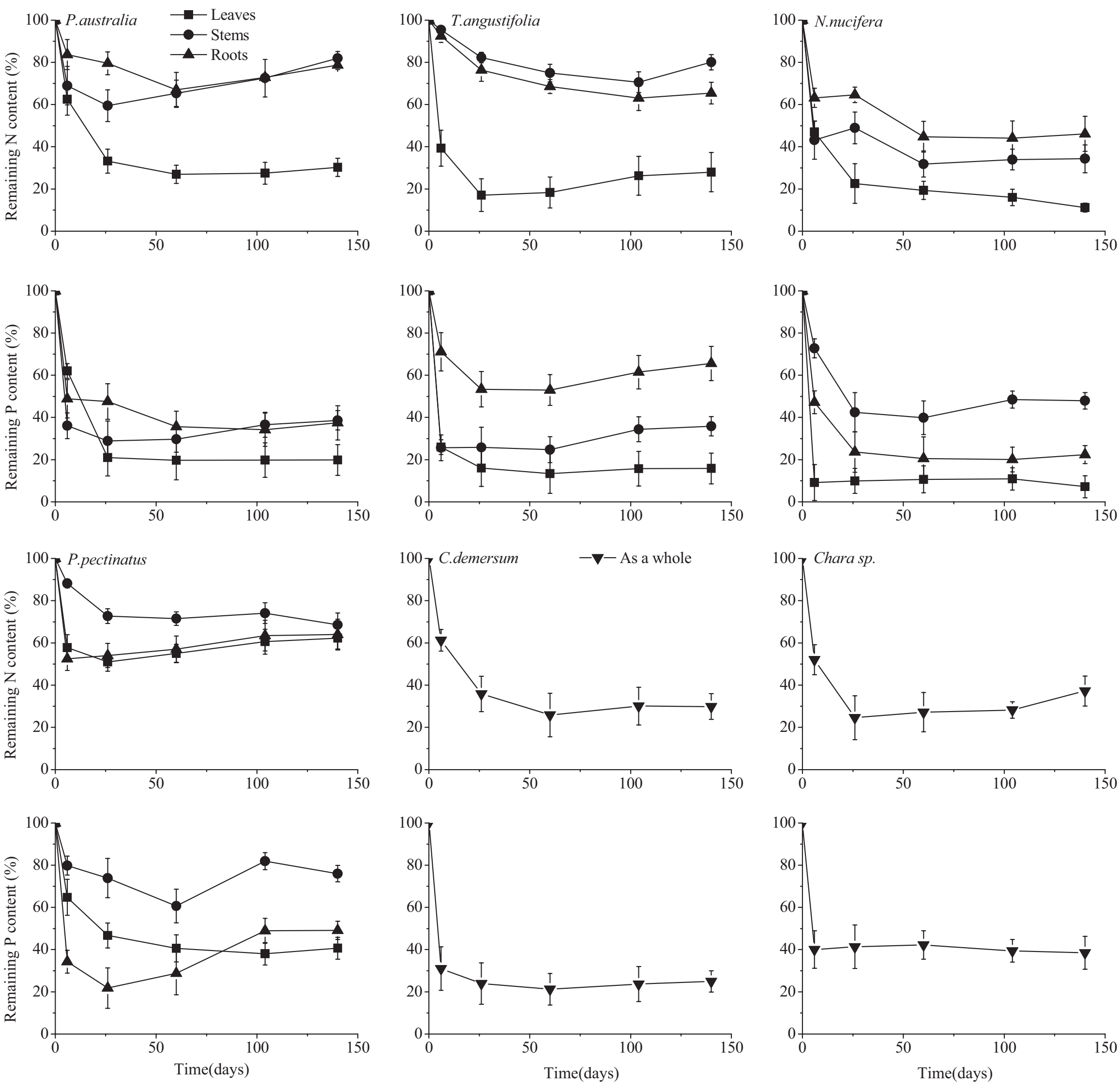

Figure 4. Remaining N and P content in the leaves, stems and roots of the six species retrieved throughout the decomposition experiment.

different species resulted from leaching during the first 6 days of incubation. Álvarez and Bécares [15] also found a loss of 12–15% of the total weight during the first 3 days of incubation in the summer and winter, respectively, in *Typha latifolia*. Bedford [29] observed that *P. australis* leaves lost approximately 15% of their initial weight and that the stems lost 5% after 65 days. Litter does not always decay at a constant rate. The decay is most rapid at the beginning and becomes gradually slower over time [18]. The results of our research correspond well with previous data from similar systems.

Different decomposition rates were observed for the leaves, stems, and roots of the dominant emergent and submerged macrophytes. At the end of the experiment, none of the plant material was decomposed completely. The highest dry weight loss, 88.4%, was observed for the leaves of *N. nucifera*. The weight loss of all submerged macrophytes and the leaves of emergent macrophytes was >60%. The lowest weight loss, 35%, was observed for *T. angustifolia* stems. Kirschner et al. [17] observed 50–60% weight loss for *P. australis* leaves and 30–40% loss of the initial mass for *T. latifolia* leaves after 1 year. *S. californicus* attained a dry weight loss of 15–17% after 7 months in a floodplain marsh of the Lower Paraná River [22]. The decomposition rates of plant litter in our study were higher than in previous studies of decomposition. Recently, Lopes et al. [30] showed that in most cases, the decomposition rate of reed litter was higher in freshwater than in brackish wetlands, lagoons and coastal lakes. Because Baiyangdian Lake is a typical macrophyte-dominated eutrophication lake, its water quality and hydrological conditions differ substantially from those of other lakes. Decomposition is a biological process controlled by the feeding and growth rates of microorganisms and macroinvertebrates. It is therefore possible that the high nutrient content and still water of Baiyangdian Lake facilitates a higher growth rate and propagation of microorganisms, producing the relatively higher decomposition rates observed in this study [31, 32].

Certain researchers argued that the initial litter characteristics are more important than environmental factors in decomposition process [17, 33, 34]. The initial litter N and P concentrations, the C/N, C/P, and N/P ratios are commonly believed to be important indexes of litter quality [35]. The C/N ratio has been widely recognized as one of the dominant factors that determine the variation in decomposition rate of plants [22]. This ratio explains approximately 80.9% of the variation in the biomass changes observed in our study. The N/P ratio and N concentration are also closely related to decomposition rate. These characteristics have a significant negative effect on the remaining biomass over the experimental period. Because of their higher C/N ratio, lower N/P ratio, and lower N concentration, both the stems and the roots always have a lower decomposition rate than the leaves of the same species. These findings indicate that microbial colonization and N concentration are closely related. The decomposition rate also depends strongly on the contents of refractory substances (e.g., cellulose, hemicelluloses, and lignin). The cell walls of certain species may be encrusted with SiO_2 and calcium to ensure higher stability. These inorganic constituents make the cell walls more difficult for microorganisms to decompose. The C/N ratio and cellulose contents of stems and roots were high. For this reason, these tissues were not an attractive food source for the macroconsumers [17].

Under the natural field conditions, different macrophyte species usually grow together and fall closely. Decomposition process usually occurs in litter mixtures instead of in monocultures [36]. An idea has been put forward that positive interactions were existed at a rational allocation of species and ratios, depending on the change of the initial chemical composition of the litter [37, 38]. The difference in C and N concentrations could cause positive, non-additive interaction effects of mixture species [39, 40]. Mixing litter of different plant species and tissues also change the activities of microorganism. There are obvious difference in the lengths of fungal hyphae, bacterial numbers, nematodes, and microarthropod abundances of litter bags between the single-species and mixed-species [41–43]. Thus, more and more researchers are trying to find out the positive effects existed in the litter mixtures. It will be the theory foundation for plant configuration and harvest.

4.2 Nutrient release during the decomposition period

Decomposition initially released nutrients by leaching, as shown by the initial decrease in tissue N and P concentrations in the litter bag experiment. During the initial 6 days, the decrease in P was higher than the decrease in N. We hypothesized that the water-soluble fraction of P in plant tissues was greater than the water-soluble fraction of N during the initial 6 days [35]. The substantial loss of P from litter serves as a rapid, short-term source of P for the wetland ecosystems [8]. After the first leaching stage, the decomposition material gradually enriched the N and P concentrations throughout the experiment. Our findings are consistent with those of Davis and of Villar et al. [22, 44]. In the second stage, microorganisms and invertebrates played major roles in plant decay. The initial characteristics of the litter strongly affected the biodegradation process. Low cellulose content and a low C/N ratio facilitated the utilization of the plant litter by microorganisms and invertebrates [44, 45]. Environmental conditions also limited the release of nutrients release from litter. The availability of P in the water significantly affected the release rates of N and P, whereas the impacts of N availability were not statistically insignificant [46].

The release of nutrients resulted from the combined effects of changes in tissue nutrient concentrations and the weight loss of the matter in each bag. An increase in the N and P concentrations in the litter was modified by a decrease in dry weight loss. The general net effect of these two changes was an apparent decrease in the total N and P content. The results of the study showed that >50% of the N and P were released from the plant litter during the experimental periods and that the proportion released could even reach 90%. Moreover, the biomass of aquatic macrohpytes is relatively great. Due to this substantial amount of biomass, large amounts of N and P are transferred from plant tissue to lake water or sediment. In turn, this process will facilitate a marked proliferation of aquatic macrophytes in Baiyangdian Lake, and will then cause a much greater accumulation of sediment as a result of the decomposition of the tissues of aquatic macrophytes.

5 Conclusions

This study discussed the decomposition rules of dominant macrophytes in a eutrophic shallow lake. Different decomposition rates were observed for different plant species and tissues. The initial N concentration of the litter and the nutrient mass ratios, such as the C/N ratio and N/P ratio, have significant effects on decomposition. We therefore believe that proper initial detritus characteristics are beneficial to encourage the decomposition process. Moreover, results also demonstrated that nutrients were released tremendously from the residues of plant residues to the lake water. One challenge emerging from this study is the need to understand how environmental conditions control decomposition rates and nutrient release.

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