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Winter Decomposition of Emergent Macrophytes Affects Water Quality under Ice in a Temperate Shallow Lake

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Abstract: Decomposition of emergent macrophytes is now recognized as an internal nutrient source for shallow lakes. Temperate lakes always experience seasonal ice cover in winter, but the influences of emergent macrophytes decomposition on water quality have rarely been examined under ice. Here, we conducted an incubation experiment to investigate winter decomposition of two common emergent macrophytes species (*Typha orientalis* and *Phragmites australis*) and its influences on water quality in the Hengshui Lake, North China. Mesocosms simulating a lake ice regime were incubated in the field for 120 days in winter and were treated with and without plant material addition. Water quality was monitored through dissolved oxygen (DO), dissolved organic carbon (DOC), total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N). We found that both species were significantly decomposed in winter and that the majority of mass loss occurred in the first 10 days of decomposition when the water surface of mesocosms were already frozen. The concentrations of DO rapidly dropped to values close to zero after plant material submergence. At the end of incubation, the concentrations of DOC, TN, and NO_3-N in the mesocosms with plant material addition were significantly higher than initial concentrations. In contrast, the concentrations of DOC, TN, TP, NO_3-N, and NH_4-N in the mesocosms without plant material addition were equal to or less than initial concentrations. Our research suggests that winter decomposition of emergent macrophytes produces negative influences on water quality under ice that lasts for the whole winter.

Keywords: emergent macrophytes decomposition; ice cover; dissolved oxygen; dissolved organic carbon; nitrate

1. Introduction

Emergent macrophytes play an important role in energy flows and nutrient cycling in shallow lakes [1]. During the growing season, emergent macrophytes convert solar energy to biomass and absorb nutrients from sediments and overlying water [2]. After emergent macrophyte senescence, plant detritus accumulates on sediments, supporting the heterotrophic food web, and the nutrients incorporated in plant material are released back into the water column [3,4]. In oligotrophic temperate lakes, more than 20 percent of nitrogen and phosphorus in lake water is stored in plant materials and is regulated by vegetation phenology of emergent macrophytes [5].

Shallow lakes suffer from eutrophication worldwide due to anthropogenic inputs of nutrients in recent decades [6]. Emergent macrophytes will assimilate unnecessarily high concentrations of

nutrients, which is known as luxury uptake, and will produce extraordinarily abundant biomass in response to increasing nutrient availability [7]. Since the senescent emergent macrophytes collapse and immerse into water, excess nutrients released from plant materials undermine the efforts of reducing external nutrient inputs on eutrophic lakes restoration [8,9]. Thus, emergent macrophyte decomposition has received particular attention for its influence on water quality [10–12].

Decomposition of emergent macrophytes generally involves three interlinked process: leaching of water-soluble compounds, physical fragmentation to small pieces, and biochemical degradation to basic inorganic molecules [13,14]. Deterioration of water quality, including eutrophication and dissolved oxygen (DO) deficit, will come with the leaching and the biochemical degradation processes. For instance, the concentrations of total nitrogen (TN) and total phosphorus (TP) in receiving water quickly rise to above 2 mg/L and 0.2 mg/L, respectively, as a considerable proportion of nutrients is leached from emergent macrophytes detritus in a short time after submergence [15,16]. Organic matter degradation consumes plenty of DO by both biological respiration and chemical oxidation [17], and nitrogen released from plant materials increases the supply of ammonium for nitrification; the autotrophic microbial oxidation of ammonium to nitrate exerts another oxygen demand on the water column [18]. As a result, the concentrations of DO in water columns drop more than 50% when receiving 1 g/L emergent macrophytes detritus [12].

In temperate regions, the seasonal variation in vegetation phenology leads the initial stage of emergent macrophytes decomposition to experience the harsh winter when air temperature is always below the freezing point [19,20]. A characteristic of temperate lakes in winter is the ice cover, which excludes gas exchange and insulates thermal transmission [21,22]. However, the understanding of emergent macrophyte decomposition affecting water quality has been dominated by observations in ice-free conditions [11,12,15,16]. The winter ice cover creates a unique environment for decomposition, but there is little knowledge about emergent macrophyte decomposition under ice and its influences on water quality.

The objectives of this paper were (1) to examine the winter decomposition of two common emergent macrophytes species (*Typha orientalis* and *Phragmites australis*) and (2) to investigate water quality dynamics of the ice-covered water columns with decomposing emergent macrophytes. We hypothesized that emergent macrophytes would be significantly decomposed in winter and that the winter decomposition would cause serious DO depletion as ice cover excludes gas exchange.

2. Materials and Methods

2.1. Study Area

This study was conducted in Hengshui Lake (115°34′ E and 37°36′ N), a shallow freshwater lake located in Hebei provinces, North China. The Hengshui Lake has a surface area of 75 km^2 and an average depth of 2.1 m. The climate of this area is temperate continental monsoon with a mean annual temperature of 12.7 °C The littoral zone of the Hengshui lake, which occupies 17% of the total surface area of the lake, is dominated by *T. orientalis*, *P. australis*, and *Nelumbo nucifera* [23].

2.2. Experiment Design

An incubation experiment was conducted in the field to study winter decomposition of emergent macrophytes and its influences on water quality under ice (Figure 1). First, nine containers made of glass fiber-reinforced plastics were constructed and placed on the bank of the Hengshui Lake in September 2015. The container had a cuboid shape with 80 cm length, 80 cm width, and 100 cm height, and every three containers were connected in parallel. Later, the containers were filled with sediment and surface water, which were collected from the littoral zone of the lake, to 10 cm and 20 cm depth, respectively. The sediment used in the incubation experiment was a silty clay (Appendix A, Table A1). On 14 November 2015, the containers were filled with lake water to 50 cm depth until the water volume of each mesocosms was approximately 320 L at the beginning of experiment. Two common species of

emergent macrophytes, *T. orientalis* and *P. australis*, were harvested as standing-dead on the same day. After that, plant materials were air dried for 7 days. Eight subsamples of each species were oven dried at 55 °C for 72 h to constant weight in order to obtain the relation between air dried and oven dried weight. On 21 November 2015, the nine mesocosms were randomly classified as three groups; two groups were added *T. orientalis* and *P. australis*, respectively; the other group was treated as a control without plant materials addition; and each group had 3 replicates. Most of the plant materials added to the mesocosms were intact aboveground parts of emergent macrophytes, and a small proportion of the plant materials was cut and placed into nylon litterbags to assess the decomposition rate. Each litterbag (20 × 20 cm with 2 mm mesh size) was filled with 5 g of air-dried plant materials, and 10 litterbags were placed into each mesocosm. The total amount of plant materials added to each mesocosm was 320 g, meaning the water column received 1 g/L of plant materials. The water columns in the control were stirred by a plastic rod to simulate disturbance of placing plant materials. Water samples and litterbags were collected simultaneously at days 0, 1, 3, 5, 10, 15, 30, 60, 90, and 120. The DO concentrations were measured by a multi-parametric probe (YSI 6820, YSI Environmental Inc., Yellow Springs, OH, USA) at each sampling time before sampling the water. On the second day of experiment, the water surface of mesocosms began to freeze after a heavy snowfall and the ice cover lasted for more than 100 days (Figure A1).

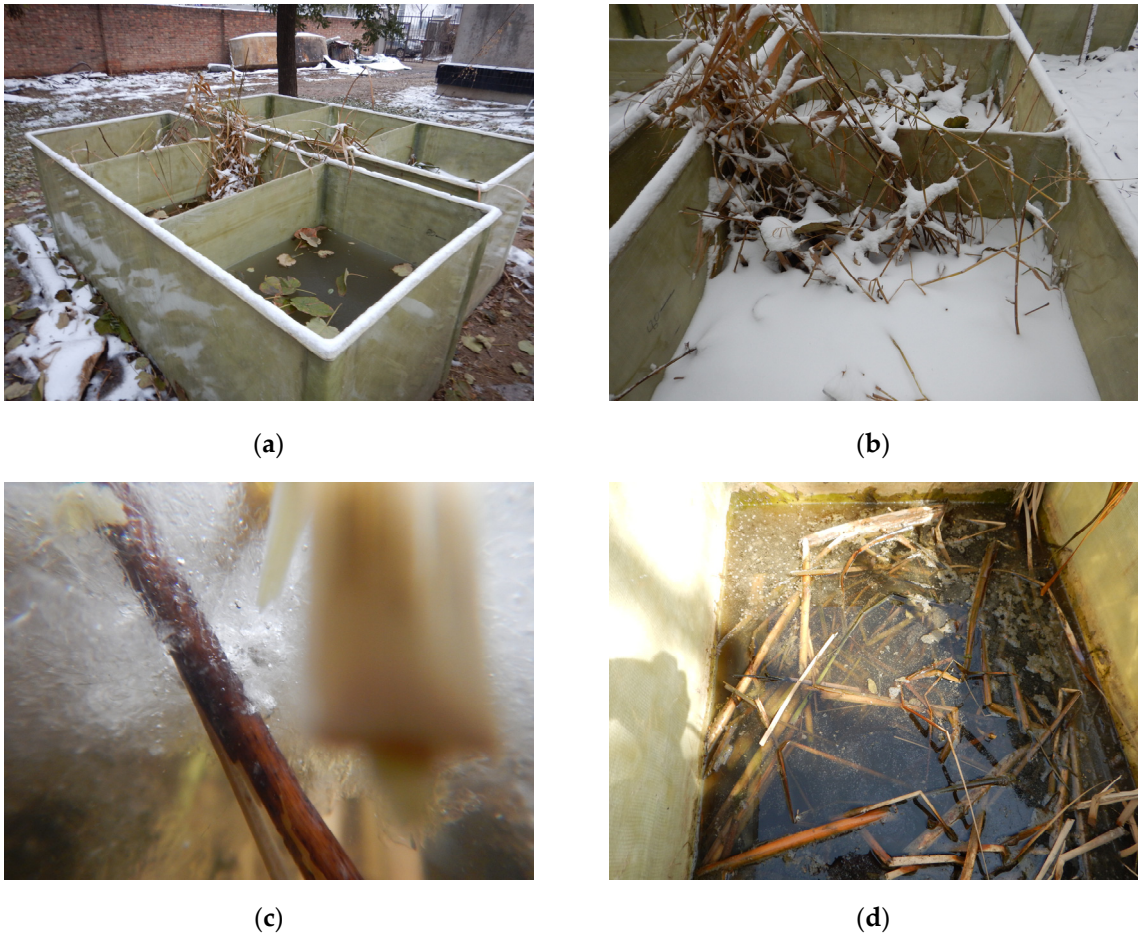

Figure 1. (**a**) On 22 November 2015, the water surface of mesocosms began to freeze. (**b**) On 25 November 2015, the water columns of mesocosms were under snow and ice cover. (**c**) On 1 December 2015, *P. australis* decomposed under ice. (**d**) On 20 March 2016, the decomposition of *T. orientalis* in the mesocosm after ice-off was incomplete.

2.3. Chemical Analysis

The water samples were filtered and refrigerated before chemical analysis. The dissolved organic carbon (DOC) concentrations were measured on a total organic carbon (TOC) analyzer (Vario TOC, Elementar Analysensysteme GmbH, Langenselbold, Germany). The concentrations of TN, TP, ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) were analyzed on a discrete auto analyzer (Smart-Chem 200, WESTCO Scientific Instruments, Brookfield, CT, USA).

The initial and remaining plant materials were analyzed for the total C, N, and P contents after samples were oven dried at 55 °C for 72 h and ground to fine powders. The total C and N contents were analyzed on an elemental analyzer (Vario ELIII CHNOS Elemental Analyzer, Elementar Analysensysteme GmbH, Langenselbold, Germany). The total P contents were measured by the ammonium molybdate ascorbic acid method using an UV-visible spectrophotometer (Shimadzu UV-2550, Kyoto, Japan).

2.4. Calculations and Statistical Analysis

The C, N, and P release rates from plant materials were calculated as a percentage of the initial total contents:

$$R = ((C_0M_0 - C_tM_t)/(C_0M_0)) \times 100\%, \quad (1)$$

where R represents the release rate of C, N, and P from plant materials at sampling time t; M_0 is the initial mass of plant materials; Mt is the remaining mass of the decomposed plant materials at time t; C_0 is the initial concentrations of C, N, and P in the plant materials; and C_t is the concentration of C, N, and P in the plant materials at sampling time t.

The change ratios of DO, DOC, TN, TP, NH_4-N, and NO_3-N in the water columns before and after experiment were calculated as follows:

$$A = ((B_e - B_0)/B_0) \times 100\%, \quad (2)$$

where A represents normalized change ratios of DO, DOC, TN, TP, NH_4-N, and NO_3-N in the water columns; B_e is the concentrations of DO, DOC, TN, TP, NH_4-N, and NO_3-N in the water columns at the end of experiment; and B_0 is the concentrations of DO, DOC, TN, TP, NH_4-N. and NO_3-N in the water columns at the beginning of experiment.

The differences in DO, DOC, TN, TP, NH_4-N, and NO_3-N concentrations in the water columns between *T. orientalis* treatment, *P. australis* treatment, and the control were tested by repeated measures one-way Analysis of Variance (ANOVA) and post hoc Dunnett's tests. In addition, paired comparisons of the DO, DOC, TN, TP, NH_4-N, and NO_3-N concentrations in the water columns between the beginning and the end of experiment were conducted by Student's t test. Principal component analysis (PCA) was applied to evaluate and visualize the change in water quality through the experimental period. Time-series correlation analysis was performed to assess the relationship between the release rates of C, N, and P from plant materials and the concentrations of DO, DOC, TN, TP, NH_4-N, and NO_3-N in the water columns using the mean value of each sampling time. The releases of C, N, and P from plant materials and the dynamics of DO, DOC, DOC:NH_4-N, and NH_4-N:NO_3-N in the water column were used to construct a structural equation modelling (SEM). All tests were conducted in SAS 9.3 (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Mass Loss and C, N, and P Release

Both *T. orientalis* and *P. australis* were significantly decomposed in winter ($p < 0.001$). The remaining mass after 120 days of *T. orientalis* and *P. australis* was 65.4% and 76.4% of its initial mass, respectively, and more than 15 percent of mass was lost in the first 10 days of decomposition (Figure 2).

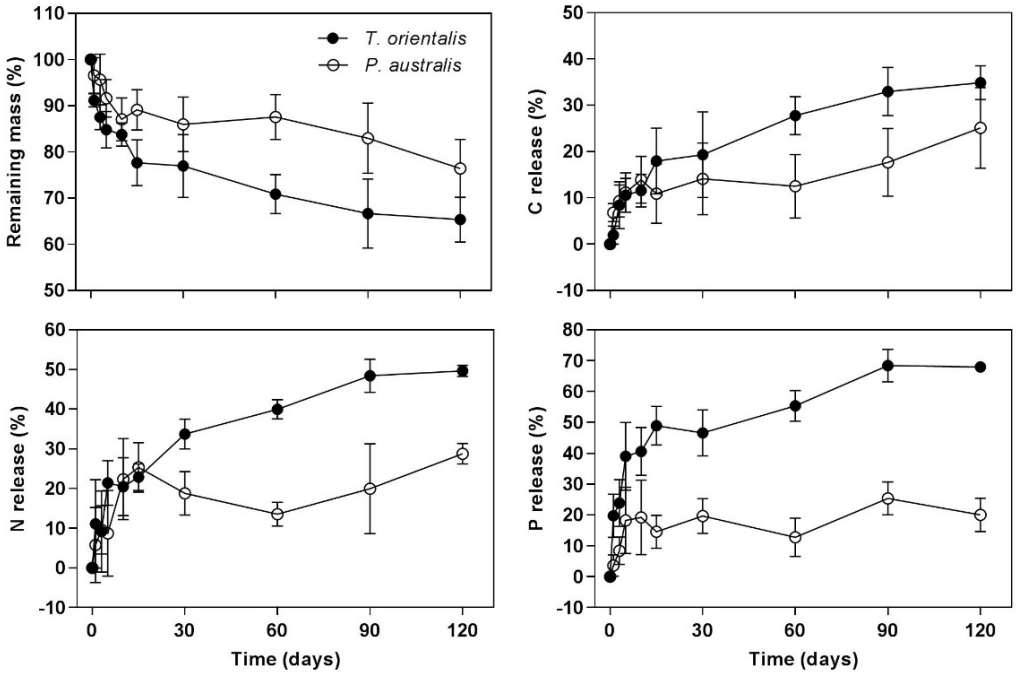

Figure 2. The remaining mass of plant materials and C, N, and P release from plant materials during decomposition.

The initial contents of C, N, and P were significantly higher in *T. orientalis* than in *P. australis* (Table A2). During decomposition, both species gradually released C. *T. orientalis* consistently released N, and *P. australis* mobilized N in the first 20 days and immobilized N in the following days. The release of P mainly occurred in the first 20 days, and *T. orientalis* released a higher proportion of P than *P. australis* (Figure 2).

3.2. Dynamics of Water Quality

Repeated measures ANOVA indicated that there were significant differences in DO, DOC, TN, TP, NH_4-N, and NO_3-N among treatments and sampling times (Table 1). The concentrations of DO in the water columns with plant material addition rapidly dropped to nearly zero and lasted for the whole winter. In contrast, the concentrations of DO remained above 8 mg/L in the control. The concentrations of DOC increased to above 15 mg/L and 10 mg/L in the *T. orientalis* treatment and the *P. australis* treatment, respectively, and fluctuated around 5 mg/L in control. The concentrations of TN rose to above 2 mg/L in the *T. orientalis* treatment and the *P. australis* treatment and remained below 2 mg/L in the control. The concentrations of TP varied between 0.10 to 0.25 mg/L in the *T. orientalis* treatment and the *P. australis* treatment and declined from 0.10 to 0.05 mg/L in the control. During incubation, DO concentrations were significantly lower in the *T. orientalis* treatment and the *P. australis* treatment than in the control, and the concentrations of DOC, TN, and TP were significantly higher in the *T. orientalis* treatment and the *P. australis* treatment than in the control (Figure 3).

Table 1. Repeated measures ANOVA results for the effects of treatments (*T. orientalis* treatment, *P. australis* treatment, and control) and sampling time (days 0, 1, 3, 5, 10, 15, 30, 60, 90, and 120) on water quality indices, including dissolved oxygen (DO), dissolved organic carbon (DOC), total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N).

Source	DO	DOC	TN	TP	NH_4-N	NO_3-N
Treatment (T)	$F_{2,6}$ = 2702.39 **	$F_{2,6}$ = 471.37 **	$F_{2,6}$ = 24.26 **	$F_{2,6}$ = 244.92 **	$F_{2,6}$ = 15.47 **	$F_{2,6}$ = 16.07 **
Sampling time (S)	$F_{9,54}$ = 125.36 **	$F_{9,54}$ = 11.72 **	$F_{9,54}$ = 6.63 **	$F_{9,54}$ = 4.71 **	$F_{9,54}$ = 10.25 **	$F_{9,54}$ = 3.02 **
$T \times S$	$F_{18,54}$ = 37.29 **	$F_{18,54}$ = 5.22 **	$F_{18,54}$ = 3.72**	$F_{18,54}$ = 4.11 **	$F_{18,54}$ = 1.74 ^{ns}	$F_{18,54}$ = 0.88 ^{ns}

** Significance at $p < 0.01$; ns, no significant differences, i.e., $p > 0.05$.

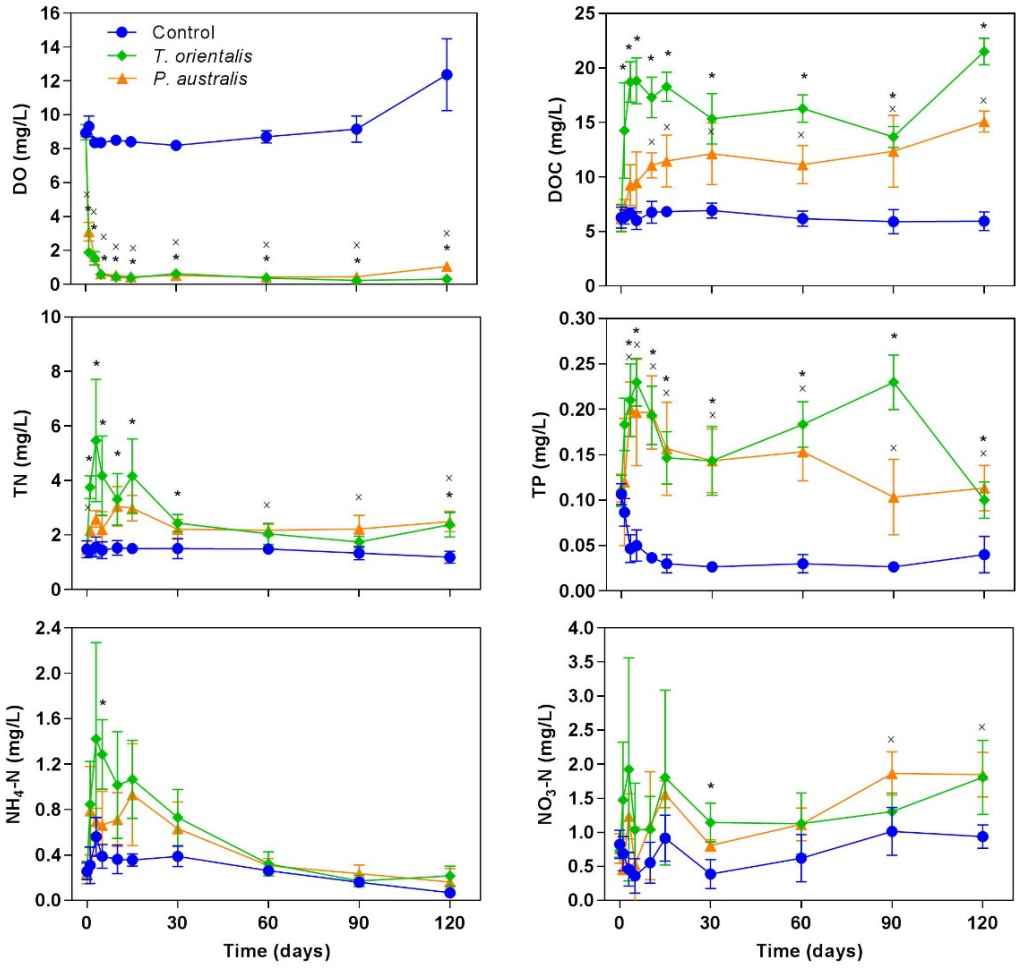

Figure 3. Dynamics of dissolved oxygen (DO), dissolved organic carbon (DOC), total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) in the water column during the 120-day incubation. * Significant difference between *T. orientalis* treatment and control, × significant difference between *P. australis* treatment and control (repeated measures ANOVA, post hoc Dunnett's tests, $p < 0.05$).

The concentrations of NH_4-N in the water columns with plant material addition rose to above 0.5 mg/L in the first 20 days and then decreased to 0.2 mg/L. The concentrations of NH_4-N gradually declined to below 0.1 mg/L in the control but were not significantly different from that in the *T. orientalis* treatment and the *P. australis* treatment at most sampling times. The concentrations of NO_3–N varied between 0.5 to 2.0 mg/L in the *T. orientalis* treatment and the *P. australis* treatment and were slightly higher than in the control (Figure 3).

At the end of experiment, DO concentrations were significantly lower than at the beginning of the experiment, and DOC, TN, and NO_3-N concentrations were significantly higher than at the

beginning of the experiment in the *T. orientalis* treatment and the *P. australis* treatment. Moreover, the concentrations of TP and NH_4-N were significantly lower at the end of the experiment than at the beginning of the experiment in the control (Figure 4).

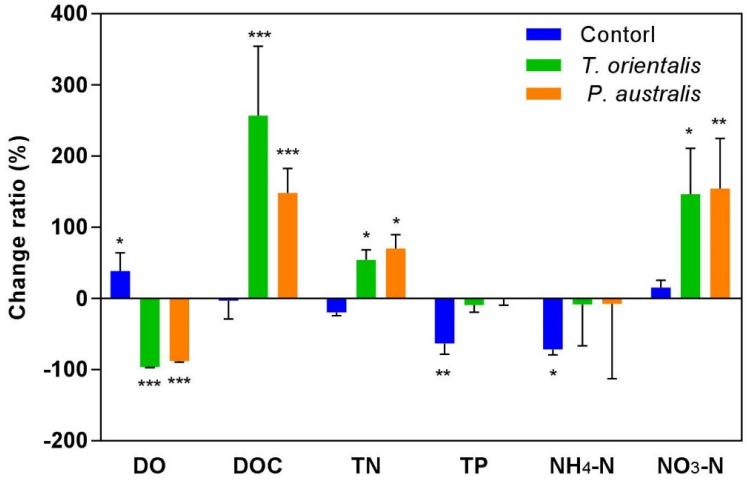

Figure 4. Change ratios of DO, DOC, TN, TP, NH_4-N, and NO_3-N in the water columns before and after the experiment. *** Significance at $p < 0.001$; ** significance at $p < 0.01$; and * significance at $p < 0.05$ (paired t test).

The first principal component (PC I) was negatively related to DO and positive related to DOC, TN, and TP, which explained 70.2% of total variance. The second principal component (PC II) was negatively related to NO_3-N and positive related to NH_4-N, which explained 14.7% of total variance. The water quality of *T. orientalis* treatment and *P. australis* treatment was distinct from the control and mainly moved in the positive direction of PC I in the first 30 days and moved in the negative direction of PC II in the following days (Figure 5).

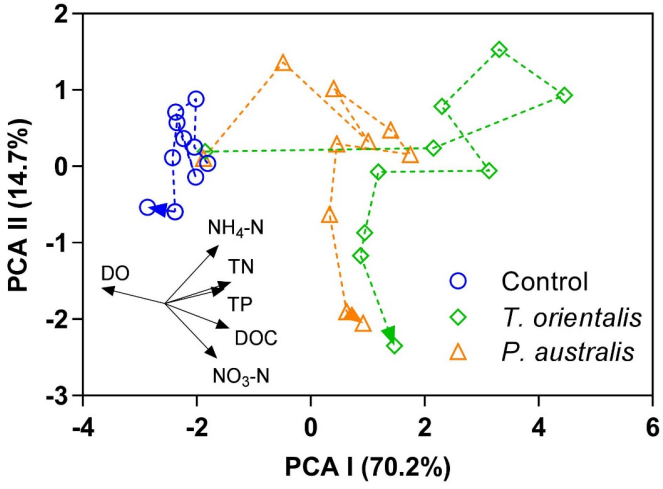

Figure 5. Principal component analysis (PCA) on water-quality dynamics through the experimental period: the dashed arrow indicates the succession of water quality from 0 to 120 days.

3.3. Relationship between Water Quality and Decomposition

The releases of C, N, and P presented a negative effect on DO dynamic in both the *T. orientalis* treatment and the *P. australis* treatment. A positive relationship between DOC concentrations and C, N, and P releases was found in the *P. australis* treatment. The concentrations of TN and NO_3-N were positively correlated with N release, and the concentrations of NO_3-N were also positively correlated

with C release in the *P. australis* treatment. The concentrations TP and NH_4-N showed nonsignificant correlations with C, N, or P release (Table 2).

Table 2. Pearson's correlation coefficients between the concentrations of DO, DOC, TN, TP, NH_4-N, and NO_3-N in the water column and the release rates of C, N, and P from plant materials.

	DO	DOC	TN	TP	NH_4-N	NO_3-N
T. orientalis						
C release	−0.605 ^{ns}	0.453 ^{ns}	−0.409 ^{ns}	−0.045 ^{ns}	−0.528 ^{ns}	0.277 ^{ns}
N release	−0.656 *	0.447 ^{ns}	−0.441 ^{ns}	0.003 ^{ns}	−0.523 ^{ns}	0.183 ^{ns}
P release	−0.788 *	0.599 ^{ns}	−0.238 ^{ns}	−0.112 ^{ns}	−0.320 ^{ns}	0.306 ^{ns}
P. australis						
C release	−0.717 *	0.954 **	0.458 ^{ns}	−0.119 ^{ns}	−0.313 ^{ns}	0.683 *
N release	−0.696 *	0.923 **	0.718 *	−0.022 ^{ns}	−0.015 ^{ns}	0.750 *
P release	−0.785 **	0.842 *	0.458 ^{ns}	0.071 ^{ns}	−0.139 ^{ns}	0.547 ^{ns}

** Significance at $p < 0.01$; * significance at $p < 0.05$; ns, no significant differences, i.e., $p > 0.05$.

A structural equation modelling (SEM) was constructed to quantify the contribution of emergent macrophyte decomposition to DO depletion, based on the known mechanisms of oxygen consumption including organic matter degradation and nitrification. The SEM showed a reasonable fit to our hypothesized causal relationships ($\chi^2 = 4.18$, $p = 0.52$, df = 5, comparative fit index (CFI) = 1.00, goodness of fit index (GFI) = 0.98, and root mean square error of approximation (RMSEA) < 0.001). The parameters included in the model explained 47% of the variation in DO dynamics. The release of C and N from plant material was negatively correlated with DO concentrations. Emergent macrophyte decomposition also indirectly influenced DO concentration by increasing DOC concentration and changing DOC to the NH_4-N ratio and NH_4-N to the NO_3-N ratio (Figure 6).

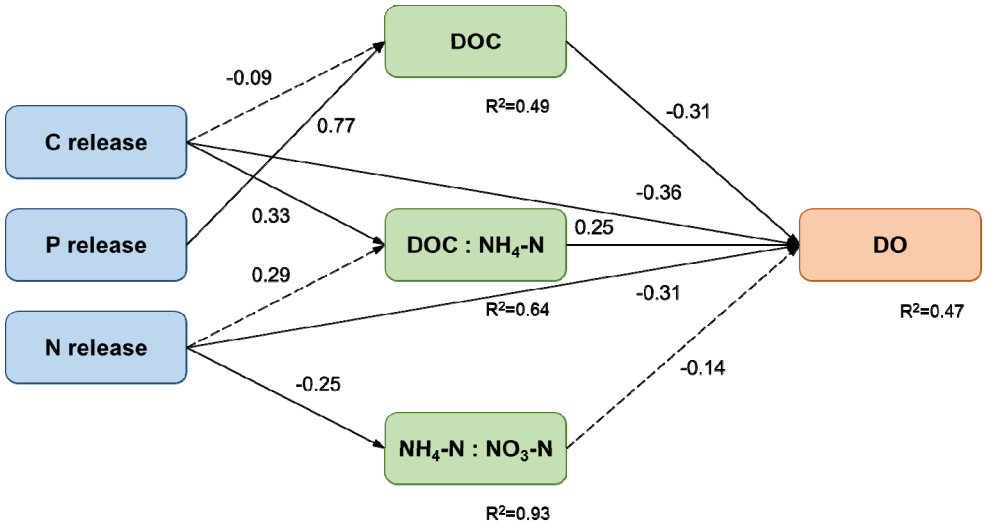

Figure 6. A structural equation model (SEM) of the causal relationships among C, N, and P release and DO, DOC, NH_4-N, and NO_3-N dynamics in the water column: the solid and dashed lines indicate significant ($p < 0.05$) and nonsignificant effects, respectively. The numbers above arrows are path coefficients. The R^2 values represent the proportion of variance explained for each endogenous variable.

4. Discussion

Our results confirm that emergent macrophytes are significantly decomposed in winter when temperate lakes are under ice cover. The mass loss is similar to a field experiment conducted in another temperate lake in North China [19], which indicates that winter decomposition under ice will not be an artificial phenomenon in our incubation experiment. Winter decomposition of emergent macrophytes

under ice may result from several factors. First, leaching of soluble materials is relatively independent of temperature [24] and rapid mass loss at the initial stage of decomposition is likely attributed to the leaching process in spite of low water temperature. Second, the cold but stable habitats in ice-covered lakes favors psychrophilic microorganisms in the water column and sediments [25]. Although we did not measure microbial metabolism during decomposition, an aquatic decomposer including both of bacteria and fungi is known to exhibit relatively high diversity and activity under ice cover [26,27]. Moreover, biological degradation of organic matter from temperate lake sediments in cold environments is sometimes more efficient than in warm environments due to microbial community shift [28]. Third, some of plant materials lay across the water–air interface after emergent macrophytes senescence. When ice lifts, freezing performs physical fragmentation on these plant materials (Figure 1c), which prompts soluble materials to release from the cracks in plant materials and increases the surface area of plant material exposed to microbial colonization [29]. Fourth, macroinvertebrates in sediments also remain active and contribute to decomposition as they are protected from freezing by the ice cover [30]. Regardless of the causes, the mass loss of *T. orientalis* and *P. australis* under ice (about 30% of initial mass) is only a little less than in ice-free condition (30–40% of initial mass) for the same incubation time [12,31,32]; thus, winter decomposition under ice should not be ignored.

The inputs of plant materials in our experiment (1 g/L or 0.5 kg/m^2) did not exceed normal emergent macrophytes biomass, but such an amount of plant materials will rarely be submerge into water simultaneously in nature, so the influences of emergent macrophyte decomposition on water quality may be overestimated. In spite of this weakness, our experiment provides a novel insight into the influences of winter decomposition on water quality, which has always been investigated in ice-free water columns [11,12,15,16]. In general, the great discrepancy of water quality between *T. orientalis* treatment, *P. australis* treatment, and the control suggests that winter decomposition of emergent macrophytes exerts negative and multiple influences on water quality under ice (Figure 5).

The addition of plant material resulted in 150–250% increases in DOC concentration in receiving water at the end of incubation compared to initial concentrations (Figure 4). In contrast, DOC concentrations in the control remained unchanged during incubation (Figure 3), indicating that little DOC was released by sediments and that the increases in DOC in the *T. orientalis* treatment and the *P. australis* treatment originate from decomposing emergent macrophytes. The increase in DOC in the water column after plant material submergence coincides with previous research [12,33,34]; however, the high concentration of DOC only lasts for several days and recovers to normal in the growing season [34]. The decrease in DOC in the later period of incubation is the result of DOC mineralization exceeding formation [35]. Cold water temperatures could constrain the microbial consumption of DOC but not hinder the leaching of DOC from plant materials [36]. Therefore, the released DOC accumulates in the water columns for the whole winter.

A significant rise in TN in the water column was observed in the *T. orientalis* treatment and the *P. australis* treatment. Although NO_3-N contributed to the majority of TN increases at the end of incubation, most of the NO_3-N might not be directly released by plant materials [24]. The accumulation of NO_3-N was accompanied with the decrease of NH_4-N (Figure 3), implying that the increases of NO_3-N would be produced by nitrification. Without the supply of nitrogen by decomposing emergent macrophytes, nitrification could induce exhaustion of NH_4-N. Unlike our results, decomposition of emergent macrophytes will not cause NO_3-N accumulation in the water columns in a warm environment, since the generated NO_3-N from nitrification will be removed by denitrification [11]. Furthermore, liable dissolved organic carbon released by plant materials provides high-quality carbon sources for denitrifying bacteria, prompting the removal of NO_3-N [37]. As the efficiency of denitrification is inversely related to temperature and will decline to a negligible level below 5 °C [38], most of the NO_3-N generated during decomposition would accumulate in the cold water.

The dynamics of TP in the water column were somewhat different from TN. While a considerable proportion of P was released, accumulation of TP in the water columns was not found at the end of incubation in the *T. orientalis* treatment or the *P. australis* treatment, and the concentrations of TP

significantly declined in the control (Figure 4). A possible explanation is that P in the water columns will absorb to Al, Mn, and Ca minerals or form organic matter in sediments, especially in a static environment [39]. The water columns under ice cover benefited from such removal of P that offset P releases from plant materials.

As we anticipated. serious DO depletion in the water columns occurred in the *T. orientalis* treatment and the *P. australis* treatment. The negative correlation between DO dynamics and C, N, and P releases from plant materials indicates that emergent macrophyte decomposition might directly contribute to the deficit of DO in the water columns (Table 2), but DO depletion under ice would result from a series of complex processes. Most importantly, ice cover cuts off oxygen replenishment from the atmosphere [21], so DO concentration will reasonably decline when there is a great DO demand in the water columns. The demand of DO in ice-covered lakes is generally attributed to organic matter degradation [40], and our results suggest two possible pathways for emergent macrophyte decomposition to consume DO by organic matter degradation. One is the microbial metabolism of liable organic matter in plant materials which might account for part of the carbon loss during decomposition; another is the mineralization of released DOC from plant materials in the water columns (Figure 6). In addition, recent research also points out the contribution of nitrification on DO depletion in ice-covered lakes [41]. A decease in the ratio of NH_4-N to NO_3-N in the water column, which is the evidence of nitrification, was found in our experiment but was not significantly related with the dynamics of DO (Figure 6). This paradox can be explained by the rapid decreases of DO at the initial stage of incubation. When the NH_4-N to NO_3-N ratio declined, DO concentrations were already below 1 mg/L with no obvious decrease trends, so the relationship between nitrification and DO depletion was difficult to recognize. Even so, nitrification can occur under DO concentrations as low as 0.4 mg/L [42] and constantly consumes DO at later periods of incubation. Moreover, the accumulated DOC in the water columns may constrain nitrification for the competitive advantage of heterotrophic bacteria to nitrifying bacteria [43]. Although the DOC to NH_4-N ratio is positively related to DO dynamics, both DOC mineralization and nitrification will consume DO. The combined effects of all these factors finally result in DO depletion for the ice-covered water columns.

5. Conclusions

By 120 days of incubation in winter, we found substantial mass loss of emergent macrophytes, significant accumulation of DOC and NO_3-N, and depletion of DO in the water columns with decomposing plant materials. Our results imply that winter decomposition of emergent macrophytes in the littoral zone of temperate lakes will not be inhibited by ice cover and that emergent macrophytes decomposition could contribute to DO depletion under ice by organic matter degradation and nitrification. We conclude that winter decomposition of emergent macrophytes produces negative influences on water quality and that the indices and duration of water-quality change affected by emergent macrophytes decomposition under ice are different from in ice-free conditions [11,12,15,16,34]. Further research should evaluate the influences of emergent macrophyte decomposition under ice on whole-lake water quality based on field observation.

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Appendix A

Table A1. The physicochemical properties of the sediment used in the incubation experiment.

pH	Sand (%)	Silt (%)	Clay (%)	Total Organic Carbon (mg/g)	Available Nitrogen (mg/kg)	Available Phosphorus (mg/kg)	Available Potassium (mg/g)
8.39	15.57	36.40	48.03	1.79	20.61	3.96	0.13

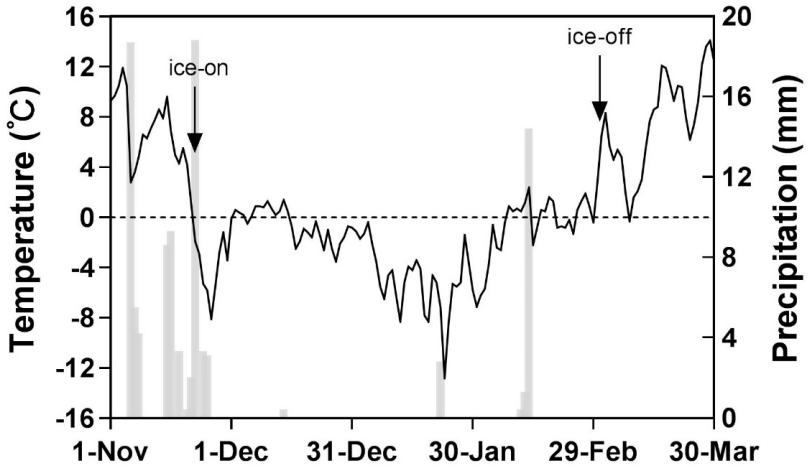

Figure A1. Dynamics of air temperature and precipitation from 1 November 2015 to 30 March 2016 at Hengshui Lake.

Table A2. The initial contents of C, N, and P of plant materials (mean ± standard deviation, n = 8).

	C (mg/g)	N (mg/g)	P (mg/g)
Typha orientalis	412.56 ± 7.93 ^{a}	13.77 ± 1.68 ^{a}	1.35 ± 0.09 ^{a}
Phragmites australis	395.31 ± 9.45 ^{b}	9.95 ± 1.05 ^{b}	0.49 ± 0.05 ^{b}

Different lowercase letters mean significant differences between species at 0.05 level.

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