The initial mass of residue can regulate the impact of *Phragmites australis* decomposition on water quality: a case study of a mesocosm experiment in a wetland of North China

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ABSTRACT

Plant residue decomposition can significantly affect the water environment of wetland ecosystems. However, little is known about the trajectory and the key drivers of the different initial mass of residue (IMR) that regulate water quality. Here, we conducted a study of 210 days with an *in situ* experiment to examine the impact of the change in IMR and the key decomposition parameters of *Phragmites australis* on the water quality in the growing season of 2019 in Baiyangdian wetland in North China. Five IMR of the Phragmites were applied, ranging from 0 to 1000 g with 250 g increments. The chemical oxygen demand (COD$_W$), total organic carbon (TOC$_W$), total nitrogen (TN$_W$) and total phosphorus (TP$_W$) of the water, and the total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), cellulose, lignin, decomposition rate ($k$) and the remaining mass of the Phragmites in the bag (RM) were monitored. Our results showed that the IMR of the Phragmites only marginally influenced the decomposition of itself and; the variations in the level of the water indicators were ranked as TN > TP > COD > TOC and; the impacts of IMR were longer on TOC and COD than on TP and TN and; the change in water quality was significantly influenced by the Phragmites decomposition and highly correlated with the change in TOC, cellulose and $k$ of decomposing Phragmites residue. These results indicated that the impact of 250 g of IMR on the water was negligible after 120 days, suggesting that the optimal harvest rate of the Phragmites should be above 75% in the Baiyangdian wetland, despite the strong impact at the beginning and; the impact of change in IMR on water quality can be explained by the change in the decomposition parameters of the plant residue.

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decomposing Phragmites residue, where such a decomposition-based explanation might be a promising tool to link wetland plant management and water quality.

**Abbreviations:** COD: chemical oxygen demand; TOC: total organic carbon; TN: total nitrogen; TP: total phosphorus; COD_W: chemical oxygen demand of the water; TOC_W: total organic carbon of the water; TN_W: total nitrogen of the water; TP_W: total phosphorus of the water

1. Introduction

The links between wetland plant management and water quality can be important when balancing the relationships between human wellbeing and the natural world at the local, regional and global scales (Johnston 1991; Hansson et al. 2005; Scholte et al. 2016). In addition, it has been reported that water quality can be closely relevant to wetland plant management measures that involve harvesting, selecting species and planting (Handa et al. 2014; Li et al. 2014; Xu et al. 2014). Moreover, water quality could be improved by wetland plants, such as *Phragmites australis* and some other submerged macrophytes during their growth. However, the water quality could be negatively influenced by the ‘after-life’ effects of the plants as in the case of wetland plants decomposition processes (Bonanomi et al. 2015; Gao et al. 2017; Pan et al. 2020). Previous studies have also indicated that despite the negative short-term effects in the early decomposition period, a small amount of residue could improve or could have no impact on water quality (Li et al. 2014; Pan et al. 2017). Although, harvesting has been proven to be an effective way to diminish the negative influences of wetland plants, but identifying both the optimum mass of the residue and the possible effects on water quality in the long-term need to be further confirmed (Xu et al. 2014; Wang et al. 2015; Kohzu et al. 2019). Developing a practical harvest plan at the management level also is far from being established.

A large volume of nutrients could be released from the residue to water via the residue decomposition process, resulting in the increase in the total organic carbon (TOC_W), the total nitrogen (TN_W), the total phosphate (TP_W) and the chemical oxygen demand (COD_W) of the water (Hai and Yakupitiyage 2005; Li et al. 2014; Wu et al. 2017; He et al. 2018). In general, the influence magnitude of the plant decomposition on the water can be directly proportional to the initial mass of residue (IMR), especially during the beginning of the decomposition (Hai and Yakupitiyage 2005; Pan et al. 2017). However, the influence magnitude of the plant decomposition can dramatically decrease over time as the key parameters of the decomposing plant residue, that is, decomposition rate (*k*) and contents of materials, can continuously change during the decomposition process, which varies within the major indicators of water quality (Li et al. 2014; Wu et al. 2017).

Although a few studies have attempted to relate the residue decomposition or submergence to water quality, how the decomposition parameters of residue relate to the water quality changes as well as the remaining mass of residue impact on the water quality during decomposition is still largely undetermined and lacks evidence of the residue IMR influence on its decomposition in the wetland environment (Liu et al. 2017; Xie et al. 2017). Furthermore, Phragmites can provide valuable ecosystem services including products for human use, habitat functions for other organisms and sequestration of carbon, nutrients and heavy metals. (Batty and Younger 2004; Kiviat 2013). The management of Phragmites often affects the livelihood of the people living around the wetland (Hazelton...
et al. 2014) as in the case of the harvest of Phragmites in the Baiyangdian wetland, where local residents have been making a living by managing Phragmites for over 1000 years. This not only is of great importance for the water security of the Xiong’an New Area of China (Zhao et al. 2012), but is also vital for the wellbeing of the local residents who rely on this wetland (Zhao et al. 2012; Jiang et al. 2017). Having a high annual biomass production as well as a high proportion of slow decomposable materials, such as cellulose and lignin, Phragmites residue can cause a strong and long-lasting impact on the water quality during its decomposition (Van Ryckegem et al. 2006; Hazelton et al. 2014; Dolinar et al. 2016). Hence, the relationships between IMR and the variations in the key parameters of the decomposing Phragmites residue should be investigated as well as their relationships with water quality.

As a consequence, we performed an in situ experiment in the field in Baiyangdian wetland to examine the changes in the Phragmites residue decomposition impact on water quality along the IMR gradients during a long period of time via monitoring decomposition-related parameters, including the decomposition rate, remaining mass of the Phragmites residue in bags (RM), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), lignin and cellulose of the Phragmites residue as well as the indicators of water quality (COD_W, TOC_W, TN_W and TP_W). Hence, we hypothesised that the impact of the Phragmites residue IMR on water quality could be explained by the changes in the parameters of the Phragmites residue, but the relative importance of each parameter relative to the indicators of water quality would change over time. Thus, this study provides a decomposition-based approach to link wetland plant management and water quality.

2. Material and methods

2.1. Study area

Baiyangdian wetland (38°43’N–39°02’N, 115°45’E–116°07’E) is the largest freshwater wetland in North China, where approximately 30% (110 of 366 km²) of the land is covered by the Phragmites (Figure 1) with an annual productivity of approximately 1 kg/m² dry mass. The region is classified as having a temperate continental monsoon climate with an annual average rainfall of 550 mm, an evaporation of approximately 1050 mm (Yuan et al. 2013), and an annual mean ambient temperature of 7°C (Wang et al. 2012; Yan and Zhenguo 2019). The height (height of Da Gu, similarly hereinafter) of the bottom of the Baiyangdian wetland is between 5.5 and 6.5 m, while the height of the Phragmites land is between 7.5 and 8.0 m (Wei et al. 2020). Moreover, the water level of the Baiyangdian wetland mainly depends on artificial regulation and has ranged between 7.8 and 8.9 m in the past three years (Xiao et al. 2017) since the establishment of the Xiong’an New Area, where the highest water level was recorded between January to March when the Phragmites residue began to rapidly decompose. This area is very similar to a semi-closed wetland, where only a little amount of water flows out of the wetland every year. Given that the nutrient input from the adjacent farmlands and the pollutants from the residential areas have been completely eliminated, while most of the Phragmites land (approximately 80%) in the Baiyangdian wetland has been flooded after 2017, it seems that the vast volume of the leftover Phragmites residue in the field became one of the major nutrient sources of the water body in the Baiyangdian wetland as large amounts of nutrients are released during Phragmites residue decomposition.
2.2. Raw material

The above ground part of the dead Phragmites was collected from the Baiyangdian wetland in February before the ice melted and classified in terms of leaf or stem, which were washed with ultrapure water to remove the surface impurities, then cut into approximately 10 cm-long sections. Next, the plant sections were oven-dried at 80°C for 72 h to a constant weight and were stored in a dryer until used. The first 20 cm of the sediment surface that was obtained from the same Phragmites land was evenly mixed and sieved to remove any gravel or plant root residue before utilization.

2.3. Experimental setup

The experiment was conducted between March and October in 2019, corresponding to the growing season of the Phragmites in the Baiyangdian wetland. A total of 20 cubes of 1 m$^3$ were randomly placed on the Phragmites land next to the Shao Zhuangzi village, which is surrounded by water in the middle of the Baiyangdian wetland (Figure 2). Next, a 0.5 m thick sediment was placed at the bottom of each cube within water of 0.2 m in depth. Water from a nearby pond was added to the cubes every three days to maintain the water height for a more realistic simulation. Different masses of 0, 250, 500, 750 and 1000 g of the Phragmites residue were added into the cubes to reflect the control (C), treatment 1 (T1), treatment 2 (T2), treatment 3 (T3) and treatment 4 (T4) groups, where each group included four replicates, respectively.

Furthermore, a total of 2.5 and 10.0 g of leaf and stem sections, respectively, were evenly mixed according to the average mass ratio of the leaves to the stem of the dead Phragmites that were collected from Baiyangdian and placed into 1 mm mesh nylon bags (15 × 20 cm). Seven bags containing the Phragmites residue were placed in the cubes that contained the residue, while 28 empty bags were evenly placed in the control group. The
bags of each group were randomly collected on days 0, 5, 15, 30, 60, 120 and 210 after being placed. The materials recovered from the bags were carefully brushed with ultrapure water to remove any attached soil particles and oven-dried at 85°C to measure the dry mass. The water samples were collected from each cube using 500 mL glass bottles in days 0, 5, 15, 30, 60, 90, 120, 150 and 210, in which all the bottles were rinsed three times prior to collection using the sampling water and sent immediately to the laboratory kept at 4°C.

2.4. Nutrient analysis

After filtering the water samples through a Whatman GF/C filter (Sigma-Aldrich, USA) (0.45 µm), they were measured spectrophotometrically for their COD, TOC, TN and TP levels using the Hach DR3900 (Hach Company, USA). The oven-dried residue samples were ground and then sieved through a 0.5 mm mesh to be analysed for their TOC, TN, TP, lignin and cellulose concentrations. TOC was analysed using the H2SO4–K2Cr2O7 heat method, while TN and TP were quantified using the Kjeldahl digestion method followed by a colorimetric analysis. The cellulose and lignin contents were determined by hydrolysis using 10% and 72% H2SO4, respectively, followed by a Na2S2O3 titration (Xie et al. 2017).
### 2.5. Data analysis

The decomposition rate, \( k \), was derived from a single negative exponential model,

\[
-k = \frac{\ln(X/X_0)}{t}
\]

where \( X_0 \) is the initial dry weight and \( X \) is the dry weight at time \( t \) in days (SOJ. Energy storage and the balance of producers and decomposers in ecological systems, 1963).

The Pearson correlation coefficients (two-tailed test) were calculated for the Phragmites residue decomposition parameters and the indicators of water quality, where the difference in water indicator variations among the treatment and control groups were tested by a one-way analysis of variance (ANOVA). Within each decomposition parameter of the Phragmites residue and water indicator value at each sampling time, a two-way ANOVA was used to test the effect treatment, time and their interaction as contributing factors. All the statistical analyses were performed using the SPSS v25 software (SPSS Statistics, IBM, USA), while the redundancy analysis (RDA) was performed using CANOCO v5.0 (Microcomputer Power, USA). The decomposition parameters of the Phragmites residue were set as variables to explain the variation in the water quality.

### 3. Results

#### 3.1. The decomposition of the Phragmites residue

The variations in all the Phragmites residue decomposition parameters were evident over time. However, the Phragmites IMR only resulted in marginally significant changes in the variations of TOC (\( F = 4.870, p = .004 \)), TN (\( F = 8.193, p < .001 \)), lignin (\( F = 4.229, p = .008 \)), RM (\( F = 3.065, p = .032 \)) and the decomposition rate (\( k \)) (\( F = 2.732, p = .049 \)) over time (Table 1). No interaction between time and treatment was observed in TP (\( F = 0.941, p = .438 \)) and RM (\( F = 0.032, p = .113 \)) of the Phragmites residue (Table 1), while the TOC, TN, TP, lignin and cellulose of the Phragmites residue displayed fluctuations. TP and lignin showed an overall increasing trend (Figure 3(c, d)), while cellulose showed an initial increase, followed by a decrease (Figure 3(e)). TOC displayed a drastic decrease in the first 30 days with a subsequent increase that was relatively stable after day 60 (Figure 3(a)), while TN levels fluctuated (Figure 3(b)). RM had a constant decrease during the experiment with a dramatic change before day 5, followed by a relatively gradual decrease after day 60 (Figure 3(f)). Finally, \( k \) showed pronounced and temporal dynamic changes with a drastic decrease in the first 30 days, followed by a gradual decreasing trend until the end of the experiment at day 210 (Figure 3(g)).
3.2. The change in water quality in terms of the IMR gradients

Significant differences were observed among the treatment and control groups after applying the different IMR (Table 2). Higher levels of COD_W, TOC_W, TN_W and TP_W were obtained as well as a greater variation in the water quality, which was evident when using higher levels of IMR during the initial stage of the experiment (Figure 4). The variations in the water indicators can be ranked as TN_W > TP_W > COD_W > TOC_W from day 5 (Figure 5), where the maximum fold increases of TN_W, TP_W, COD_W and TOC_W reached 16.8, 9.4, 6.8 and 5.8 folds, respectively, relative to the control group (Figure 4(a)). The differences among the treatment and control groups became smaller with time, illustrating an interaction between treatment and time relative to the water quality (Figure 4, Table 2). In contrast with TN_W and TP_W, where no significant differences were observed after day 120 (Figure 4(e)), the impacts of IMR on TOC_W and COD_W were still evident at the end of the experiment at day 210 (Figure 4(f)).

Furthermore, all the indicators of water quality changed significantly over time according to the one-way ANOVA (Table 2), in which the effect of the Phragmites residue on COD_W decreased over time until it reached a plateau after day 120 (Figure 5(a)). In addition, the TOC_W displayed an increasing trend before day 90, except for the treatment with the highest level of RM level, which showed a rapid increase before day 5 followed by a constant decreasing trend until the end of the experiment at day 210 (Figure 5(b)). The TN_W across all the treatments displayed the same fluctuations between days 5 and 90, with decreases then increases until reaching a peak at day 90, which gradually decreased. The slight variations in TN_W persisted after day 150, resulting in no significant difference across all treatments at day 210 (Figure 5(c)). Hence, the effect of RM level on TP_W showed a constant decrease over time after the first 5 days with no significant change after day 90 (Figure 5(d)).

Table 2. Results of two-way analysis of variance (F-ratios) analysing the impact of treatment, time and their interaction on the chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN) and total phosphate (TP) of water.

| Parameter | COD      | TOC      | TN        | TP        |
|-----------|----------|----------|-----------|-----------|
| Treatment | **207.138** | **217.213** | **41.968** | **57.801** |
| Time      | **89.631**  | **74.727**  | **40.263** | **103.995** |
| Treatment x Time | **11.439** | **11.614** | **6.995**  | **13.4**  | **p < .01.**
3.3. The relationship between water quality and the Phragmites residue decomposition

The changes in water quality were significantly influenced by Phragmites residue decomposition and highly correlated with the change in TOC, cellulose and k of the...
decomposing Phragmites residue (Figure 5(a)). During the first 30 days, a relatively strong correlation was found between \( k \) and water quality, but rapidly became weaker compared to the other parameters of the decomposing Phragmites residue after day 60 (Figure 5(b)). Eventually, the TOC, TP, lignin and cellulose of the decomposing Phragmites residue became the main factors that regulated the water quality (Figure 5(b)).

During the period between day 60 and 120, the change in water indicators largely depended on the variations in cellulose of the decomposing Phragmites residue, which were subsequently more influenced by variations in residue lignin towards the end of the experiment at day 210 (Figure 5(b)). Furthermore, the correlations between the residue TOC and COD\(_W\), TOC\(_W\), TN\(_W\) and TP\(_W\) were significantly negative, respectively, but significantly positive between cellulose, \( k \) of residue and the water indicators, respectively (Table 3). In addition, the change in residue lignin was negatively correlated with COD\(_W\), TP\(_W\) and TOC\(_W\), respectively. Moreover, residue TN and TP were negatively correlated with COD\(_W\) and TP\(_W\), respectively, while a significant correlation was identified between residue RM and TP\(_W\).

### 4. Discussion

The impact of plant residue on the water quality during the residue decomposition is a dynamic and complicated process, which is not only closely related to the IMR, but is still regulated by the changes in the residue decomposition parameters as well (Bonanomi et al. 2015). Previous studies, most of which were short-term indoor experiments, have mostly attempted to link plant residue with water quality by comparing the initial residue composition, nutrient releases and the decomposition rates in the water, demonstrating that the water quality changes largely depended on the initial biochemical quality of the plant residue (Bonanomi et al. 2015; Wu et al. 2017; Xiao et al. 2017; Pan et al. 2020). Our long-term dynamic analyses included repeated measurements of the decomposing Phragmites residue parameters, which indicated that the impact of the Phragmites IMR on water quality decreased over time. In addition, the relative importance of the parameters that regulated the decomposition impact on the indicators of water quality were different at different stages of the decomposition. Additionally, the IMR only marginally influenced the decomposition of the residue itself.

### 4.1. Phragmites residue decomposition under different IMR environments

According to our results, the variations in the decomposition parameters of the Phragmites residue were evident over time, while the treatment influence on the residue

|        | TOC   | TN    | TP    | Cel   | Lig   | RM    | \( k \) | COD\(_W\) | TN\(_W\) | TP\(_W\) | TOC\(_W\) |
|--------|-------|-------|-------|-------|-------|-------|--------|-----------|-----------|-----------|-----------|
| COD\(_W\) | 0.536** | 0.204* | 0.059 | 0.310** | \(-0.188^*\) | \(-0.001\) | 0.565** | 1         |
| TN\(_W\)  | 0.313** | 0.011 | 0.102 | 0.253** | \(-0.185\) | 0.003 | 0.755** | 0.796** | 1         |
| TP\(_W\)  | 0.459** | 0.002 | 0.283** | 0.190* | \(-0.327**\) | 0.283** | 0.829** | 0.743** | 0.843** | 1         |
| TOC\(_W\) | 0.463** | 0.096 | 0.088 | 0.297** | \(-0.220^*\) | \(-0.031\) | 0.471** | 0.909** | 0.773** | 0.687** | 1         |

TOC, TN, TP, Cel, Lig, RM, and \( k \) represent total organic carbon content, total nitrogen content, total phosphorus content, cellulose content, lignin content, remaining mass in bag, and decomposition rate of Phragmites residue, respectively, while COD\(_W\), TN\(_W\), TP\(_W\), and TOC\(_W\) represent the chemical oxygen demand, total nitrogen content, total phosphorus content, and total organic carbon content of water, respectively.

\(*p < .05; **p < .01.\)
decomposition was relatively weak though such influence seemed obvious during the later stages of the decomposition (Table 1, Figure 1). These results were consistent with previous studies, where the high carbon ratio and the high proportion of slow decomposable carbon, such as cellulose and lignin, were considered as important factors that often negatively affect the microbial activity and cause the decomposition of the Phragmites residue, especially the stem, to be less susceptible to the changes in the environment compared to the plants containing more degradable materials (Van Ryckegem et al. 2006; Rejmáneková and Sirová 2007; Tylová et al. 2008; Ferreira et al. 2015a, 2015b). The increase in the residue TP and TN after the rapid leaching stage could be an evidence of the impact of high carbon ratio on microbial activities. Microbes on plant residue often immobilise the nitrogen and phosphorus from the environment to meet their demand when the residue carbon content is too high (Zhao et al. 2017; Fortino et al. 2020). Although a few studies suggested that the plant residue could create an environment that retarded or accelerated residue decomposition through its negative or positive effects on the microbial activity, this tends to occur in plant residues that are easily decomposable (Xie et al. 2017; Santonja et al. 2019).

4.2. The impact of Phragmites IMR on the water quality during the decomposition

In this study, the impact of IMR on water quality changed significantly over time (Table 2), where the change seemed especially clear during the initial stages of the residue submergence and remained relatively constant during the later stages of the residue decomposition (Figures 4 and 5). The drastic changes in the respective impacts of IMR on TOC_W, COD_W, TN_W and TP_W in the first 30 days could be largely attributed to the rapid changing decomposition rate of the Phragmites residue during this period, which mainly depended on the leaching phase of the decomposition (Li et al. 2014; Wu et al. 2017), which was a rapid abiotic process, where a large amount of the water-soluble materials in the residue was lost in a short amount of time (Del Giudice and Lindo 2017). Hence, this caused the substantial release of different elements, such as carbon, nitrogen and phosphorus to the environment, especially during the first few weeks (Davis et al. 2006; Del Giudice and Lindo 2017; Liu et al. 2017). TOC_W, TN_W, TP_W and COD_W were often more correlated with IMR of the Phragmites during the beginning of the decomposition, which was consistent with previous studies (Hai and Yakupitiyage 2005; Li et al. 2014; He et al. 2018), as this physical process was mainly regulated by abiotic factors and the initial residue traits (Bradford et al. 2016; He et al. 2018). Moreover, the decomposition rate rapidly decreased as most of the leachable materials were exhausted in a short span of time, thus decreasing the impact of IMR on the water quality (Rejmánková and Houdková 2006).

After the rapid leaching stage, the residue impacts through time on the water quality were mainly influenced by variations in the composition of the Phragmites residue, especially the TOC concentration (Figure 6, Table 3). It is generally assumed that the increase in carbon content and recalcitrant materials, such as cellulose and lignin, could slow down the decomposition process, thus reducing the nutrients released from the residue to the environment (Bonanomi et al. 2015; Bradford et al. 2016; Pan et al. 2020). In some studies, phosphorus-related indicators of the residue were also purported as important regulators of residue decomposition (Li et al. 2013), though it was proved to be only significantly related to the TP of water in our study (Table 3). The correlation between TN of the residue and the water quality was not evident during the later stage (Figure 6), which might be due to the slight influence of the residue TN on the decomposition.
according to previous studies (Chimney and Pietro 2006; Li et al. 2013). We also found that both the TP and TN in the water reached a stable state towards the end of the experiment with no significant differences between the treatment and the control groups (Figure 4(f)), while the TOC of the decomposing Phragmites residue had a longer lasting impact on water quality, which generally acted as the main contributor to the COD of water (Figure 3). This could be caused by a relatively small fraction of phosphate and nitrogen in the Phragmites residue compared to the carbon content (Van Ryckegem et al. 2006), in which the recalcitrant materials increased at a later stage (Van Ryckegem et al. 2006; Liu et al. 2017).

4.3. Implications for wetland plants management

This study effectively explained how the change in the wetland plant IMR impacted water quality, which is important for wetland plant management and wetland ecosystems preservation. Our results showed that the treatment group with a relatively low IMR (250 g/m²), corresponding to a 75% harvest rate of the Phragmites in the Baiyangdian wetland, could yield a similar water quality as the control group without the Phragmites residue after 120 days of submergence, which is much longer than the residue of some submerged labile macrophytes (Bonanomi et al. 2015; Pan et al. 2017). This indicated that we could, to some extent, predict that the water quality change by the newly generated the Phragmites residue could hardly be fuelled by the leftover residue from the year before when the mass of residue were kept under 250 g/m² and the optimal harvest rate of Phragmites was above 75% in the Baiyangdian wetland. Moreover, we also showed that the optimal harvest rates of the wetland plants could be predicted based on the decomposition characteristics of the wetland plant residue, in which our results support studies that link wetland plant management with water quality (Hai and Yakupitiyage 2005; Pan et al. 2017; He et al. 2018).
5. Conclusions

In summary, this study exposes an evidence that we can explain the changes in the IMR impact of the Phragmites residue on the water TOC, TN, TP and COD by the variation in the parameters of the decomposing Phragmites residue over time. To accurately evaluate the influence intensity of the Phragmites residue decomposition on the water quality, not only should the initial composition of the plant residue be taken into account, but the variations within the decomposition parameters as well. In addition, it is best that the optimal harvest rate of Phragmites in the Baiyangdian wetland is above 75%, in which more focus is given to the carbon composition of the Phragmites and its impact on water quality. Hence, our dataset and data analysis framework can be applied in future studies to develop more accurate explanations and evaluations of the influences induced by plant residue on the wetland water quality and nutrient cycle, which is crucial for the comprehensive management of the wetland ecosystem. However, the influential changes caused by wetland plants on the water quality in response to environmental and structural changes in the plant community as well as their underlying mechanisms are still largely undetermined, which calls for further field and growth-controlled studies.

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Disclosure statement

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