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Iron addition as a measure to restore water quality: Implications for macrophyte growth

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ABSTRACT

Eutrophication of shallow lakes in North-West Europe has resulted in cyanobacterial blooms, turbid water, and a decline in submerged macrophytes. Even though external inputs of phosphorus (P) are declining, internal loading of P from the sediment may delay the recovery of these aquatic ecosystems. Iron can be a useful chemical binding agent to combat internal P loading in shallow lakes, but may potentially be harmful for macrophyte growth. We tested whether iron addition as a restoration measure harms the growth of submerged macrophytes. We hypothesized that this depends on the iron dosage and the rooting strategy of the macrophytes. We experimentally tested the effects of Fe ($FeCl_3$) on the submerged macrophytes *Potamogeton pectinatus* L. and *Elodea nuttallii* (Planch.) H. St. John. Iron was dosed at a concentration of 20 g Fe m^{-2} and 40 g Fe m^{-2} to the surface water or to both the surface water and sediment. *E. nuttallii* growth was not affected by iron addition, whereas *P. pectinatus* growth significantly decreased with increasing iron concentrations. Nonetheless, biomass of both species increased in all treatments relative to starting conditions. During the experiment, propagules sprouted from a propagule bank in the sediment including species with a high conservation value and this spontaneous emergence was not influenced by increasing iron concentrations. We conclude that adding iron(III)chloride in dosages of 20–40 g m^{-2} may reduce growth of some macrophyte species, but does not prevent overall macrophyte recovery. It may however affect macrophyte community composition due to differential responses of macrophyte species to iron addition.

1. Introduction

High nutrient loading from agricultural runoff and wastewater discharge during the second half of the 20th century has led to eutrophication of many shallow lakes in north-western Europe. The excess input of phosphorus (P) and nitrogen (N) has resulted in (toxic) cyanobacterial blooms and subsequently turbid water, biodiversity loss, and a decline in submerged macrophytes (Tilman et al., 2001; Hilt et al., 2006; Hickey and Gibbs, 2009). Submerged macrophytes play a key role in the functioning of shallow water bodies by acting as a nutrient sink, providing a habitat for fauna and preventing resuspension of lake sediment. Through these actions macrophytes stabilize the clear water state of shallow lake ecosystems (Scheffer et al., 1993; Jeppesen et al., 1998; Bakker et al., 2010). After eutrophication, a strong reduction in P loading of a lake is required to restore a lake to this self-stabilizing clear water state (Cooke et al., 1993; Jaeger, 1994). However, internal loading of P from the sediment, particularly from nutrient rich organic lake sediment (Lamers et al., 2002), may significantly delay the recovery of aquatic ecosystems, even after the external loading has been reduced (Cooke et al., 1993; Jeppesen et al., 1998; Søndergaard et al., 2003, 2013).

Before the intensification of agriculture, many peaty lakes would not suffer from high internal P loading, as iron in upwelling groundwater naturally binds to phosphorus (in the form of phosphates, PO_4; Lamers et al., 2002). However, the upwelling of this iron-rich groundwater has declined due to changes in hydrological regimes and desiccation through extraction of groundwater for agricultural purposes, which consequently has led to a reduction in the amount of iron reaching the top layer of the sediment (Van der Welle

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et al., 2007b). Hence, one way to cope with internal P loading is by improving the P binding capacity of the lake sediment by adding iron (Fe) or other chemical P binding agents such as aluminium (Al), calcium (Ca), or lanthanum-enriched benthonite clay (Phoslock®) to the sediment (Cooke et al., 1993; Burley et al., 2001; Smolders et al., 2006; Hickey and Gibbs, 2009; Van Oosterhout and Lürling, 2011). These chemical binding agents, if added on a regular basis, will not only precipitate with the available PO_4 in the sediment, but can potentially provide long-term control of internal P loading from the sediment (Boers et al., 1992, 1994; Cooke et al., 1993; Smolders et al., 2006; Kleeberg et al., 2013).

Various mesocosm and field experiments have shown that the addition of Fe to the sediment indeed results in lower total phosphorus (TP) concentration in the water column, which is why iron is often used to decrease P concentrations of lake inlet water before the water enters the lake (Klapwijk et al., 1982; Boers et al., 1992; Van Donk et al., 1994; Smolders et al., 1995; Kleeberg et al., 2013). High Fe concentrations in the sediment, however, can have deleterious effects on macrophytes (Kamal et al., 2004). Recent experiments have shown that growth of plants can be directly inhibited by high iron concentrations in the sediment for instance by the formation of necrotic leaf spots and iron plaques on roots (Lucassen et al., 2000; Van der Welle et al., 2007a). Evidently, iron can also have indirect effects on macrophytes by lowering the phosphorus concentration in the sediment, thereby decreasing the available nutrients for growth and by lowering the pH of the water (Boers et al., 1994). Moreover, the addition of iron to the sediment may be possible in mesocosms, but is a real challenge for a whole lake. Alternatively, iron could be added to the surface water. However, the effects of adding iron to the surface water on submerged macrophytes are not yet known, whereas they are directly exposed to the added iron when this is added in the surface water in contrast to addition in the sediment. The place of addition may affect macrophyte species differently, as macrophytes differ in rooting strategies (Jeppesen et al., 1998). Macrophytes depending for their growth on nutrients from the water column might be more affected by iron in the water column than rooting macrophytes, which generally take up nutrients from the sediment. Over time, rooting species may become affected as well, when the iron added in the water column precipitates and mixes with the sediment through macrofaunal activity or wind-driven sediment movement (Søndergaard et al., 2003).

The objective of this study was to test whether iron addition as a restoration measure affects the growth of submerged macrophytes. We hypothesized that this depends on the iron dosage, the application mode (surface water or sediment plus water) and the rooting strategy of the macrophytes (uptake of nutrients from sediment or water column). We experimentally tested potential negative effects of iron (Fe) on the growth of two submerged macrophytes, the facultative rooting species *Elodea nuttallii* (Planch.) H. St. John and the rooting species *Potamogeton pectinatus* L. as well as on the sprouting of propagules present in the sediment propagule bank. Furthermore, to simulate a condition in which wind driven sediment resuspension and subsequent sedimentation would lead to an accumulation of iron in the sediment, we added a treatment in which we, prior to the start of the experiment, mixed half of the total dosage of iron in the sediment. To study the effect of iron addition we focused on changes in macrophyte growth and appearance, biomass allocation, nutrient composition and sprouting of propagules from the sediment. The experiment is based upon planned restoration measures in peat lake Terra Nova, The Netherlands (Van de Haterd and Ter Heerdt, 2007), where water managers are proposing to add iron to the surface water.

2. Materials and methods

2.1. Study species and study site

The study species *E. nuttallii* and *Potamogeton* species are often observed to be the first dominant species after lake restoration measures have been taken (Van Donk et al., 1994; Van Donk and Otte, 1996; Perrow et al., 1997; Irfanullah and Moss, 2004; Hilt et al., 2006). This was also the case in lake Terra Nova, where *E. nuttallii* became dominant and multiple *Potamogeton* species occurred (including *P. pectinatus*) after sediment disturbing fish were removed through biomanipulation in a restoration attempt in the past (Van de Haterd and Ter Heerdt, 2007; Bakker et al., 2013). Therefore, these are the first species that are expected to return when iron supplementation is a successful restoration measure and thus the first to be exposed to potential negative effects of iron addition. Lake Terra Nova (52°12′55.87″ N, 5°2′23.00″ E) is an 85 ha shallow peat lake with a mean depth of 1.4 m. The bottom is covered with a 0.9 m organic sediment layer, with an organic matter concentration of 62.8% and a moisture content of 95.2%. According to Brouwer and Smolders (2006), the internal loading of P from the sediment is estimated at 0.10 $g\,m^{-2}\,year^{-1}$. The restoration measure of iron supplementation was proposed to bind this extra influx of P into the lake surface water.

2.2. Experimental set-up

In February 2010, 90 polyethylene tanks ($w \times l \times h = 0.19 \times 0.19 \times 0.29$ m) were set up at the NIOO-KNAW in Nieuwersluis. The tanks were placed in a temperature and light controlled culture room with a constant temperature of 18 °C and a light intensity of 100 ± 5 μmol photons $m^{-2}\,s^{-1}$ at the water surface in the tanks and a 14:10 h light:dark cycle. Each tank contained 2 L peat sediment, collected from Lake Terra Nova. Before tanks were filled combinations of three different variables, (i) levels of iron addition (0, 20 g Fe m^{-2}, 40 g Fe m^{-2}), (ii) mode of iron application (in the water or in the sediment plus water) and (iii) two different macrophyte species plus control (*E. nuttallii*, *P. pectinatus*, no macrophyte), were randomly allocated to the tanks in a full factorial design, each with 5 replicates.

The total iron concentration that is planned to be dosed in lake Terra Nova is 100 g Fe m^{-2} over a period of 1.5 years. This dosage was also used in various experimental and field studies (Boers et al., 1994; Burley et al., 2001). To mimic the effects of (gradual) iron addition in Terra Nova, we recalculated this dose according to the volume of our experimental units (containing only 7.3 L water) and the short duration of our iron addition, which resulted in a total addition of 100 mg Fe per tank and this corresponds to an iron treatment of 20 g Fe m^{-2} in Terra Nova. A high iron addition was calculated which would receive a total addition of 200 mg Fe, which corresponds to an iron treatment of 40 g Fe m^{-2} in Terra Nova. The iron added to both treatments was in the form of $FeCl_3$. Two control treatments were designed; a zero Fe addition treatment and a treatment without macrophytes, as a control for the effects of macrophytes on pore and surface water composition. The no iron control treatment received NaCl in equal molar amounts of chloride as in the high iron treatments. The goal of the experiment was to test whether iron addition would affect macrophyte growth. We hypothesized that a no iron control treatment without a dose of iron would show differences in growth compared to macrophytes with iron dosing, as iron naturally binds to phosphate in the water, resulting in different growth rates due to differences in phosphate availability. Therefore we added once a low dose of 0.73 mg $FeCl_3$ on day 1 to the surface water of the no iron control treatments to bind the available 0.1 μmol L^{-1} P in the water column and sediment in order to equalize these differences.