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Vegetation growth and sediment dynamics in a created freshwater wetland

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ABSTRACT

Understanding how the hydrological regime in relation to sediment type interferes with ecosystem development is important when wetlands are created with soft muddy material. Especially when plants are used as ecological engineers to promote crest stability and soil formation. We carried out a two-year mesocosm experiment with sediments derived from the Dutch lake Markermeer to identify the effects of the hydrological regime and sediment type on ecosystem functioning in terms of nutrient availability. We measured plant productivity, plant nutrient stoichiometry, and concentrations of N, P, and K in shoots and roots of *Phragmites australis* and *Rumex maritimus* and monitored how the clay-rich sediment from lake Markermeer changed into a wetland soil. Plants grown on Markermeer sediments tend to be N limited when periodically inundated and P limited when not inundated at all. The P availability was determined by the hydrological regime, while the N availability was determined by both the hydrological regime and the sediment type. Ecosystem development on created wetlands can be manipulated by adequate management of the hydrological regime, as plant species respond differently to changes in nutrient availability. This should be considered in eco-engineering projects where plants are used as ecological engineers to fasten ecosystem development on wetlands that are to be created from clay-rich material.

1. Introduction

Wetlands are among the most valuable biomes on our planet providing important ecosystem services such as nutrient cycling, soil formation and wastewater treatment (Costanza et al., 1997; Zedler and Kercher, 2005). In the past 100 years, vast areas of wetlands have disappeared, but programs have been initiated to restore and create wetlands to compensate for this loss (e.g. Mitsch et al., 1998; Verhoeven, 2014). Although most created wetlands have been designed for wastewater treatment (Vymazal, 2011), they can also be designed to increase the ecological value of the ecosystem itself (e.g. Weller et al., 2007; Whigham et al., 2007; Stefanik and Mitsch, 2012). When designing such ecosystems, natural processes are oftentimes used to promote self-design, fasten ecosystem development and to replace conventional engineering structures (Mitsch, 1998). This concept is called ecological engineering and is implemented globally nowadays (Temmerman et al., 2013). However, to make ecological engineering projects successful, it is essential to understand how ecological, geomechanical and hydrological processes interact before making any decision on the design of such a project.

An important factor when creating wetlands is the hydrological regime as it determines the plant community and the speed of ecosystem development (Ernst, 1990; Seabloom et al., 1998; Bernhardt and Koch, 2002; Casanova and Brock, 2002). Periodical inundation often speeds up ecosystem development although the effectivity is unclear. For example, Peterson and Baldwin (2004) showed that flooding significantly decreased plant biodiversity in a freshwater wetland, but Brock et al. (1999) argued that when flooding regimes are managed correctly in terms of depth and duration of the flood, the number of habitat types increases, in turn positively affecting species richness. How wetland ecosystems respond to changes in the hydrological regime also depends on the geochemical composition, as it determines the biogeochemical processes that are induced when the water saturation gets altered (Speelman et al., 2007). For example, oxidation of pyrite can lead to severe acidification of soils, negatively impacting the environment by potential heavy metal release (Golez and Kyuma, 1997). On the other hand, if the sediment contains high amounts of iron-bound phosphorus, alternating water regimes can affect ecosystem development by inducing P mobilization (Satawathanont et al., 1991; Portnoy, 1999; Lamers et al., 2012).

Understanding how the hydrological regime influences ecosystem development in relation to sediment type is important when the concept of ecological engineering is used. Oftentimes, fast initial plant growth is a prerequisite for vegetation to act as ecological engineers,

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especially when wetlands are created with soft muddy material. Wetland creation in lake Markermeer, a lake in the Netherlands located northeast of Amsterdam, is an example. In this lake, a part of the soft clay-rich lake-bed sediment is currently being dredged and used as a building material in creating approximately 10,000 ha of wetland.

Two distinct layers from the lake bed can be used as substrate for the wetlands: the relatively undisturbed consolidated near-shore Holocene marine deposits and the disturbed soft mud layer on top of these deposits. Saaltink et al. (2016, 2017a) showed that these layers have a very distinct geochemical composition, also in terms of pyrite, iron-bound phosphorus and nutrients. The soft clay-rich layer is produced by bioturbation and physical weathering of the near-shore marine deposits and continuously resuspends because of wave action (Van Kessel et al., 2008; De Lucas Pardo et al., 2013).

To improve crest stability and promote soil formation on these artificial wetlands, it is important to understand how the hydrological regime could interfere with ecosystem development and what type of sediment functions best as building substrate. Because conducting small scale experiments can be an effective method to anticipate ecological engineering designs that might follow if implemented on a larger scale (Odum and Odum, 2003), we carried out a mesocosm experiment to identify the effects of the hydrological regime – i.e. periodical inundation vs no inundation – and the sediment type on ecosystem functioning in terms of nutrient availability. To reach this aim, we measure plant productivity, plant nutrient stoichiometry, and concentrations of N, P, and K in shoots and roots of *Phragmites australis* and *Rumex maritimus*. Subsequently, we monitor how the clay-rich sediment from lake Markermeer is changing into a wetland soil by regularly measuring geochemical variables of the sediment. We hypothesize that the hydrological regime especially influences the P availability as Markermeer sediments are rich in pyrite and Fe-P (Saaltink et al., 2016), and alternating water regimes may result in P mobilization as reduction of sulfate decouples iron from phosphorus. We, therefore, expect that in sediments that are periodically inundated more P is available for plants than in sediments that receive no inundation. Since N is available in reduced (i.e. NH_4) as well as oxidized (i.e. NO_x) conditions, N availability is expected to be determined by the sediment type. This study will enhance knowledge on how the interplay between the hydrological regime and the sediment type influences ecosystem functioning by determining nutrient availability. Consequently, applications for management practices in ecological engineering projects can be extracted.

2. Materials and methods

2.1. Experimental mesocosms

A greenhouse experiment was conducted for 2 growing seasons at the greenhouse test facility of Utrecht University in the period April 2015–November 2016. Mesocosms (diameter 30 cm, height 80 cm) were filled up to 50 cm with one sediment type from lake Markermeer. The sediment types were collected in March 2015 by mechanical dredging at a location (coordinates 52.5462N; 5.3878E) within the dredging area assigned for the collection of building material for the wetlands (Flach, 2014). The sediment types used are composed of the sediment from the soft, clay-rich layer (0–10 cm depth) and the underlying, consolidated, near-shore marine deposit of Holocene origin (10–50 cm depth); these sediments are hereafter referred to as mud and clay, respectively. Sediments were stored in air-tight containers at 4 °C prior to the start of the experiment.

Two species were selected to be transplanted in the mesocosms: 1. *Rumex maritimus* (golden dock) – an annual or biennial, dicotyledonous plant species – was chosen because this plant was frequently found on the pilot wetland in lake Markermeer during monitoring studies (Dankers et al., 2015), and 2. *Phragmites australis* (common reed) – a perennial, monocotyledonous plant species – was selected because it is foreseen that this plant is used as eco-engineering species on the wetlands. Plants were grown from seeds for c. 40 days on nutrient-poor turf soil before transplantation into the mesocosms. Each mesocosm started with three seedlings of *R. maritimus* and three seedlings of *P. australis* (i.e. six seedlings in total). Tinfoil was attached to the inner walls of the mesocosms to improve the light conditions for the seedlings.

Mesocosms were either periodically inundated or received weekly irrigation water. Following Güsewell et al. (2003) and Banach et al. (2009), the periodically inundated mesocosms were flooded for 7 weeks to a height of 10 cm above the sediment, after which the water was removed and the sediment could dry for two weeks. Drying is important for consolidating the soft building material so alternating dry and wet periods should be preferred over long-term inundation. The mesocosms that were not inundated received 17.3 mm water every week, which corresponds to a total water supply of 900 mm yr^{-1}. However, to prevent water stress in the plants grown in the non-inundated mesocosms an extra dose of water was added when temperatures in the greenhouse increased to 30 °C or more (some weeks in July and August). For both hydrological conditions Markermeer water was used, thereby avoiding any impact on sediment geochemistry and plant function caused by chemical differences. Because lake Markermeer is nutrient limited with low values of nitrate, ammonium and phosphate (Noordhuis et al., 2014), nutrient concentrations in the water added to the mesocosms were low, averaged at 0.1 mg NO_3^- L^{-1}, 0.01 mg NH_4^+ L^{-1}, and < 0.003 mg PO_4^{3-} L^{-1} (Ministry of Infrastructure and the Environment, 2016).

Six mesocosms were used for each sediment – hydrology combination (24 in total). Seedlings from other plants that spontaneously emerged in the mesocosms were removed immediately.

2.2. Data collection

Aboveground biomass was clipped after each growing season (i.e. November 2015 and November 2016). At the end of the experiment, belowground biomass was measured for three mesocosms per condition (12 in total) by thoroughly washing and sieving the sediment. Plant material was separated per plant species, air-dried for 48 h at 70 °C, weighed, clipped and mixed prior to chemical analysis. Tissue was randomly selected and ground to determine contents of K and P using total reflection X-ray fluorescence (S2 Picofox, Bruker) and N using a CN analyzer (NA1500, Fisons Instruments). Total uptake was calculated by multiplying biomass with tissue concentration.

The sediment samples were collected at the start of the experiment and were freeze-dried prior to geochemical analysis. Elemental contents of Al, Ca, Fe, K, Mg, Mn, Na, P, Sr, Ti, and Zn were determined using ICP-OES following aqua regia destruction. Sulfur contents were measured on an elemental CS analyzer (CS-300, LECO) and the N contents were determined on a CN analyzer (NA1500, Fisons Instruments). Quantitative bulk mineralogical compositions of the crystalline fraction of the sediments were determined by Rietveld refinement from the X-ray diffraction patterns (Scarlett and Madsen, 2006). Organic matter was determined by slowly heating to 550 °C and then calculating the weight loss between 105 and 550 °C (Howard, 1965). A sequential extraction method based on Ruttenberg (1992) was applied to characterize solid P speciation and to determine the content of iron oxides (Table 1). The extractable content of iron oxides was measured from the citrate-dithionite-bicarbonate (CDB) filtrate from the second step using ICP-OES. All geochemical analyses were carried out for 5 replicates per sediment type, except for the XRD analysis (1 replicate per sediment type).

In addition, sediment samples from the topsoil (0–2 cm) were collected in each mesocosm at t = 6, 11, and 18 months as in the topsoil highest geochemical effects caused by the vegetation are expected (Saaltink et al., 2016). These samples were freeze-dried and analyzed immediately in terms of solid P speciation, extractable iron oxides, N and organic matter contents.