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Decomposition of aquatic pioneer vegetation in newly constructed wetlands

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ABSTRACT

Artificial wetlands are constructed around the globe for a variety of services, including wastewater treatment and carbon storage. To become a carbon sink, a newly constructed wetland must have a fully developed vegetation, consisting of species that can produce more organic matter than is being lost through decomposition. However, the effects of environmental conditions on the overall balance between production and decomposition might be complex. In this study, two large-scale field litterbag experiments were performed in a three-year old constructed wetland in the Netherlands, to separate the effects of litter characteristics and environmental conditions on decomposition rates of aquatic pioneer vegetation. Dimension reduction by principal component analysis was used to limit the number of variables for subsequent analyses in linear models. When transplanted to one common environment, litter characteristics alone could explain 52% and 26% of the variation in decomposition after 6 and 12 months, respectively. When both litter characteristics and environmental conditions were tested simultaneously and litter was decomposed in its original environment, 37% and 23% of the variation could be explained after 6 and 12 months, respectively. Both experiments showed two phases of decomposition: the initial leaching phase with an important role for litter characteristics and microbial communities in the model, and the second, slower phase, which is predominantly determined by litter characteristics and environmental conditions such as water quality. Model results could not be extrapolated to a fully developed reference area. Optimization of conditions in order to limit decomposition rates seems difficult and therefore we suggest using management options to influence biomass production and thereby fully exploit the use of newly constructed wetlands for carbon storage.

1. Introduction

Artificial wetlands are constructed around the globe for a variety of services (Zhao et al., 2015), including wastewater treatment (Kivaisi, 2001; Vymazal, 2014) and carbon storage (Klein and Werf, 2014). For optimal functioning of constructed wetlands, a fully developed vegetation is required. In newly constructed wetlands, similar to other pioneer systems, autonomous vegetation development will depend on environmental conditions as well as the seed bank present in the sediment. Characteristic vegetation types can develop in a couple of years, even without the introduction of species (Fennessy et al., 1994; Mitsch et al., 1998; Odland, 1997), but it may take several decades for the wetland to become a stable functioning ecosystem (Mitsch and Wilson, 1996). In the first years after construction, vegetation diversity is generally lower in unplanted than in planted wetlands (Mitsch et al., 2005; Williams and Ahn, 2015), but richness will increase over time (Reinartz and Warne, 1993). In contrast, unplanted wetlands or those with monocultures can be more productive in the initial years after the

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construction of the wetland than more diverse ones (Means et al., 2016; Mitsch et al., 2005).

A newly constructed wetland built for carbon storage will require production of biomass to exceed decomposition. Autonomous development of such systems can result in a range of environmental conditions and plant and litter characteristics. For example, higher soil organic matter content and lower bulk density stimulate establishment of emergent rather than submerged vegetation (Galatowitsch and Valk, 1996). Such differences most likely have a big impact on both production and decomposition rates in these wetlands. However, the effects of environmental conditions on the overall balance between production and decomposition might be complex. For example, while higher nutrient availability increases biomass production (Fennessy et al., 2008; Sarneel et al., 2010), it will also stimulate decomposition rates (Fennessy et al., 2008; Lee and Bukaveckas, 2002; Rejmánková and Houdková, 2006; Sarneel et al., 2010). Biomass production and nutrient content of plant material increases with increasing nutrient concentrations in the environment (Dee and Ahn, 2014; Fennessy et al., 2008), resulting in changes in the type and activity of the organisms that feed on this plant material (Andersen et al., 2010; Boulton and Boon, 1991; Dimitriu et al., 2010; Reed and Martiny, 2013; Straková et al., 2011; Trinder et al., 2009). These changes could in turn result in altered decomposition rates (Fennessy et al., 2008). In the process of decomposition, different phases can be recognized (Berg and Laskowski, 2006). The most easily degradable water-soluble compounds and non-lignified carbohydrates will be decomposed in the first phase, after which lignified carbohydrates and lignin will be decomposed at a lower rate in the second phase. Decomposition rates in the first phase can be increased by high nutrient availability in the litter, while high tissue concentrations of N can inhibit lignin-degrading enzymes and thereby decrease decomposition rates in the second phase. In the third and last phase, decomposition rates will approach zero.

Still, most studies on constructed wetlands focus on production only, and those studies considering decomposition only quantify the effects of single factors (e.g. nitrogen or phosphorus levels, or pH) on decomposition rates, mostly in a controlled setting (Aerts et al., 2005; Kok and Velde, 1991; Qualls and Richardson, 2000). To improve our understanding of carbon sequestration rates in newly constructed wetlands, it is therefore necessary to determine the combined effect of autonomous vegetation development and environmental conditions (including the presence of a decomposer community) on decomposition rates in these systems. In this study we aim to determine the influence of both plant and litter characteristics and environmental conditions on decomposition rates of aquatic pioneer vegetation in newly constructed wetlands. A large-scale field litterbag experiment was performed in the Volgermeerpolder (the Netherlands), a three-year old constructed wetland consisting of different experimental basins, using aquatic pioneer vegetation from within the basins. In addition, we used vegetation samples from the Weerribben (the Netherlands), as a fully developed reference area. We measured 35 variables, 28 abiotic and 7 biotic, and converted these to single factors for litter characteristics, sediment quality, water quality, microbial community composition and fraction of macroinvertebrate detritivores to determine which predictor variables best explain decomposition rates. To separate the effects of litter characteristics from those of environmental conditions, two experiments were performed. In Experiment 1, aquatic pioneer vegetation of different origin was left to decompose in one environment to determine only the influence of differences in litter characteristics on decomposition, while in Experiment 2 the same aquatic pioneer vegetation was placed in its original growing environment to study all factors simultaneously. This experimental approach will provide us with important insight into the drivers for decomposition of plant material under different environmental conditions in newly constructed wetlands and may lead to improved design criteria for building wetlands for carbon sequestration purposes.

2. Materials and methods

2.1. Site description

The experiments were carried out using aquatic pioneer vegetation collected at the Volgermeerpolder (52°25′17″N; 4°59′35″S) and the Weerribben (52°47′30″N; 5°54′37″S), in the Netherlands. The Volgermeerpolder is a newly constructed wetland, which was created in 2011 on a sand covered geomembrane on top of a former waste dump, with the geomembrane separating the waste hydrologically from the wetland, with the aim to initiate peat development (Egbring, 2011). It contains multiple basins ranging in size from 500 to 1600 m^2, formed by clay dikes and sand substrate. Some basins were complemented with a layer of ~30 cm organic sludge (originating from a nearby peatland area, 52°17′13″N; 4°46′12″S), resulting in a range of organic matter fractions in the sediment from 0.01 to 0.23 in the different basins. Initial vegetation development depended on sediment and water composition and presence of seeds in the sediment. Three years after construction of the wetland, mainly submerged vegetation developed in basins with low fraction of organic matter in the sediment, generally the basins with bare sand sediment without the complementary layer of organic sludge. In basins with a higher fraction of organic matter mainly emergent vegetation developed. The 12 basins used in this study were fed either with nutrient-rich surface water from the surrounding agricultural fields, or with rainwater (collected in a separate storage basin). Water levels were kept at 60 ± 15 cm above the sediment surface.

The Weerribben is a well-developed peatland with many shallow man-made ditches (~60 cm water depth) and sediments with high organic matter fractions (0.61–0.71). Vegetation at our research sites in the Weerribben consisted mainly of floating and occasionally some emergent plants.

2.2. Physico-chemical variables

Starting three years after construction, various physico-chemical characteristics of surface water and sediment were measured several times in one year (details in Supplementary Material A). Surface water temperature (T), electrical conductivity (EC) and pH were measured at 10 cm below the water surface using a HQ40D portable meter (HACH-Lange, Tiel, the Netherlands). Alkalinity was determined on unfiltered samples by titration down to pH 4.2 using an auto-burette with accurately determined titer (ABU901, Radiometer, Copenhagen, Denmark, or Metrohm 716 DMS Titrino, Metrohm Applikon, Herisau, Switzerland). Surface water samples were filtered before further analysis in the laboratory. Nitrate (NO_3^-), ammonium (NH_4^+), dissolved organic nitrogen (DON), soluble reactive phosphorus (SRP), potassium (K^+) and sodium (Na^+) were measured on an auto-analyzer (AA3 system, Bran & Luebbe, Norderstedt, Germany, or San ++ system, Skalar, Breda, the Netherlands). Chloride (Cl^-), calcium (Ca^{2+}), total iron (Fe), total manganese (Mn), total phosphorus (P) and total sulphur (S) were measured using inductively coupled plasma spectrometry (ICP-OES iCAP 6000, Thermo Fisher Scientific, Waltham, MA, USA, or Optima 8000DV, Perkin Elmer, Waltham, MA, USA).

Sediment samples were pooled from five subsamples per basin, using the top 5–10 cm, and stored at 4 °C until further analyses. Fraction organic matter (OM) was determined using loss on ignition (LOI, 4 h at 550 °C). Percentage carbon (C), nitrogen (N) and sulphur (S) were measured on an elemental analyser (Carlo Erba

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