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Above and below-ground nutrient cycling: a criteria for assessing the biogeochemical functioning of a constructed fen

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ABSTRACT

Recent peatland restoration studies have highlighted the need to modify the conventional approach of monitoring the recovery of biogeochemical functions through above-ground processes by integrating below-ground components, which are potentially sensitive indicators of reclamation trajectory in long-term monitoring programs. In this study, the recovery of nutrient cycling processes were assessed from both above and below-ground perspectives in a fen constructed on a post-mining landscape in the Athabasca oil sands region, Canada. The goal of this study was to understand if and how different revegetation strategies (seedlings (SDL); moss layer transfers (MLT); seedlings with moss transfer (SMLT) and a control treatment (CTRL)) influence the evolution of biogeochemical functions in the constructed fen relative to a natural reference (REF). The treatments were replicated 6 times and monitored over 2 growing seasons. Our results showed that revegetation facilitated both above-ground productivity and the cycling of below-ground nutrients, especially in the species-rich SMLT plots. Supply of labile substrates in the re-vegetated plots increased microbial potential activity. This was reflected in higher rates of respiration (c.7.8 g CO_2 m^{-2} day^{-2}), nutrient acquisition (net immobilization) and productivity (c. -16.3 g CO_2 m^{-2} day^{-2}) among revegetated plots relative to the CTRL. Nutrient dynamics within the constructed fen suggest that phosphorus limitation (N:P ratio > 20) could hamper the establishment of a diverse plant community, whereas the build-up of microbial biomass appears to be NO_3^- limited. Our results also emphasize the need to track the evolution of nutrients cycling processes through long-term monitoring programs, and identify the potential use of ammonification, nitrogen mineralization and phosphorus availability as functional indicators of a fen's recovery trajectory towards conditions present in natural fens.

1. Introduction

The often observed overlap between deposits of natural resources and pristine ecosystems (Durán et al., 2013; Kobayashi et al., 2014) suggests that meeting the increasing global resource demand through mining will inevitably be associated with the loss of vital ecosystems and supported services (Sims et al., 2013; Soni et al., 2014). Resource exploration sites are known hotspots of environmental change, where the need to ensure sustainability remains a critical challenge to environmental stakeholders (Audet et al., 2015; Giurco and Cooper, 2012; United Nations, 2012). As with any responsible mining operation around the world, implementation of ecosystem-scale ecological reclamation is a regulatory requirement and a major aspect of mine-closure procedures in the Athabasca oil sands region (AOSR), Canada. In this region, minerotrophic peatlands (fens) are the dominant wetland type in pre-mining landscapes (Vitt et al., 1996). Fens such as those found in the region, are known to support vital ecosystem services such as the regulation of nutrient cycling and carbon sequestration, and hence are of major importance to regional and global biogeochemical cycles (Blodau, 2002; Vitt et al., 2000). These peatlands are lost through oil sands exploration (Rooney et al., 2012); however, reclamation efforts are testing the feasibility of re-creating functional and self-sustaining fen ecosystems on post-mining landscapes (Daly et al., 2012).

Currently, there are two pilot fen projects in the Athabasca oil sands region, which were built by reconfiguration of the post-

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mined landscape with overburden materials (Ketcheson et al., 2015). To form the fen watershed, a shallow basin created within the constructed landscape was capped with a layer of peat (0.5–2 m) from a donor site (Price et al., 2010; Wytrykush et al., 2012). In the fen created on the Suncor Energy Inc. site, vegetation was introduced using four revegetation strategies: a seedling treatment; a moss layer transfer treatment; a combination of seedling with moss transfer; and a control (no vegetation) (Daly et al., 2012). Following implementation of these revegetation strategies, a comprehensive ecohydrological monitoring program was initiated to assess the development of ecological and hydrological processes in the constructed fen. One major objective of this monitoring program is to identify the revegetation strategy that has the highest potential to facilitate the recovery of ecosystem biogeochemical functioning in a constructed fen, and ensure a stable successional trajectory.

Evaluating the functional state of the constructed fen through a comprehensive ecohydrological monitoring program is imperative to understanding the reclamation trajectory. An evaluation based on microbially-mediated nutrients cycling processes has been proposed as essential for assessing the functional state of the fen (Nwaishi et al., 2015a). The central aspect of this evaluation involves exploring the recovery of biogeochemical transformation functioning, an integral mechanism of peatland ecosystem functioning. The appropriateness of this concept is grounded on the potential of exploring the sensitivity of microbial-mediated processes to a range of variability in biotic and abiotic conditions (Artz et al., 2008; Jaatinen et al., 2008; Keller et al., 2006; Lin et al., 2012), which can then be used as a criterion to define the functional characteristics that might evolve in a constructed ecosystem (Harris, 2003; Ruiz-Jaen and Aide, 2005), where multiple successional pathways are possible and an endpoint is unknown.

Under pristine conditions, biogeochemical transformations support the cycling of various forms of nutrients, and maintain the continuous flow of energy and matter between ecosystem trophic levels. The overall ecosystem biogeochemical cycling is a combination of above-ground (*e.g.* net ecosystem exchange of CO_2 and gross productivity) and below-ground (*e.g.* nutrient cycling processes and microbial activity) components. Soil microbes are the biological engine of the below-ground component of nutrients cycling processes, and soil edaphic variables such as substrate quality, water chemistry, moisture conditions and peat temperature control microbial activities, and thus the mineralization rate (Updegraff et al., 1995; Westbrook et al., 2006). At the same time, mineralization is often a major control on nutrient turnover, net ecosystem exchange of CO_2 and subsequent productivity of surface vegetation in peatlands (Keller et al., 2006). This feedback loop creates a tight coupling between above and below-ground nutrients cycling processes in natural peatlands. Plants serve as the biological link connecting above and below-ground nutrients cycling processes by supporting microbial activities through rhizodeposition, and depending on microbially-mediated nutrient supply for above and below-ground biomass productivity (Bragazza et al., 2015; Van Der Heijden et al., 2008; Wardle et al., 2004). Since the biogeochemical functioning of an ecosystem is sustained by the feedback mechanism between above and below-ground processes, assessing the recovery of this mechanism may be a useful criteria for defining the functional state of a constructed fen ecosystem (Wardle and Peltzer 2007; Nwaishi et al., 2015a).

Because fen construction is still at an experimental stage, there is a dearth of information on the state of biogeochemical functionality of these new ecosystems. Previous studies have focused on natural peatlands and provided some indications of key controls on processes such as nutrient mineralization (Aerts et al., 1999; Bridgham et al., 1998), organic matter accumulation (Belyea and Clymo 2001) and carbon cycling (Bellisario et al., 1999; Blodau 2002; Keller et al., 2006; Strack et al., 2009). However, it is not yet known if the mechanisms that sustain the feedback loop between above and below-ground processes can be established in constructed fens. Indeed, since the biotic and abiotic controls of nutrients cycling processes are compromised in post-mining landscapes (Johnson and Miyanishi 2008; Rooney and Bayley 2011), there is a possibility that nutrient cycling processes will also be modified. For instance, Nwaishi et al. (2015b) showed that the peat soil used as vegetation establishment substrate in the constructed fen has a higher bulk density, and lower organic matter and moisture content than undisturbed sites. This was attributed to drainage and subsequent decomposition of peat before it was transferred to the constructed fen (Nwaishi et al., 2015b). Studies examining the effect of peat degradation on nutrient dynamics suggest that the quality of peat substrate is a major control on nutrients cycling processes (Updegraff et al., 1995), which could be attributed to the substrate dependency of below-ground microbial communities (Fisk et al., 2003; Andersen et al., 2010a). Hence, the introduction of labile substrates to the constructed fen is crucial to the recovery of microbially-mediated processes. Although revegetation introduces new plant materials into the constructed ecosystem, the different revegetation strategies under trial in the constructed fen will likely have different effects on below-ground microbial community and function (Fisk et al., 2003; Kowalchuk et al., 2002; Zak et al., 2003), and also on available nutrient pools due to differences in vegetation nutrient demands (Aerts et al., 1999).

Our study explores the temporal trends in microbially-mediated processes of carbon (C), nitrogen (N) and phosphorus (P) cycling, as quantifiable proxies of biogeochemical transformation function, by building on established knowledge from previous peatland studies (Andersen et al., 2013; Macrae et al., 2013; Strack et al., 2009; Wood et al., 2015). Here, we report nutrient dynamics and edaphic conditions in a constructed fen over the first and second growing seasons post-construction. The specific objectives of the study are: (1) to evaluate the effect of different revegetation treatments on temporal variability in above and below-ground processes, relative to a natural analogue; (2) to determine the effect of revegetation treatments on the strength of the association between above and below-ground processes, and the relationship with environmental variables; and (3) to identify ecosystem processes that can be explored as potential key indicators of biogeochemical functions in a constructed fen.

We hypothesize that nutrient dynamics in the moss transfer plots will mirror the processes dominant in natural analogues, while soil nutrient pools will be reduced in seedling plots in response to high nutrient demands by vegetation. Given the recalcitrant nature of the peat substrate, we also hypothesize that following revegetation; microbial nutrient immobilization will be the dominant process, especially in the seedling plots, as microbes will favour the accumulation of biomass.

2. Materials and methods

2.1. Site description and preparation

The field research for this study took place at a natural peatland (Poplar fen) and a constructed fen on the Suncor Energy Inc., Millennium lease (Suncor pilot fen). Both are located within the oil sands development area, about 50 km north of Fort McMurray, Alberta. A general description of the study area, and specific information about the two study sites were presented in Nwaishi et al. (2015b). Six monitoring plots (measuring 2 m^2 and 10 m apart) that represent typical site conditions were selected in the natural peatland to serve as a reference for the study (REF). In each reference plot, monitoring spots were located at the interface of micro-topographic features (hummocks and hollows) for relative