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Biophysical indicators based on spatial hierarchy for informing land reclamation: The case of the Lower Athabasca River (Alberta, Canada)

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ABSTRACT

In the Lower Athabasca region of Alberta (Canada), surface mining for bitumen from oil sands creates highly disturbed environments, which need to be restored, after mine closing, to equivalent land capability in terms of biodiversity and ecosystem services. We demonstrate a method to characterize ecosystem diversity and conditions using biophysical indicators of the Lower Athabasca meant for informing land reclamation planning and monitoring by identifying and creating a typology of the main assemblages of topography, soil and forest vegetation at the watershed, landform and ecosite scales, and analysing the relationships among land units of various scales. Our results showed that watersheds could be classified into distinct groups with specific features, even for a region with a generally flat or gently rolling topography, with slope, surficial deposits and aspect as key drivers of differences. Despite the subtle topography, the moisture regime, which is linked to large-scale cycles that are dependent on the surrounding matrix, was of primary importance for driving vegetation assemblages. There was no unique and homogeneous association between topography and vegetation; the specific landforms each displayed a range of ecosites, and the same ecosites were found in different landforms. This suggests that landscapes cannot be defined in a qualitative manner but rather with quantitative indicators that express the proportion occupied by each class of ecological units within the coarser units, therefore requiring during land reclamation that sufficient care is given to create heterogeneity within a given landform in terms of soil texture and drainage so that a mosaic of ecosite conditions is created.

1. Introduction

With the transition towards ecosystem-based management (CBD, 1992; Duraiappah et al., 2005), ecologists from different fields are shifting from a plot to a landscape perspective (Wu and Hobbs, 2002). Understanding ecological heterogeneity on the landscape requires knowledge of geophysical and ecological processes operating at a range of scales (Rowe, 1992; Tansley, 1935). To help with this understanding, different ecological land classification (ELC) systems have been developed in various jurisdictions to define spatial units that have an homogeneous structure from a coarser scale (such as ecoregions, which are often homogeneous in terms of climatic variables) to local scales (such as ecosites, based on a combination of vegetation, landform and soil). These ELC systems provide a hierarchical spatial framework within which ecosystem functioning at various levels of organization can be described, monitored and assessed (Loveland and Merchant, 2004; Omernik, 2004). Within an ELC system, spatial units integrating biophysical attributes at different levels of organization represent components that indicate landscape potential to sustain biodiversity (Fitterer et al., 2012; Turner et al., 2003) and ecosystem services (Burkhard et al., 2009; Burkhard et al., 2012; Troy and Wilson, 2006) and could thus serve as indicators for planning and monitoring.

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In the Lower Athabasca region of Alberta (Canada), surface mining for bitumen from oil sands is currently responsible for disturbance of 813 km^2 of Boreal Plain ecosystems, on a total potential mineable area of 4800 km^2 (Alberta Government, 2015). As part of its environmental protection regulations, the Alberta government mandates the oil mining industry to recreate functioning ecosystems with an 'equivalent land capability' and to restore biodiversity and ecosystem services (e.g., carbon sequestration, timber harvesting, habitat, water provision, sources of traditional foods and medicinal plants, and recreation) provided by the land prior to mining disturbance (Alberta Government, 1999). The Reclamation Working Group of the Cumulative Environmental Management Association has set as a goal that the reclaimed soils and landforms are "capable of supporting a diverse self-sustaining, locally common boreal forest landscape" (Alberta Government, 2013).

A fundamental step for informing practices of land reclamation and restoration of ecosystem services is to assess how pre-disturbance (or baseline) landscapes are assembled in ecological units that are functional and meaningful for encompassing ecosystem functioning. The current Land Capability Classification System developed for Alberta's oil sands area and intended to facilitate the evaluation and monitoring of land capability and forest site productivity on reclaimed areas is based on a site-level evaluation of soil moisture and nutrient regimes and of potentially limiting physical properties of a 1-m deep soil profile (Cumulative Environmental Management Association, 2006). However, providing guidance for reclamation in the form of indicators that incorporate an understanding of how site-level physical, chemical and biological processes scale up to create landscape dynamics (Johnson and Miyanishi, 2008; Quideau et al., 2013) has yet to be achieved. Under the objective of ensuring that reclaimed landscapes can support natural ecosystem functions, the Reclamation Working Group of the Cumulative Environmental Management Association has identified as criteria that landforms are integrated within and across lease boundaries, and that landforms have natural appearance (Alberta Government, 2013); indicators related to connectivity within the landscape and of landscape mosaic have been discussed, but definitions and methods for application have yet to be agreed on. Such indicators could serve as targets during the early stages of land reclamation, to inform the reconstruction of landscape, landform and site components and for monitoring ecological development and compliance to reclamation objectives (Audet et al., 2014). Although perfect re-establishment of pre-mining conditions is often not possible, efforts to create novel ecosystems that are self-sustaining and resilient in their environment (Audet et al., 2014) should entail a hierarchical spatial complexity of abiotic and biotic factors (Drake et al., 2010).

In the context of the Lower Athabasca, a useful hierarchy of spatial biophysical entities for describing ecological patterns in forested landscapes is the hydrological network (Anderson and Burt, 1990) because water flows and moisture gradients are among the primary factors that drive vegetation distribution in this region (Beckingham and Archibald, 1996; Corns and Annas, 1986; Lesko and Lindsay, 1973). Within a regional basin (10^6 m) that has uniform climatic conditions, watersheds (10^4–10^5 m) are areas where surface waters converge and within which geology and localized orographic weather effects drive ecohydrological patterns. Within watersheds, landforms (10^2–10^3 m) are assembled along hillslopes that are created from subsurface and surficial geology and its weathering. Along the landforms of the hillslope, geomorphology drives the transport of dissolved and particulate material creating different soil units (10^0–10^1 m). At this scale, the moisture and nutrient gradients drive vegetation associations, which in turn also influence soil formation (Augusto et al., 2002; Miles, 1985; Nikodemus et al., 2013; Pawlik, 2013), therefore forming vegetation-soil units, or ecosites. Depending on the region, natural disturbance regimes also contribute to shaping the ecological mosaic at the landscape scale (Certini, 2014; Šamonil et al., 2010). For the need of land reclamation, developing biophysical indicators based on a spatial hierarchy allows inference on the importance of connectivity within the landscape (Klijn and de Haes, 1994). Such an approach would provide a means to examine interactions among overlapping environmental gradients at various scales, which could help to ensure that reclamation of a given site is compatible among oil sands leases and fits into the context of the surrounding landscape; it would emphasize the fact that indicators of reclamation 'success' of a given site is dependent on management of the surrounding matrix.

Over the past decades, automated techniques based on remote sensing or other spatial information have been shown to provide a robust, standardized and practical way to stratify landscapes into meaningful units at various scales (MacMillan et al., 2004). In automated methods, landscapes are tessellated into spatial units, and each unit is given a value for various environmental variables. Multivariate techniques are then used to group units into classes or clusters (Bryan, 2006). Relative to conventional, expert knowledge-based methods (e.g., aerial photo interpretation), automated methods have the advantage of being explicit, repeatable and easy to update when new spatial information becomes available (Burrough et al., 2000; Schneider and Klein, 2010; van Asselen and Seijmonsbergen, 2006). A benefit of these methods is to harmonize classifications and to apply them across boundaries, which represents an important advantage for transjurisdictional planning, policy-making and stewardship issues. To date there have been few examples of the use of automated techniques in Canada, but their results have shown that it is possible to produce accurate and cost-effective ecological-landform maps using such approaches (Nadeau et al., 2004), even in biophysically complex areas (Fitterer et al., 2012; MacMillan et al., 2007).

Standardized digital products of forest and site characteristics are now available at a 250 m resolution for the whole of the Canadian forest landbase (Beaudoin et al., 2014; Mansuy et al., 2014); they provide an opportunity for testing automated methods of ecological land classification. For the particular case of the Lower Athabasca, it is the occasion to assess how these methods can assist in developing indicators for informing land reclamation planning and monitoring. The aim of this paper is to demonstrate a method to characterize ecosystem diversity and conditions using biophysical indicators of the Lower Athabasca arranged according to a hierarchical complexity gradient and describe them by: (1) identifying and creating a typology of the main assemblages of topography, soil and forest vegetation at the watershed, landform and ecosite scales, and; (2) analysing the relationships among land units of various scales. The Lower Athabasca region is an interesting case study not only because of the important anthropogenic pressure that it is experiencing, but also because ecological gradients are relatively shallow and species richness is relatively low, which make ecological classification more challenging than in regions with greater contrasts.

2. Methods

2.1. Study area

The Lower Athabasca region is located in northern Alberta, covering an area approximately 93 212 km^2 (Alberta Government, 2012) (Fig. 1). The terrain is characterized by subdued relief consisting of low-lying valleys and plains. Underlying these landforms are horizontal layers of sedimentary bedrock laid down during the Cretaceous and Tertiary periods. The majority of soils have developed on glacial and glaciofluvial deposits. Gray Luvisols are generally