Ecological Indicators 72 (2017) 173–184

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

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

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ARTICLE INFO

Article history:
Received 19 April 2016
Received in revised form 4 July 2016
Accepted 10 August 2016

Keywords:
Land reclamation
Landscape
Watershed
Landform
Ecosite
Automated classification
Ecosystem services

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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http://dx.doi.org/10.1016/j.ecolind.2016.08.020
1470-160X/

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

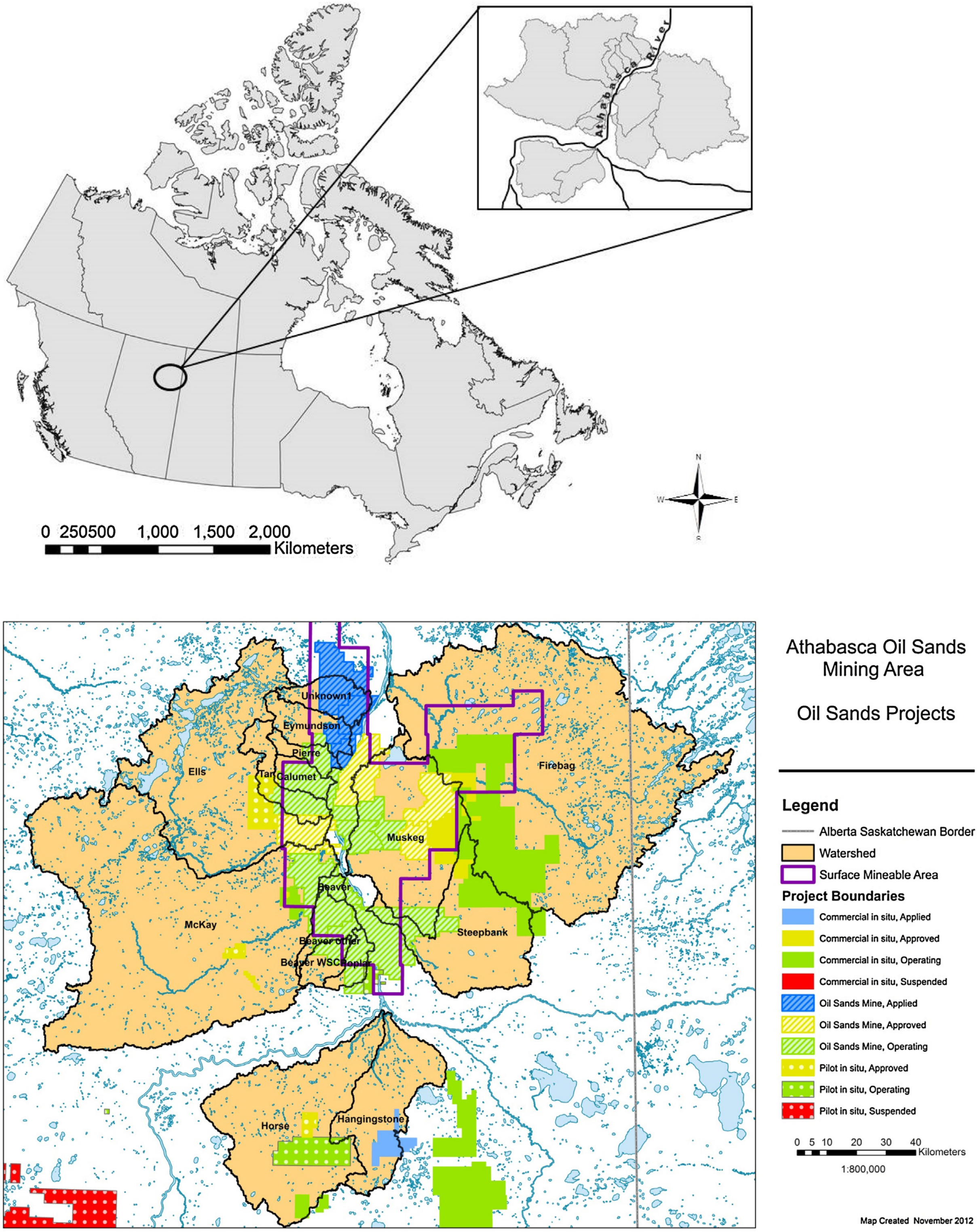

Fig. 1. Location of the study area within Alberta and Canada (upper panel) areas of mining disturbance within the watersheds (lower panel).

associated with till and lacustrine deposits, while Dystric Brunisols are found on coarse parent materials such as glaciofluvial outwash and eolian sands (Turchenek and Lindsey, 1982).

The study area is part of the Boreal Plains Ecozone. The dominant tree species include jack pine (*Pinus banksiana* Lamb.), white spruce (*Picea glauca* [Moench [Voss), black spruce (*Picea mariana* [Mill.] BSP), trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and white birch (*Betula papyrifera* Marsh.) (Fung et al., 2000). Large, intense forest fires are the dominant natural disturbance agent in the region (Kasischke and Turetsky, 2006), with a fire return interval between 59–180 years (de Groot et al., 2013; Larsen, 1997).

The climate is characterized as dry continental with a water deficit over the long term (potential evapotranspiration ≥ precipitation) (Devito et al., 2012). The average (1981–2010) annual temperature is 1.0 °C and average annual precipitation is

Table 1
Spatial information on landform, hydrological, geological, soil and tree cover attributes compiled at a 250 m resolution.

Parameter	Attribute	Description	Units	Data Source
Topography	DEM- watershed shape files	Watershed shape files generated from NHN source	250 m	NHN database
	Slope	Slope using a filled/de-pitted DEM	Deg	ArcMap
	Aspect	Aspect using a filled/de-pitted DEM	Deg	ArcMap
	Plan Curvature	Plan Curvature on the filled/de-pitted DEM	Deg 100 m^{-1}	ArcMap
	Profile Curvature	Profile Curvature on the filled/de-pitted DEM	Deg 100 m^{-1}	ArcMap
	Mean Curvature	Mean Curvature on the filled/de-pitted DEM	Deg 100 m^{-1}	ArcMap
	Wetness Index	Wetness Index done using the Ln (flow accumulation* 62,500m2)/(TAN (Slope radians))	(m^2 rad^{-1})	ArcMap
	Stochastic Depression Analysis	Performed in "Whitebox" using the Stochastic Depression Analysis tool. Done on the 250 m DEM		Whitebox
Hydrology	Water bodies and watercourses	Shape file was made in ARCMap and converted to a raster changing the output cell size to 25. All values of 1 indicate that it is water. 0′s and NO Data are land or whitespace.		ArcMap
Surficial geology	Surficial geology type	Surficial geology type	Unitless	Alberta Geologic Survey
Soil properties	Silt	Soil silt content	%	NFI_MODIS250m
	Sand	Soil sand content	%	NFI_MODIS250m
	Clay	Soil clay content	%	NFI_MODIS250m
	OC_FF	Forest floor organic carbon	g kg^{-1}	NFI_MODIS250m
	OC	Mineral soil organic carbon	g kg^{-1}	NFI_MODIS250m
	N_FF	Forest floor total nitrogen	g kg^{-1}	NFI_MODIS250m
	N	Mineral soil total nitrogen	g kg^{-1}	NFI_MODIS250m
	DEP_FF	Forest floor depth	cm	NFI_MODIS250m
	CN_FF	Forest floor Carbon: Nitrogen Ratio	Unitless	NFI_MODIS250m
	Bulk density	Soil bulk density	g cm^{-3}	NFI_MODIS250m
Tree cover	*Abies balsamea* (L.) Mill. (ABBA)	Balsam Fir	% cover	NFI_MODIS250m
	Betula papyrifera Marsh. (BEPA)	White Birch	% cover	NFI_MODIS250m
	Larix laricina (Du Roi) K. Koch (LALA)	Tamarack	% cover	NFI_MODIS250m
	Picea glauca (Moench) Voss (PIGL)	White Spruce	% cover	NFI_MODIS250m
	Picea mariana (Mill.) B.S.P. (PIMA)	Black Spruce	% cover	NFI_MODIS250m
	Pinus banksiana Lamb. (PIBA)	Jack Pine	% cover	NFI_MODIS250m
	Populus balsamifera L. (POBA)	Balsam poplar	% cover	NFI_MODIS250m
	Populus tremuloides Michx.(POTR)	Trembling Aspen	% cover	NFI_MODIS250m
Disturbance	Disturbance Category	Mining disturbance categories	%	Alberta Environment and Water, Government of Alberta
Wetland	Wetland Area	Stochastic depression analysis 40–79%	%	TAS
Water	Water Area	Stochastic depression analysis >80	%	TAS

418 mm, with 60% falling during the growing season (Fort McMurray weather station) (Environment Canada, 2014). The average number of degree-days (>5 °C) is 1376, with a frost-free season of about 60 days, with frost occasionally occurring during the growing season.

2.2. Source data

Spatial information was compiled at a consistent resolution of 250 m (i.e. 1 pixel = 6.25 ha) corresponding to the grid of orthorectified mosaics from TERRA MODIS satellite imagery (Pouliot et al., 2009), to take advantage of the similarly scaled and newly available digital products for the Canadian forest landbase (Beaudoin et al., 2014; Mansuy et al., 2014). Within the Lower Athabasca region, a case study area comprising the river valley and 16 watersheds that drain into the Lower Athabasca River were extracted from a depitted 250 m resolution digital elevation model (DEM) (USGC/NASA SRTM) in ArcMap using pour points where the contributing river enters the Athabasca (Fig. 1). In total the area comprised 297 000 250-m pixels.

Raster layers of spatial information related to topography, surficial geology, soil and forest vegetation were compiled for the area (Table 1). Topographic attributes (slope, aspect, profile, plan and mean curvature, and wetness index) were derived using ArcMap from the DEM. Data on forest and soil attributes were taken directly from the digital products of Beaudoin et al. (2014) and Mansuy et al. (2014). Surficial deposit attributes were taken from a vector-based surficial geology map at 1:1 000 000 scale (Fenton et al., 2013) and converted to a raster at 250 m resolution. The water layer was taken from the National Hydrological Network waterbodies vector map (Natural Resources Canada Centre for Mapping and Earth Observation, 2015) and converted to a 250-m raster.

Areas disturbed by oil sands development (i.e. currently under mining operations) within the region were identified from a 2011 disturbance map layer from Alberta provincial government (Alberta Environment, 2011).

Table 2
A description of the fuzzy attributes used in the topographic feature classification and the fuzzy semantic import model and parameter used to define them. The b1 and b2 are the upper and lower limits, respectively, of the dispersion (d) from the maximum probability.

Fuzzy attribute	Description	Units	Topographic derivative derived from	Model	B1 and/or B2	D
Near divide	Near local divide	%	Elevation relative to channel and divide	Upper	85	15
Near peak	Near local peak	%	Elevation relative to peak and pit	Upper	85	15
Near mid	Near peak to pit midslope	%	Elevation relative to peak and pit	Central	15, 85	30
Near channel	Near local channel	%	Elevation relative to channel and divide	Lower	15	15
Near pit	Near local pit	%	Elevation relative to peak and pit	Lower	15	15
High WI	High wetness index	$m^2/°$	Wetness index	Upper	10	5
Convex D	Convex in profile curvature	°/100 m	Profile curvature	Lower	−0.005	0.005
Concave D	Concave in profile curvature	°/100 m	Profile curvature	Upper	0.005	0.005
Planar D	Planar in profile curvature	°/100 m	Profile curvature	Central	−0.005, 0,005	0.005
Near level	Nearly level slope	%	Slope gradient	Lower	3	3
Relatively steep	Not level	%	Slope gradient	Upper	3	3

2.3. Watershed classification

Watersheds were classified into different types using a cluster analysis of key terrain attributes averaged for all pixels within a watershed. Key terrain attributes were first identified from a Principal Component Analysis (PCA) based on all attributes (i.e. slope, aspect, plant, curvature, and wetness index) and surficial geology using the Factor analysis function within JMP 11.0 (SAS, 2012). Key variables identified in the PCA were then used in a fuzzy k-means classification procedure on whole watersheds (Bezdek, 1981). The fuzzy k-means classification determines the membership values for objects (i.e. watersheds in this case) on the basis of minimizing the objective function J(M,C). Consider a set of n objects (i = 1,. . ., n) each having p attributes (v = 1,. . ., p) grouped into k classes (c = 1,. . ., k), J(M,C) can be expressed as:

$$J(\mathrm{M,C}) = \sum_{i=1}^{n}\sum_{c=1}^{k} m_{ic}^{\phi} d^2(x_i, c_c); \quad (1)$$

where $\mathrm{M} = m_{ic}$ is a $n \times k$ matrix of membership values, $\mathrm{C} = c_{cv}$ is a $k \times p$ matrix of class centroids, c_{cv} denotes the centroid of class c for variable v, $\mathrm{c}_c = (c_{c1},\ldots, c_{cp})^{\mathrm{T}}$ is the vector representing the centroid of class c, $\mathrm{x}_i = (x_{i1},\ldots, x_{ip})^{\mathrm{T}}$ is the vector representing object i, $d_{ic}{}^2$ (x_i,c_c) is the square distance between $\mathrm{x_i}$ and $\mathrm{c_c}$ according to a chosen distance metric (Euclidean, Mahalanobis' or Diagonal) and ϕ is the fuzziness exponent which determines the degree of fuzziness of the classification (ranges between 1 and infinity, representing a crisp and a completely fuzzy classification, respectively). The fuzzy k-means classification was performed using JMP 11.0 (SAS, 2012). The fuzziness exponent was fixed to the conventional value of 1.35 (Odeh et al., 1992) and used the Mahalanobis' distance metric as it accounts for the differences in variances (Bezdek, 1981). The classification was repeated for a range of classes, i.e. k was set to a value between 2 and 8.

The optimum k-value was identified on the basis of maximizing the cubic clustering criterion (Sarle, 1983). The Cubic Clustering Criterion (CCC) was developed as a comparative measure of the deviation of the clusters from the distribution expected if data points were obtained from a uniform distribution. The criterion is calculated as:

$$\mathrm{CCC} = \ln\left[\frac{1 - E(R^2)}{1 - R^2}\right] \times K; \quad (2)$$

where $E(R^2)$ is the expected R^2, R^2 is the observed R^2, and K is the variance-stabilizing transformation. Larger positive values of the CCC indicate a better solution, as it shows a larger difference from a uniform (no clusters) distribution. The number of classes chosen was based on the highest CCC.

2.4. Landform classification

Conacher and Dalrymple (1977) concept of a hillslope catena provided a theoretical framework for defining landforms along hillslopes. To reflect the hillslope gradients in soil moisture and nutrients, hillslope topographic features (i.e., crest, backslope, footslope, toeslope) (Conacher and Dalrymple, 1977) were delineated using digital terrain analysis software (Terrain Analysis System 2.0.9) (Lindsay, 2005) and a four-step method briefly described below (refer to Webster et al. (2011) and MacMillan et al. (2000) for more complete details):

1. Five terrain derivatives were derived from the 250 m DEM as the basis of defining the topographic features: (a) percent height relative to local pits and peaks; (b) percent height relative to local channels and divides; (c) wetness index; (d) slope curvature; and (e) slope gradient.
2. The five terrain derivatives were converted from "crisp" to "fuzzy" through the application of a fuzzy membership function, where the shape of the probability function is determined by the attribute values where it has complete membership (i.e., the central concept, b) and the rate of decline in membership (i.e., its dispersion, d) (Table 2).
3. Fuzzy attributes were combined to define the topographic features. A function was created from the set of fuzzy attributes (Table 3), with each fuzzy attribute having a weight determined by expert knowledge of boreal landscapes (Webster et al., 2011),

Table 3
The fuzzy attributes and weights used to define each of the topographic features. Multiple rows occur for each feature indicating their alternative definitions.

Topographic feature	Near divide	Near peak	Near mid	Near channel	Near pit	High WI	Convex D	Concave D	Planar D	Near level	Relatively steep
Crest	50									50	
		50								50	
Backslope	50						50				
		50					50				
			50						50		
Footslope						25		25			50
				50				50			
					50			50			
Toeslope				50					25	25	
					50				25	25	
Wetland	Stochastic depression analysis										

and combined weights summing to one (MacMillan et al., 2000). A map was created for each topographic feature with each grid cell assigned the probability of belonging to that feature. The individual maps were reclassified by assigning a given grid cell to the topographic feature with the highest probability of all the topographic feature maps.

4. Wetlands were identified using a probabilistic approach that determines the likelihood of an area being flat or in a depression was used to delineate the wetlands (Lindsay and Creed, 2006). The analysis was developed by Lindsay and Creed (2006), based on a Monte Carlo procedure (Burrough and McDonnell, 2011; Fisher, 1998), which identifies the probability that a pixel in the DEM is a depression. The stochastic depression analysis was run within Whitebox (Lindsay, 2014) using a normal distribution of error, 100 iterations and 1000 turning bands.

2.5. Ecosite classification

A PCA combining all topographic, surficial geology, soil and vegetation attributes at the pixel level (i.e. 6.25 ha) was run to establish key attributes that drive variation among pixels, which were deemed to correspond to soil-vegetation units, i.e., ecosites. Key variables identified in the PCA were then used in a fuzzy *k*-means classification procedure as described above. Ecosites derived from this automated classification method were qualitatively matched to the provincial (Beckingham and Archibald, 1996) based on vegetation, wetness index, and soil and geological substrate characteristics.

2.6. Relationships among land units

To analyse the relationships among ecological land units of various scales (i.e. watersheds, landforms and ecosites), contingency tables representing the frequency of landforms within watershed types, and the frequency of ecosites within both watershed types and landforms were built. The chi-square test was run on each contingency table to evaluate the independence or correlation between land unit classes. The analysis was performed using the chisq.test function in R (version 3.1.1).

3. Results

3.1. Watershed classification

The PCA was run on terrain attributes that were averaged for all pixels within each of the 16 watersheds of the study area; it identified slope, aspect, wetness index, plan, profile, curvature and surficial deposits as the key attributes for explaining the variation between watersheds and creating a typology. The classification of watersheds yielded 4 clusters, corresponding to watershed types (Table 4). There was a fairly even distribution of the watersheds among the groups (3–5 watershed per type). Watershed Type 1 included those in the northern part of the study area (Calumet, Ells, Firebag and Tar) and was characterized by intermediate slopes (1.25°), intermediate wetness index (17.6), and mainly covered by glaciolacustrine and moraine surficial deposits. Watershed Type 2 (Hangingstone, Horse, McKay, Muskeg and Steepbank) included large southern watersheds that were characterized by low slopes (0.70°), high wetness index (18.0), and mainly covered by glaciolacustrine and moraine surficial deposits with high proportion of organic deposits (11.1%). Watershed Type 3 were smaller watersheds that contain some level of mining disturbance (Fig. 1); they were located adjacent to the Athabasca River (Beaver, Beaver Other, Beaver WSC, Poplar) and were characterized by relatively low slopes (0.85°) mainly oriented towards the east (76%), and mainly

Table 4
Landform and geological attributes of watershed types determined from *k*-means clustering analysis.

Watershed type	Watersheds	Slope	Wetness index	Aspect in% of pixels within each category				Surficial deposits in% of pixels within each category									
		°	$m^2\ rad^{-1}$	East	West	North	South	Colluvial	Aeolian	Fluted moraine	Fluvial	Glacio-fluvial	Glacio-lacustrine	Ice-thrust moraine	Moraine	Organic	Stagnant ice moraine
1	Calumet, Ells, Firebag, Tar	1.25	17.6	57.1	23.7	17.9	33.3	2.2	0.8	14.7	0.7	9.0	24.1	1.9	31.3	2.8	8.2
2	Hangingstone, Horse, McKay, Muskeg, Steepbank	0.70	18.0	35.1	44.8	15.3	37.2	0.7	0.6	2.8	1.6	8.0	32.2	2.2	35.0	11.1	5.7
3	Beaver, Beaver Other, Beaver WSC, Poplar	0.85	17.5	76.0	11.9	29.3	0.0	0.3	1.5	0.0	0.9	17.4	64.9	0.0	0.0	3.8	11.1
4	Eymundson, Pierre, Unknown 1	1.73	17.1	71.4	11.1	47.5	27.1	13.9	6.7	0.9	32.0	10.8	3.8	2.8	24.3	0.1	4.8

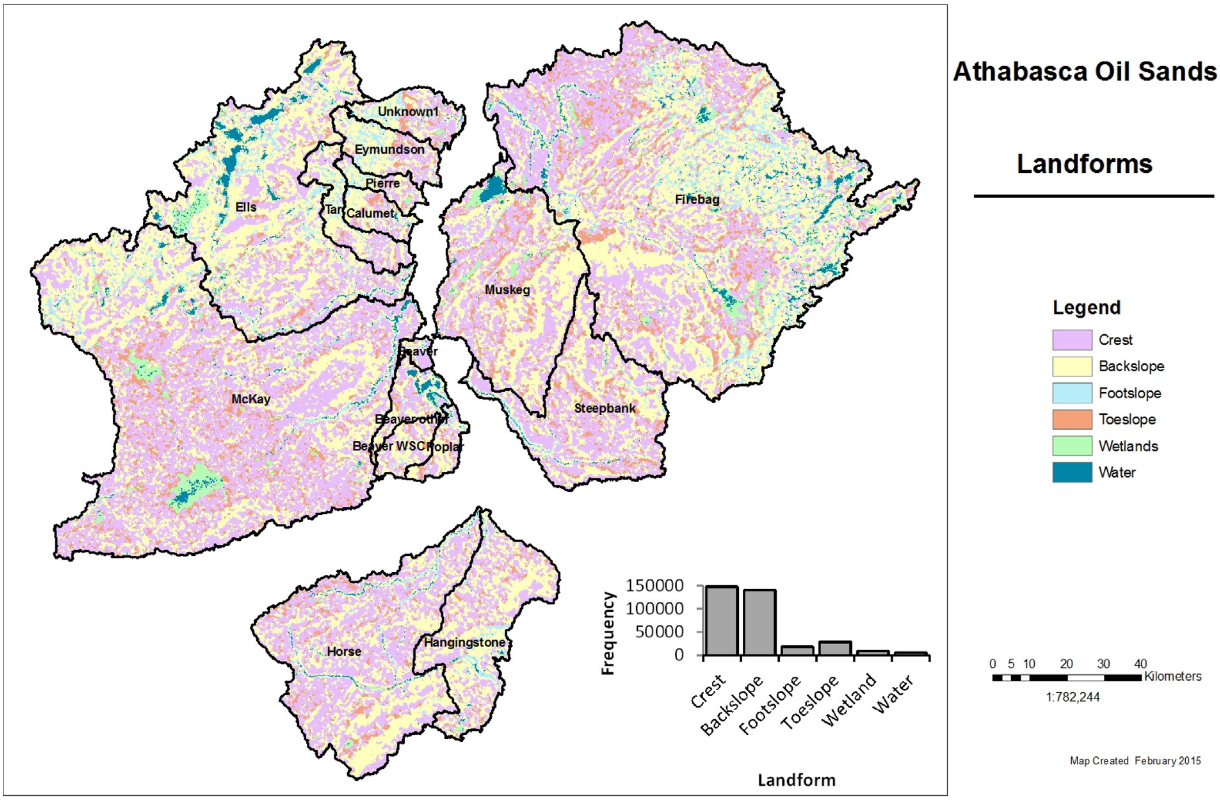

Fig. 2. Distribution of landforms within watersheds.

covered with glaciolacustrine and glaciofluvial deposits. Finally, Watershed Type 4 regrouped steeper watersheds in the northwest section of the study area (Eymundson, Pierre, Unknown 1) and were characterized by steeper slopes (1.73°), mainly oriented towards the east (71%), and covered mainly by fluvial and moraine deposits, with almost no organic deposits (0.1%).

3.2. Landform classification

Delineation of landforms over the case study area showed that the crest was the most abundant landform, followed by backslope, and toeslope (Fig. 2). However, crests appeared to be over-represented on the landscape, which may be due to the algorithm that defines the location of the divide, which is hard to adjust for a region with such as subdued topography. This over-representation was persistent even with changes in the upper limits and dispersion described in Table 2.

3.3. Ecosite classification

The *k*-means clustering among all pixels based on topographic attributes, soil and forest vegetation characteristics (Table 5) yielded 11 clusters, and are referred to as automatically derived ecosites. Ecosites 1, 4, 9, 10 and 11 were the most common, with each encompassing greater than 10% of the study area, while Ecosites 6 and 8 were the least common, each encompassing less than 3% of the study area.

The typology of ecosites was mainly driven by slope, wetness index and tree species cover, and to a lesser extent by soil properties and slope curvature (plan, profile, curvature) (Table 5). Based on these environmental variables, ecosites could be arranged along an ordination of moisture and fertility gradients (Table 5), ranging from ecosites with generally low wetness index, high sand proportion in the soil matrix and dominated by *P. banksiana* (e.g. Ecosite 3), to sites with flat ground and high wetness index dominated by *P. mariana* and *L. laricina* (Ecosite 1). Surimposed on the moisture gradient was a fertility gradient, with an increase in the presence of *P. glauca*, *P. tremuloides* and *P. balsamifera* on richer ecosites (e.g. Ecosite 7) with higher concentration of total nitrogen in the forest floor, and poorer sites characterized by *P. mariana* and *P. banksiana* (e.g. Ecosites 2-3-4). The most abundant ecosites (Table 5) were those located at the hygric extreme of the moisture gradient, with a high wetness index and dominated *by P. mariana*. Much less abundant were the ecosites located at the xeric end of the moisture gradient, i.e. the drier, *P. banksiana*-dominated sites. The least abundant types were relatively rich ecosites located on steeper slopes, and associated with a mixture of *P. tremuloides* and *P. glauca* (Ecosites 6, 8).

3.4. Relationships among ecological land units of various scales

Landforms were significantly correlated with watershed types (chi-squared test p value <0.001). Although areas of all watershed types were dominated by crests and backslopes, Watershed Type 2 had the highest area proportion of crests, and Watershed Type 1 the highest proportion of backslopes (Fig. 3a). Apart from those two landforms, Type 4 had a high area proportion of footslopes, whereas watersheds of the Type 2 had a higher proportion of toeslopes relative to footslopes. In Type 1, toeslopes and footslopes were equally presented.

The contingency tables and chi-square test of ecosites versus watershed types also showed that the two types of land unit were significantly correlated (i.e. ecosites were not randomly distributed among watershed types; $p < 0.001$). Watershed Type 1 was mainly associated with drier, poorer ecosites, whereas Watershed Type 2 was characterized by wetter ecosites (Fig. 3b and Table 5). Watershed Type 3 also had a high proportion of the wetter ecosites but

Table 5
Topographic, soil and tree cover attributes, and moisture and fertility regimes of ecosites determined from *k*-means clustering analysis. Topographic, soil and tree cover attributes are means for each cluster of pixels. Moisture and fertility regimes were qualitatively determined based on attribute means for each cluster.

Attributes	Ecosite type										
	1	2	3	4	5	6	7	8	9	10	11
Number of pixels	87 800	24 293	12 308	65 873	10 431	8251	11 496	8 200	33 097	34 122	27 787
Topography											
Slope (°)	0.5	0.98	1.51	0.46	2.23	2.48	1.22	2.46	0.81	1.1	0.99
Plan (°100 m^{-1})	0	−0.002	0.014	0	0.003	−0.019	0.001	0.027	0.001	0.001	0.002
Profile (°100 m^{-1})	0.001	0.005	−0.013	0.001	−0.003	0.003	−0.001	−0.032	0	0.001	−0.001
Curvature (°100 m^{-1})	0	−0.007	0.027	−0.001	0.006	−0.047	0.002	0.059	0.001	0	0.003
Wetness index (m^2 rad^{-1})	18.2	17.2	16.2	18.3	15.8	16.5	17.4	16.3	17.4	16.8	17.4
Soil properties											
Sand (%)	58.2	62.1	62.6	67.6	51.4	57.7	58.5	57	61.9	49.7	58.9
Mineral soil organic C (g kg^{-1})	31.7	32.4	30.8	27.2	57.1	39.2	31.1	37.6	28.1	66.4	27.9
Forest floor total N (g kg^{-1})	11.5	10.4	9.9	8.9	12.3	11.3	11.2	11.3	10.4	12.3	11.3
Forest floor depth (cm)	10.9	10.6	9.1	9.1	8.1	9.4	9.3	9	9.5	7.6	9.8
Tree species cover (%)											
L. laricina	12.9	1.3	2.8	10	0.7	3.8	2.1	2.6	2.5	3.7	1.4
P. banksiana	10.3	70.4	54.8	11.1	8.4	14.9	1.6	8.2	5.5	22.3	1.7
P. glauca	4.9	0.3	1	4.5	27.1	12	9.8	14.2	25.2	4.2	10.4
P. mariana	46.3	19.4	28.9	53.2	15.4	24.5	4.9	16.7	18.6	38.6	5.4
P. balsamifera	0.3	0.2	0.2	0.3	1.4	1.4	11.3	2.1	1.1	0.2	2.9
P. tremuloides	11.7	4.5	7.7	11.5	37.7	32.5	57.4	46.4	41.1	9.7	71.1
Moisture and fertility regimes	Hygric medium	Subxeric poor	Xeric poor	Hygric poor	Submesic medium	Mesic medium	Hygric rich	Mesic medium	Subhygric rich	Submesic poor	Mesic medium

also contained a high proportion of the rich and mesic ecosites. Finally, Watershed Type 4 was dominated by mesic ecosites.

The chi-squared test performed on the landform versus automatically derived ecosite contingency table also yielded a significant correspondence between the two types of land unit ($p < 0.001$). Toeslopes were dominated by hygric ecosites (Ecosites 1–4), and even contained a higher proportion of wet types than wetland landforms. Crests were also characterized, to a lesser degree, by wet ecosites, but with a fairly high proportion of submesic/mesic types. Dry (Ecosites 2, 3) and mesic (Ecosites 6, 8) ecosites were mostly associated with backslopes and footslopes. There was also a significant association between ecosite and industrial disturbance ($p < 0.001$), with mesic to hygric ecosites of medium to high fertility (Ecosites 1,7, 9, 11) the most frequently disturbed by oil sands extraction activities (Fig. 3c).

3.5. Comparison with provincial and national ecological classifications

The automated classification of ecosites performed in this study produced results that are broadly coherent with the provincial ecological classification for the Boreal Mixedwoods (Beckingham and Archibald, 1996). Among the ecosites provided by our automated classification, Ecosite 2 and 3, with their jack pine dominance and dry, sandy soil, resembled lichen-jack pine (ecosite a1) from the provincial classification, a poor xeric ecosite mostly located on foot- and backslopes. Our ecosite type 5, with its mix of aspen and white spruce on well-drained and moderately fertile soil, was similar to ecosites of the blueberry category (ecosite b). The provincial Labrador tea-Jack Pine-Black Spruce ecosite (c1), characterized by a mesic moisture regime, poor to medium nutrient regime, might be captured by our Ecosite 10. Our Ecosites 6, 8, 9 and 11, with their various proportions of aspen and white spruce, presence of balsam fir (for Ecosites 8 and 11) are somewhat similar to the low-bush cranberry provincial ecosite category (d); Ecosites 6 and 8 are closer to the low-bush cranberry-white spruce ecosite (d1), which is found on steeper slopes, whereas Ecosite 9 is closer to bush cranberry- white spruce ecosite (d3), which is slightly wetter and found on flatter terrain, with Ecosite 11 being somewhat between d1 and d2 (low bush cranberry-aspen-white spruce (d2)). The subhygric rich provincial ecosite dogwood-balsam poplar-aspen (e1) resembles our Ecosite 7. The wet and black spruce-dominated Ecosite 4, located on very flat terrain, is similar to the provincial Labrador tea-subhygric black spruce-jack pine ecosite (g1), whereas our Ecosite 1, which is also wet but appears slightly richer than Ecosite 4, might be closer to the provincial ecosite Labrador tea-horsetail-white spruce-black spruce (h1). Lacking from the automated classification are ecosites of the very wet and nutrient rich type such as the horsetail ecosite (f), although our Ecosite 7 is somewhat close to it, as are the bog and fen ecosites (i, j, k and l).

4. Discussion

In the Lower Athabasca region of Alberta, discussions are ongoing on how to define indicators to be used in the early stages of land reclamation after oil sands exploitation, during the landscape creation phase for ensuring connectivity within the landscape and the establishment of a landscape mosaic (Alberta Government, 2013). Such indicators are meant as metrics that can be measured to evaluate whether criteria of landscape integration and natural appearance are met, with the objective of establishing landscapes that can support natural ecosystem functions, alongside indicators of e.g. soil and tree productivity and health. For this purpose, we proposed an automated method based on cluster analysis, a statistical classification method that has been used in natural and environmental science for decades due to its simplicity for revealing inherent structures in datasets (Kaufman and Rousseeuw, 2005), and on readily available and standardized digital metrics at 250 m resolution. With this relatively simple and easily applicable methodology, we were able to define typologies of homogenous land units for characterizing the Lower Athabasca region based on a tiered structure of coarse (watershed), medium (landform) and fine (ecosite) units, that can be used as reclamation targets in terms of desired proportion of area occupied by the various types and their hierarchical patterns that must be recreated on the reclaimed landscapes.

This was based on the assumption that landscape features are hierarchically organized, such that broad-scale features constrain

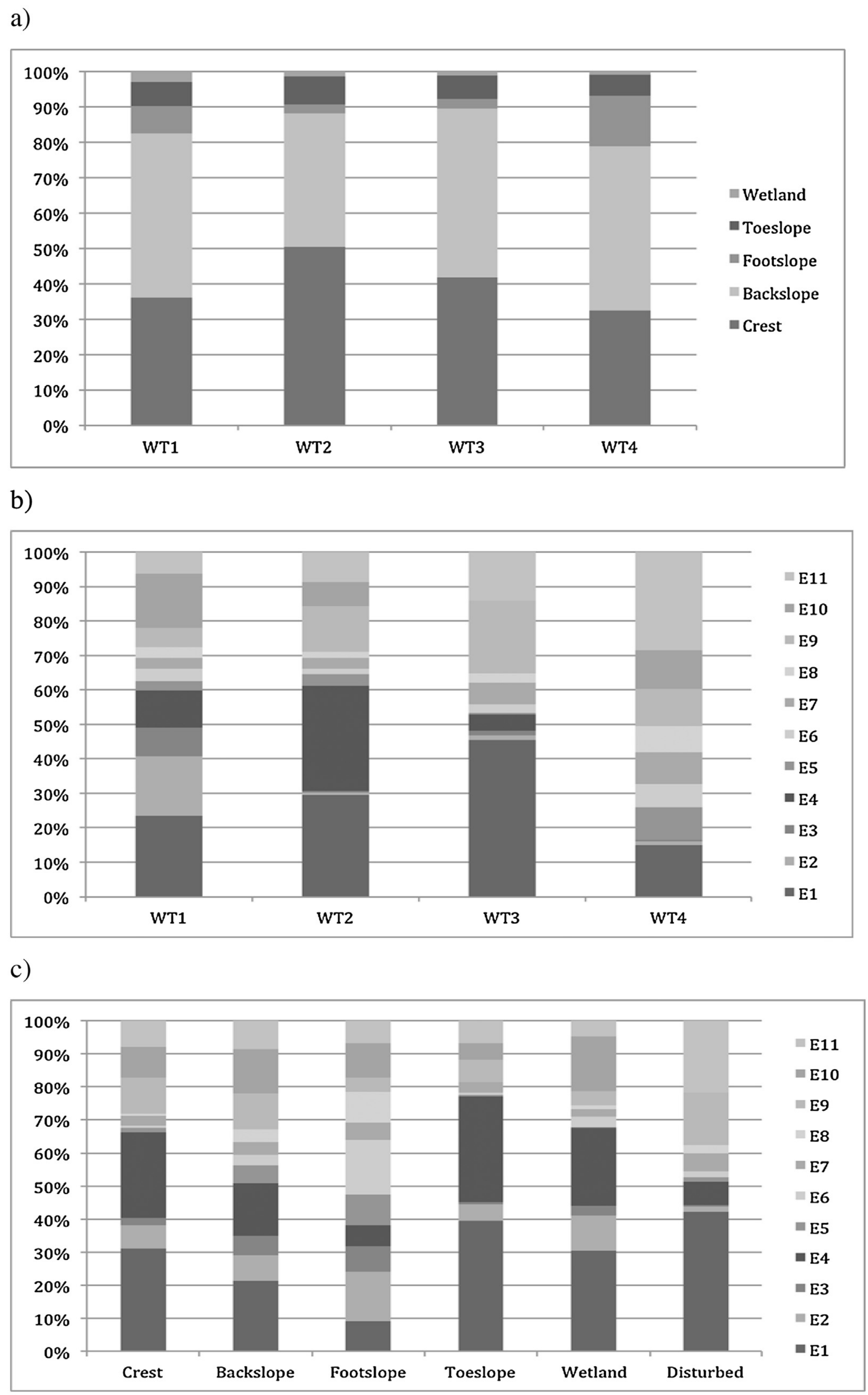

Fig. 3. Distribution of (a) landforms within watershed types, (b) ecosites within wastershed types and (c) ecosites within landforms.

the occurrence of local features and processes (Mackey et al., 2008), but also that local units interact to form specific larger-scale systems through the movement of materials and organisms (Marleau et al., 2014). The spatial patterns thus created are understood to support ecosystem functioning, biodiversity and ecological services. Therefore, our approach of classification based on biophysical metrics for the purpose of providing guidance and defining targets for reclamation after oil sands extraction is innovative in the sense that it emphasizes the scale-dependency of ecological structure and function, and the recognition that ecological units are spatial entities for which there are ecological consequences of their specific configuration (De Blois et al., 2002).

Automated methods of ecological classification, such as the one used here, differ from conventional human-based methods as they don't involve expert judgement for defining classes but are based solely on multidimensional environmental metrics to form distinct clusters, with automated user-defined rules for dividing units into clusters. Although considered more objective than manual methods as they ensure transparency and repeatability of results, they are not devoid of subjectivity. The choice of metrics for classification is dependent on the researcher (Serra et al., 2011), who also imposes some form of structure upon the data through the specification of the number of classes to be formed and the boundaries of the groupings, all of which can have impacts on the outcomes of the classification process (Bryan, 2006).

The chain of events for land reclamation at the cessation of oil sands mining starts with the preparation for landform reconstruction, with the end goal of providing a safe, stable, and nontoxic post-disturbance landscape (Audet et al., 2014). This involves heavy earthwork, with the overburden and processed tailings being configured for reconstruction of landforms, and the cover soils stocked-piled at the moment of clearing are redistributed across the post-mining landscape. Watersheds are increasingly serving as an organizing unit for assessing and managing human impacts on the environment; indicators at the watershed scale serve to provide organizing principles for prescribing effective management strategies and for developing regional scale monitoring and modelling efforts (Mayer et al., 2014). Recreating the character of the watersheds, their diversity and abundance on the landscape might be particularly important for ensuring the hydrological connectivity between terrestrial and aquatic systems, as well as connectivities related to seed dispersal and wildlife migration within the larger regional landscape, in the case of large-scale anthropogenic activities such as those seen in the oil sands operations.

Our results showed that watersheds are not random assemblages of landforms, but rather could be classified into distinct groups with specific features, even for a region with a generally flat or gently rolling topography. Slope, surficial deposits and aspect were key drivers of differences among the four watershed types, which are typical criteria for watershed classification (Jensen et al., 2001). Among types, we found a gradient from watersheds that had steep slopes and no organic deposit to those with low slope and an abundance of organic deposits, with all watershed types being more or less equally represented in the region. Dominant aspect (westerly or easterly) and changes in surficial deposits (glaciolacustrine/moraine, organic, glaciolacustrine/glaciofluvial, and fluvial/moraine) also contributed to differentiating watershed types. Ensuring that reconstructed landscapes reflect the types (in terms of frequency and distribution) of watersheds that previously existed is an essential regional-scale target in the Lower Athabasca region.

Despite the subtle topography, the primary importance of moisture regime in driving vegetation assemblages in the study area is reasonable given the dry, continental climate in central Alberta (Devito et al., 2012). The ecosite changes along the hillslope topographic features are consistent with observations by Bridge and Johnson (2000) in boreal mixedwood of Saskatchewan. Shallower hillslopes found on glaciofluvial substrates, transitioned from *P. banksiana* at the upper slope to *P. mariana* at the lower slope, while steeper hillslopes found glacial till transitioned from *P. tremuloides* at upper slope to *P. glauca* mid slope and *P. mariana* at the lower slope.

However, our results also show that there is 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. For example, no ecosite type represented more than 50% of a given landform; footslopes were characterized by an almost even distribution of all ecosite types (Fig. 3). This suggests that landscapes cannot be defined only in a qualitative manner on the basis of their average characteristics: they need to be defined by quantitative indicators that express the proportion occupied by each class of ecological units within the coarser units (De Blois et al., 2002). Moreover, site-level research has shown the primary importance of water and nutrient availability and salinity as driving factors of vegetation productivity in reclaimed areas of the Athabasca region (Duan et al., 2015); these drivers are all linked to larger-scale cycles and processes that are dependent on the surrounding matrix (Lei et al., 2016). The explicit effects of such spatial patterns on ecological processes such as forest productivity, water balance and biogeochemistry and on ecological services and biodiversity have been recognized and documented (Turner, 1989). It might represent one of the keys for successful site and landscape restoration (Shackelford et al., 2013); this would require, after landform reconstruction, that sufficient care is given to create heterogeneity within a given landform, notably in terms of soil texture and drainage so that a mosaic of ecosite conditions is created on relatively small scale. However, how this could be translated into concrete practices in the field remains to be seen, given that in most current land reclamation activities the bulk of financial resources are put on heavy, large-scale earthworks with no further major procedures applied afterwards (Audet et al., 2014). Nevertheless, assessment of the effects of various site-scale reclamation treatments (such as soil mixes, fertilisation, woody debris placement etc.) on plant community composition and growth (Pinno et al., 2016; Pinno and Errington, 2015; Pinno and Hawkes, 2015; Pinno et al., 2012) provide important insights for developing practices that can create the more subtle spatial patterns necessary to the creation of specific ecosites. This might be particularly important for ecosites showing rare natural occurrences on the landscape, such as ecosites 6 and 8, which are mesic medium ecosites mainly associated with backslopes (which are naturally abundant landforms).

Based on the PCA analyses, soil chemical properties appear not to play a large role in discriminating ecosites in this study. Other research in northern Alberta has shown that soil biogeochemical processes of this region are mostly driven by composition of the tree vegetation cover (Hannam et al., 2004; Quideau et al., 2013). In these forest ecosystems, biogeochemical cycling is shallow in the sense that it is more closely associated to the forest floor than to the underlying mineral horizons (Quideau et al., 2013) and therefore heavily influenced by inputs from leaf litterfall. Thus soil chemical properties in this region may be highly correlated to composition of tree cover and not represent a significant discriminating factor for ecosite definition. Tamminga et al. (2014) also found that despite large differences in vegetation composition, few statistically differences in chemical soil properties could be found between individual ecosite classes of Ontario's boreal forest classification. From a reclamation perspective, this would indicate that planning and monitoring indicators based on vegetation composition might be sufficient to encompass biogeochemical cycling and would be adequate proxy indicators for soil chemistry.

On the other hand, there might be significant variability of soil over relatively small areas, particularly on soils derived from the predominantly moraine and lacustrine deposits in central Alberta (Lesko and Lindsay, 1973); thus relevant soil properties might not be captured at the 250 m scale of the spatial layers used here. Furthermore, the soil properties layers used in this study were synthesized through interpolation of environmental proxies, principally topographic derivatives and are known to have large uncertainties (Mansuy et al., 2014). The quality and resolution of the digital layers is an important factor in accurate delineation of ecosite types. Although logical ecosite categories were derived using the 250 m resolution data available nation-wide, future research will assess if higher resolution data layers (<5 m–30 m) can assist in better delineating ecosite types. At higher resolution, automated methods might also be able to correctly identify ecological behaviour in transition zones (i.e. ecotones), which are often under-represented in ecological classification (McNab et al., 2015). Moreover, the classification used here was limited to using vegetation 'as is', and not potential vegetation as in provincial and national classifications. Therefore it does not capture the links between successional vegetation and climax or potential vegetation, because the influences of past land-use and disturbances are not taken into account. Expert-based ecological classification often uses potential or climax vegetation types in their nomenclature, which might encompass several different successional vegetation communities within the same ecosite type. Nevertheless, land reclamation targets in highly disturbed environments (such as those associated with oil sands mining in the Lower Athabasca) should not be based on exact ecological fidelity to the pre-disturbance environment (Audet et al., 2014; Drake et al., 2010; Quideau et al., 2013); potential, or climax, vegetation types might not make much sense is those disturbed environments anyway. Targets should rather be established based on the range of ecosystems that can be optimally supported by the post-disturbance environment, i.e. they will necessarily be engineered, or novel, ecosystems. The framework for rehabilitation of Drake et al. (2010) present as a first building block geotechnical work involving landform, parent material and climate/microclimate shaping to ensure stable coarse spatial units; it then moves up to re-establishment of water and nutrient cycling, and then to biological structure and composition at the site level. Therefore, an ecological classification that defines a hierarchy of biophysical metrics along gradients of moisture and nutrient regimes might provide a sufficient starting point for guiding reclamation.

Finally, recreating landscapes that can support diverse and self-sustaining forests regardless of end-use through the use of indicators that measure the achievement of this desired outcome is only one of the goals of successful reclamation. Consideration should also be given to the social and economic well-being and inclusion of local populations (Garibaldi, 2009).

5. Conclusion

Although superficially the landscape of the Lower Athabasca region seems homogeneous, the underlying geology and surface topography produce gradients of ecological conditions at the watershed, landform and ecosite scales resulting in unique assemblages of biophysical attributes that are indicators of land potential to sustain ecosystem functioning. 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. Moreover, 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. Understanding the small-scale processes that control landform assembly are important to understanding the patterns at regional landscape scale and to setting reclamation targets that take into account the natural ranges in variability in shape and structure. Given the extent of the landscape disturbances associated with oil sands mining, indicators and targets that also take into account the arrangement of coarse land units are all the more necessary.

On the other hand, reclaimed ecosystems may not develop according to natural toposequences that formed following fire or harvesting disturbance (Audet et al., 2014). Dramatic disturbance and replacement of subsurface substrates and soil will create a long legacy that will take time to equilibrate (e.g., sorting of sediments, settling, re-establishment of soil horizons and sub-surface hydrologic flows). However, creating the fundamental composition and shape of topographic feature landforms and that are connected to drainage network is the foundation for reclaiming higher order chemical (nutrient cycling) and biological (flora and fauna) processes and the ecological services they provide.

Acknowledgements

Funding for this project provided by the Canadian Forest Service of Natural Resources Canada. The authors also wish to acknowledge anonymous reviewers on previous versions of the manuscript.

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