A Methodology to Quantify the Topographic Characteristics of Wetland Landscapes

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be electronically available to the public.

Statement of Contributions

Dr. Derek Robinson is a contributing author to Chapter 2, which has been submitted for publication to the journal Landscape Ecology. I completed the majority of the data collection, analysis, and writing while Dr. Robinson provided conceptual guidance and editing.

Abstract

Topography underpins natural processes ranging from incident solar radiation at a location to overland flow and water pooling. Despite the influence of topography on natural processes and subsequent ecosystem function, especially in wetland ecosystems reliant on surrounding topography for water inputs, topography has not been adequately incorporated into reclamation planning and permit closure requirements. Instead, wetland restoration and reclamation projects are typically guided by simple height-to-length ratios that produce little variation or resemblance to natural wetlands. We present a methodology to quantify the topographic characteristics in wetland landscapes to guide the creation of naturally appearing and self-sustaining reclaimed wetland landscapes. Topographic characteristics in 3,434 1km^2 sample landscapes were quantified using terrain roughness and landform element composition and configuration. A large set of metrics were reduced to a parsimonious subset that was applied across three natural regions and a gradient of disturbance. Nonparametric statistical tests were used to compare landscapes across these two dimensions. We found that landscape-scale topographic characteristics can be represented by five roughness metrics and seven landform element pattern metrics. These metrics demonstrate that surface roughness and landform element patterns significantly differ among natural regions and that high disturbance landscapes significantly differ from other disturbance levels. Wetland reclamation plans should replicate the topographic characteristics found in the surrounding natural landscape. To do so, topographic characteristic benchmarks are required for reclamation design and regulatory approval of closure permits. The presented methodology and resulting metric values can be used as a step towards achieving this goal.

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Chapter 1 Introduction and Background

1 Introduction

Ecosystem restoration and reclamation are practised by resource managers to either improve the function of an ecosystem that has been degraded or recreate a naturally functioning ecosystem at a location where anthropogenic disturbance has altered the structure of a landscape and topographic characteristics need to be re-created (Nwaishi et al. 2015, Burton 1991). Wetlands have been a significant focus of restoration and reclamation projects (Wortley et al. 2013) and, despite the ecosystem services that wetlands provide (e.g., habitat for a wide variety of species Klemas 2013, Mitsch and Gosselink 2000, storm water mitigation from severe hydrologic events, improved water quality, Mitsch and Gosselink 2000), are experiencing a rate of destruction that exceeds the rate of restoration or reclamation (Hiraishi et al. 2014).

It is difficult to guarantee the success of wetland reclamation projects (Wortley et al. 2013) and not all reclamation projects result in healthy wetlands (e.g., Kauffman-Axelrod and Steinberg 2010, White and Fennessy 2005). Unsuccessful wetland reclamation projects can be caused by only focusing on wetland biota without considering the underlying hydrology and topography that exist in a region (Kauffman-Axelrod and Steinberg 2010), or by attempting to create ecosystems in locations that do not have the surrounding ecological features necessary to support healthy ecosystem function (White and Fennessy 2005). Previous research on wetland reclamation focussed on an individual wetland being reclaimed, or the wetland-scale (e.g., Newcomer et al. 2013, Price et al. 2010), without integrating reclamation with the broader landscape (Rooney et al. 2015). Wetland reclamation projects need to consider not just the individual wetland site but also the site’s integration with the surrounding ecological landscape (Kauffman-Axelrod and Steinberg 2010).

To undertake successful wetland reclamation, it is important to understand how natural topographic characteristics impact wetland function. Topography is a driver of wetland function and impacts a wetland’s resistance to inter-annual climatic variability since the position of a wetland within a landscape directly influences the source and amount of water (Mitsch and Gosselink 2007, Los Huertos and Smith 2013, Zhou et al. 2008) and dissolved nutrients it receives (Cohen et al. 2015, Piehler and Smyth 2001). For example, a wetland located in a regional topographic depression would likely have a larger influx from overland water flow than a wetland on a local topographic high, whose water input may be dominated by precipitation (Mitsch and Gosselink 2007). Regional geologic and hydrologic systems can influence the relationship between topography and wetland hydrologic inputs (Hayashi et al. 2016), such as when geographically isolated wetlands become connected to a regional hydrologic system (Rains et al. 2015) through a fill and spill mechanism, where wetlands fill with water following large rainfall events and subsequently spill water that runs downstream to an adjacent wetland (Shaw et al. 2012, Rains et al. 2015).

A landscape is not a precisely defined spatial unit and is broadly defined in landscape ecology as a region that has spatially heterogeneous variables of interest (Wu, 2013), which would vary by study and scale of interest. A wetland landscape would be one that includes a wetland ecosystem as well as surrounding land that influences that ecosystem. A landscape-scale is therefore a scale of analysis that is focussed on an entire landscape to understand the processes that occur between spatially heterogeneous variables of interest.

Understanding the topographic characteristics of wetland landscapes is a necessary component towards improving the design of wetland reclamation projects but requires a method to quantify topography across a landscape. The following sections within this chapter overview existing methods to quantify topography and highlight two key methods that can be applied to a landscape-scale: terrain roughness and landform classification. Finally, a description of the wetlands within my study area is given along with the current state of wetland reclamation before providing a framework for the rest of the thesis.

1.1 Terrain Analysis

Topographic variation within a landscape can be used to predict and model a variety of environmental variables such as: soil depth; soil type (Florinsky et al. 2002, Grabs et al. 2009); permafrost slope disturbances (Rudy et al. 2016); soil moisture content (Murphy et al. 2011); snow depth (Lapen and Martz 1996); and potential for ecosystem restoration (Herzog et al. 2001, Kauffman-Axelrod and Steinberg 2010). Individual measurements of topography, known as terrain metrics, are often used as inputs when predicting and modelling hydrologic patterns and flow regimes using GIS (Hengl and Reuter 2009) and are used to define the boundary and area of watersheds (Wilson and Gallant 2000). While terrain metrics have been adapted to predict soil moisture (Murphy et al. 2011), they have yet to be applied to wetland ecosystems (e.g., Ågren et al. 2014, Florinsky et al. 2002, Grabs et al. 2009) or to predicting hydric, gleysol soils commonly associated with wetland ecosystems (Keddy 2010).

Spatially analysing topographic characteristics is referred to as terrain analysis (Wilson and Gallant 2000) and literature on terrain analysis was reviewed to determine the most frequently used terrain metrics. While it is possible to classify terrain metrics based on a variety of factors, here I classify them into primary terrain metrics and secondary terrain metrics. Primary terrain metrics are calculated directly from elevation data and typically describe a static characteristic of a landscape (Olaya 2009, Appendix 1, Table 1.1). Secondary terrain metrics are a function of one or more primary terrain metrics and typically describe a process occurring in the landscape (Lang et al. 2013, Appendix 2).

1.1.1 Primary Terrain Metrics

Primary terrain metrics are commonly calculated for research in a variety of disciplines as the basis for secondary terrain metrics (Olaya 2009) and for their significance to ecosystem function and geophysical processes (Appendix 1, Table 1.2). Many of the primary terrain metrics are related to the first derivative of elevation, slope. Slope describes the gradient of the land surface and can be represented mathematically by the rate of change in the elevation surface. Slope can be used to estimate the rate of overland flow across a landscape and contributes to the estimation of a variety of geophysical processes, including the distribution of vegetation and soil moisture content (Wilson and Gallant 2000). A sudden change in slope, or break, occurs when a steep downward slope abruptly changes to a flat or rising slope. Regions of slope breaks can cause the water table to rise above the ground surface and produce an outflow of groundwater to the surface layer, which maintains localized soil saturation, creating a slope wetland ecosystem (Stein et al. 2004).

Change in slope, or the second derivative of elevation, is measured to describe changes in speed and direction of surface flow (Olaya 2009). Change in slope measures how convex or concave a slope is and is measured using three primary terrain metrics: plan curvature, measured perpendicular to the slope for a horizontal cross-section; profile curvature, measured parallel to the slope for a vertical cross-section, (Ågren et al. 2014, Fig 1.1); and the combination of these two metrics in what is known as mean curvature (Florinsky et al. 2002, Buckley 2010). Plan curvature influences convergence or divergence of surface flow, which can influence the path of overland flow and the distribution of soil moisture, while profile curvature influences the acceleration or deceleration of overland flow and erosion rates (Wilson 2012).

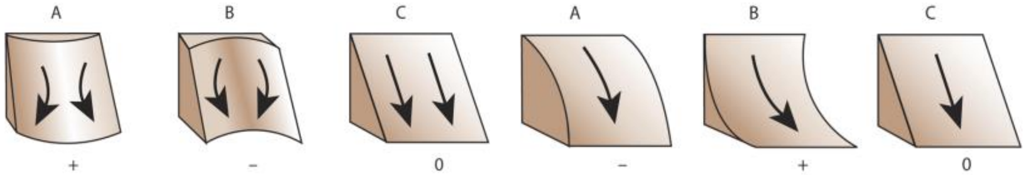


Fig 1.1 Plan curvature illustrated in left three scenarios, A shows convex (+), B shows concave (-), and C shows planar (0) plan curvature. Profile curvature illustrated in right three scenarios, A shows convex (-), B shows concave (+), and C shows planar (0) profile curvature. Copied from Buckley, 2010.

Spatial direction of elevation change is calculated using aspect, a primary terrain metric, and is often one of the first terrain metrics calculated when analyzing a surface through terrain analysis (Ågren et al. 2014, Olaya 2009). Calculating a slope's aspect determines the azimuth angle of the slope, which is measured in degrees clockwise from north (Olaya 2009). The aspect value provides a researcher with the cardinal direction that a particular slope is facing, which can be used to estimate geophysical elements of the ground surface such as the direction of water flow (Wilson 2012) and incident solar radiation, which affects the surface's sensible and latent heat flux, evapotranspiration rates, and subsequently the distribution of flora and fauna (Wilson 2012).

Terrain metrics can also be used to quantify and describe hydrologic processes across the Earth's surface. For example, the path that water flows after falling on a landscape can be estimated by using a flow routing terrain metric. Flow routing is a required input for the calculation of other terrain and hydrologic metrics, such as flow accumulation, flow path length (Gruber and Peckham 2009), depth to water index (Murphy et al. 2007), and topographic wetness index (Grabs et al. 2009). The path of overland flow directly influences the presence and location of saturated soil and, in turn, the location of wetland ecosystems (Murphy et al. 2007).

Primary terrain metrics are well-established topographic measurements that have clear relationships with ecological and physical processes (Appendix 1, Table 2) but describe elevation changes along a single hillslope, which limits their applicability to only site-specific analyses or to measuring terrain metrics at single points across a landscape. Due to these spatial extent restrictions, primary terrain metrics on their own have limited utility when the scale of interest is an entire landscape, whereas secondary terrain metrics are more applicable.

1.1.2 Secondary Terrain Metrics

Secondary terrain metrics attempt to quantify active physical processes occurring at a landscape-scale, particularly hydrological or meteorological processes, and are based on one or more primary terrain metrics (Lang et al. 2013, Wilson and Gallant 2000). Two frequently used secondary terrain metrics, the topographic wetness index and the depth to water index, describe soil saturation and the presence of wet areas, which can be used to estimate the location of wetlands across a landscapes (Lang et al. 2013, Murphy et al. 2011).

Topographic wetness index has been used to estimate areas of saturated soils across a region based on landscape-scale elevation data (Lang et al. 2013, Quinn et al. 1995). Regions that have a higher topographic wetness index are likely to be more saturated than surrounding regions with a lower value (Lang et al. 2013), which has led to the metric being used to estimate the spatial distribution of wetland features (Grabs et al. 2009). The topographic wetness index is based on an assumption that the study site has steady-state conditions and homogeneous soil transmissivity (Gruber and Peckham 2009). While soil transmissivity would not be constant across all landscapes, the impact of this assumption would change based on the location of the study. For example, research focussed on a small enough geographic scale, or in a region with uniform soil properties, may not have large changes in soil properties across the extent of the study site (Lang et al. 2013), which would not hold true for this thesis, since the study area is dominated by glacial till and would not have homogeneous soil transmissivity across the study extent (Natural Regions Committee 2006).

Depth to water index has been used in terrain analysis for estimating stream location (White et al. 2012), quantifying soil drainage (Murphy et al. 2011), and determining the spatial distribution of saturated soil (Ågren et al. 2014). Depth to water was developed as a response to the assumptions of the topographic wetness index and has been shown to outperform the topographic wetness index in Alberta (Murphy et al. 2009, Murphy et al. 2011) and New Brunswick (Murphy et al. 2007). The topographic wetness index and depth to water are frequently used in tandem for terrain analysis of saturated soils and researchers will often calculate both metrics to determine which is better suited for their unique study area and research goals (Ågren et al. 2014, Murphy et al. 2009, Murphy et al. 2011, White et al. 2012).

1.2 Analyzing Continuous Spatial Data

Primary and secondary terrain metrics have been developed with the goal of improving our understanding of the relationship between topographic characteristics and a variety of environmental variables (Florinsky 2012). These relationships are typically quantified by measuring terrain metrics along a transect (Murphy et al. 2011) or by correlating individual terrain metric values with associated ecological point data (Lapen and Martz 1996). However, in cases where relating topography with an environmental variable is not the goal, a landscape's continuous topographic variation and characteristics still need to be quantified but do not have the benefit of relating multiple topographic metrics to a common known variable. The difficulty in quantifying the characteristics of a landscape's continuous topography has been well documented (Deng 2007, MacMillan et al. 2000, Burrough et al. 2000, Wood 1996) but limited methods have been used to quantify topography across a continuous surface (Grohmann et al. 2011, Tagil and Jenness 2008).

A major research gap exists in quantifying and characterizing continuous landscape-scale elevation data and I adapted two existing secondary terrain metrics to quantify the topography of wetland landscapes, roughness analysis and landform element classification. To further quantify the classified landform elements, I calculated landscape metrics to describe the spatial composition and configuration of landform elements. The following section will provide an overview of these selected techniques.

1.2.1 Quantifying Landscape Roughness

A landscape that is topographically rough (i.e., has greater elevation variation) has been demonstrated to impact species richness (Hofer et al. 2008), vegetation growth patterns, and wildlife behavior (Nellemann and Fry 1995). High species richness is an important characteristic of ecosystems that are resistant to disturbance (Hofer et al. 2008, Nellemann and Fry 1995), which suggests that designing heterogeneous landscapes that mimic natural surface roughness can improve the success rate and ecological stability of reclamation projects.

Two types of measurements can be used to quantify a topographic surface, the previously discussed terrain metrics, such as slope, and statistical metrics, such as the standard deviation of elevation or slope (Olaya 2009). Statistical metrics are used to describe elevation variability and terrain roughness due to their applicability to any type of continuous grid data (Olaya 2009). Statistical metrics do not originate in terrain analysis research as terrain metrics do, instead, existing statistical measurements of variability, such as standard deviation, skewness, or range, were adopted to describe elevation variability (Grohmann et al. 2011).

Application of statistical metrics, referred to as terrain roughness metrics herein, are frequently divided between calculating the roughness of a single slope profile and calculating the roughness of an entire landscape (Olaya 2009). Profile-based metrics, while useful to quantify surface roughness along a slope transect, would not translate well to the landscape-scale. In total, 8 terrain roughness metrics that could be calculated at the landscape-scale were found through a literature review: standard deviation of slope, profile curvature and elevation, deviation from mean elevation, vector dispersion, topographic position index, 2D:3D area ratio, and slope variability.

Terrain roughness metrics are calculated to understand topographic drivers of environmental processes (e.g., Florinsky 2012, Hofer et al. 2008, Shaw et al. 2013) and can be used to compare the roughness of different landscapes, but these metrics do not describe the spatial pattern of topography within a landscape (McGarigal et al. 2012). The following section outlines how a landscape can be discretized into individual landform elements to characterize the spatial pattern of topography.

1.2.2 Landforms and their Classification

Landforms are broadly defined as topographic features that have similar topographic characteristics and consistent relationships with environmental variables (MacMillan and Shary 2009) such as soil type (Milne 1947, Hugget 1975, MacMillan et al. 2000), soil erosion (Kheir et al. 2007, Martin-Duque et al. 2010), and water distribution (Summerell et al. 2005). Classifying landforms has allowed terrain analysis researchers to characterize the topography of the Earth’s surface and overcome the difficulty of describing continuous elevation data (Burrough et al. 2000, MacMillan and Shary 2009) by converting continuous and ratio data about elevation into spatially continuous nominal data (Evans 2012, MacMillan and Shary 2009).

Landforms are highly dependent on spatial scale, which impacts the type of landforms that are defined (MacMillan and Shary 2009). For example, continental-scale classification may classify mountain, plain, and valley landforms (Schmidt and Hewitt 2004), whereas an ecosystem-scale classification may classify hummock or hollow landforms (Nagamatsu and Miura 1997). Clearly defining the landform classification scale is important since landforms at a larger scale do not capture topographic variation at finer scales (i.e., hummock landforms would be lost after classifying a region as a mountain) and may only conceptually incorporate the larger landform structures in which the classification is nested (i.e., a small-scale hummock landform may be conceptually located within a large-scale plateau landform) (MacMillan and Shary 2009). To differentiate between the different types of landforms at varying scales, I define landforms that occur along a single hillslope, such as a shoulder or footslope, as landform elements.

Within terrain analysis there are two unique landform classification techniques and methodologies, rule-based landform classification where classes are defined exactly (i.e., expert system, Fig 1.2) and fuzzy threshold landform classification, with the latter subdivided into supervised and unsupervised landform classification (Hengl and MacMillan 2009, Fig 1.2).

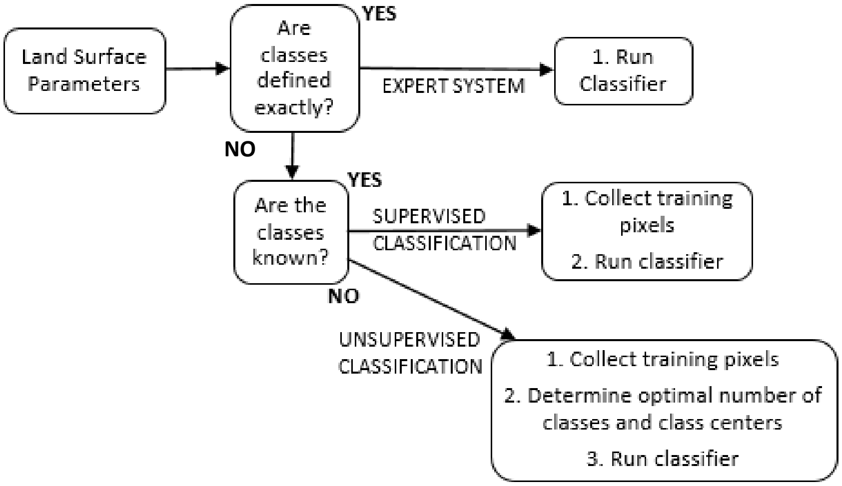


Fig 1.2 Overview of process to select landform classification methodology, primarily divided between expert classification system and fuzzy threshold classification, copied from Hengl and MacMillan 2009

Rule-based landform classification requires expert knowledge of landform types and is based on associating explicit primary terrain metric ranges with each landform type (Pennock et al. 1987). Defining the explicit terrain metric ranges is up to the researcher and multiple landform classification rules have been developed to fit unique situations. For example, a classification rule set for prairie landscapes defines 7 landform elements that occur along a hillslope but does not differentiate between crests or depressions in the landscape (Pennock et al. 1987). Further research extended the original 7 classes into 11 classes by defining flat landform elements located high or low in a catchment as well as three landform elements with linear plan curvature (e.g. planar) (Reuter et al. 2006, Fig 1.3). However, if an existing classification rule set cannot be applied to a study area, fuzzy threshold landform classification can be used to generate landform elements.

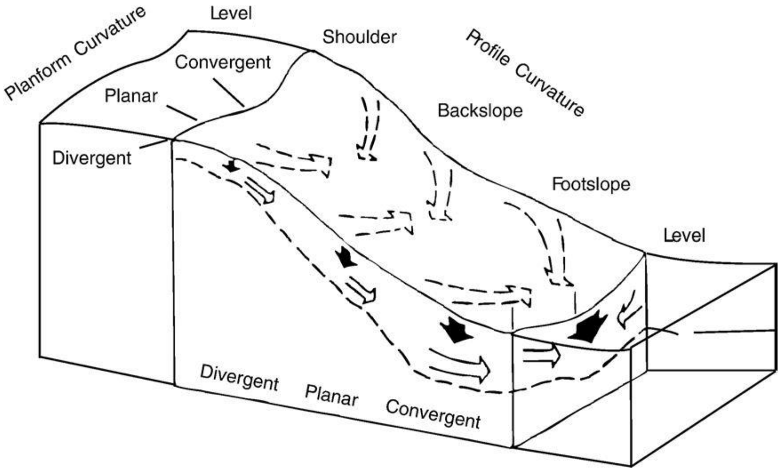


Fig 1.3 Landform elements along a hillslope, dashed arrows illustrate conceptual overland flow while solid arrows show groundwater flow. Arrow size is related to potential volume of flow. Copied from Reuter et al. 2006

Fuzzy threshold landform classification uses clustering algorithms and machine learning to classify landforms without requiring discrete terrain metric classification rules. Two key types of landform classification can be performed: supervised classification where known landform features are used to train the classifier, and unsupervised classification where a clustering algorithm generates a defined number of landform classes based on how terrain metric values cluster in different locations (Drăguţ and Blashke 2006, Hengl and MacMillan 2009).

Terrain metric clustering is performed using a clustering algorithm (e.g., fuzzy k-means clustering algorithm, MacMillan et al. 2000) to delineate a set number of landform elements based on spatial locations that have similar terrain metric values. The selection of terrain metrics in fuzzy landform classification, and the total number of metrics used, have significant impacts on the final landform classification output (Deng and Wilson 2006). The clustering output also needs to be interpreted by creating geophysical descriptions for each landform element or by defining landform classification rules after the landforms have been classified (MacMillan et al. 2000, Table 1.1).

Table 1.1 Landform elements and associated terrain metric value ranges defined in MacMillan et al. (2000)

Slope Category	Landform elements	Slope (%)	Profile Curvature (deg/100 m)	Plan Curvature (deg/100 m)
Upper Slope	Level Crest	0-2	-10 – 10	--
	Divergent Shoulder	>2	> 10	--
	Upper Depression	0-2	< -10	< -10
Mid-Slope	Backslope	>2	-10 – 10	-10 – 10
	Divergent Backslope	>2	-10 – 10	> 10
	Convergent Backslope	>2	-10 – 10	< -10
	Terrace	0-2	-10 – 10	--
	Saddle		< -10	> 10
	Midslope Depression	0-2	< -10	< -10
Lower Slope	Footslope	>2	< -10	--
	Toeslope	>2	-10 – 10	-10 – 10
	Fan	>2	-10 – 10	> 10
	Lower slope mound	>2	> 10	> 10
	Level lower slope	0-2	-10 – 10	-10 – 10
	Depression	0-2	< -10	< -10

1.2.3 Landscape Metrics

Landform element classification describes the topographic characteristics of a landscape, converting elevation data from continuous ratio data to nominal data classes, but it does not inherently quantify the topographic spatial pattern across multiple landscapes. Landscape metrics are measurements used in landscape ecology to quantify the spatial composition and configuration of discrete environmental patches at a landscape-scale (Cushman and Huettmann 2010). Although landscape metrics have been suggested for terrain analysis (Pike 2000, Olaya 2009), they have not previously been applied to quantify the spatial pattern of landform elements within a landscape.

Landscape metrics have measured the spatial pattern of land use to quantify the relationship between land use and water quality (Moreno-Mateos et al. 2008), habitat structure (McGarigal 2012), distribution and behaviour of organisms (Cushman and Huettmann 2010), and to broadly understand how landscape structure interacts with ecological processes (Wu et al. 2000). However, little research has been conducted on determining the utility of using landscape metrics for quantifying surface elevation at a landscape-scale and relevant research has only focused on determining how surface topography can be used to improve the accuracy of typically 2-

dimensional landscape metrics (e.g., Zhiming et al. 2012, Hoechstetter et al. 2008). Chapter 2 will use landscape metrics to quantify the spatial composition and configuration of landform elements in wetland landscapes.

1.3 Wetland Ecosystems

Wetlands are broadly defined as ecosystems where the soil is permanently saturated or saturated for most of the year, which creates primarily anaerobic soils (Keddy 2010). Under this broad definition, multiple types of wetlands can be defined, and wetland classification systems are typically defined for specific ecoregions. For example, wetlands in Alberta, Canada are grouped into five classes: bogs, fens, marshes, shallow open water, and swamps, which are further subdivided by vegetation type and annual water permanence (ESRD 2015).

A unique wetland occurs in the Prairie Pothole Region of central North America, which extends from Iowa in the south to central Alberta in the north, spanning three provinces and five states with an aerial extent of 750,000 km^2 (Zhang et al. 2009). This region is characterized by prairie pothole wetlands that form in thousands of small pothole depressions created during the last glacial retreat with an average wetland size of 1600 m^2 (Huang et al. 2011). Pothole wetlands are hydrologically isolated and receive most of their hydrologic input from seasonal snow-melt runoff (Fang and Pomeroy 2008, Hayashi et al. 1998, Winter and Rosenberry 1998). Due to their hydrologic isolation, pothole wetlands are highly sensitive to climatic variability (Zhang et al. 2009, Winter and Rosenberry 1998) and experience seasonal hydrologic cycles where the wetland fills with spring snow melt before the water slowly evaporates during the summer (van der Kamp and Hayashi, 2008). This cycle of annual water permanence can be used to further categorize pothole wetlands based on a wetland’s seasonal fluctuation in water availability (Stewart and Kantrud 1971, Table 1.2). While the Boreal region of Alberta is dominated by peatlands, as opposed to the pothole wetlands in the Parkland and Grassland regions, the southern Dry Mixedwood subregion of the Boreal included in this study is cultivated for the majority of its region and has similar physiography to the Grassland and Parkland, mainly undulating plains and hummocky uplands with primarily glacial till soils (Natural Regions Committee 2006).

Table 1.2 Summary of marsh wetland permanence types specific to prairie pothole wetlands (Stewart and Kantrud 1971)

Name	Description
Temporary	Wetlands where water is usually retained for only a brief period in the early spring
Seasonal	Wetlands with water persisting for more than three weeks, have a higher water table than temporary wetlands
Semi to Permanent	Wetlands with standing water throughout the year, except during extreme drought. Often adjacent to open water.
Open Water	Permanent open-water regions that are larger than 0.2 hectares
Alkali	Wetlands with a variable temporal range of still water and has a salt crust

1.3.1 Wetland Reclamation and Existing Guidelines

Topography is a key consideration when designing landscapes for wetland reclamation (e.g., Kauffman-Axelrod & Steinberg 2010, Martin-Duque et al. 2010, Thiffault et al. 2017, Ayres et al. 2006) since topography is the natural structure that drives many ecological functions associated with wetlands (e.g., water inputs, van der Kamp and Hayashi 2008). Recreating natural topographic variation is an important component of wetland reclamation when the natural topography has been completely removed due to human disturbance (Martin-Duque et al. 2010) and natural topographic baseline conditions need to be defined to provide reclamation planners with clear guidelines to mimic natural landscapes.

Landscape-scale reclamation is a complex and difficult undertaking and no standard or reference condition exists to design landscapes that mimic the natural topography of similar ecological landscapes (Martin-Duque et al. 2010). Basing reclamation plans on natural topographic landforms would maintain natural aesthetics within the landscape (McKenna 2002) and limit erosion and decrease sediment runoff whereas unnatural landforms are more likely to undergo slope failure and increased sediment runoff (Ayres et al. 2006, Martin-Duque et al. 2010).

Although current policy guidelines recommend that reclamation plans mimic natural topographic characteristics (CEMA 2014), existing wetland design guidelines do not define natural topographic features and are typically limited to basic height-to-length ratios for slopes surrounding a wetland (typically 2:1 or 3:1, Fig 1.4, Green Plan Ltd 2014), a range of length-to-width ratios for the wetland dimensions (2:1 < L:W < 4:1, CH2MHILL, 2014) and loosely defined ‘irregular shorelines’ for the wetland itself (Green Plan Ltd 2014). Current reclamation designs lead to landscapes with evident anthropomorphic history and do not successfully mimic natural topographic characteristics (Ayres et al. 2006, Martin-Duque et al. 2010).

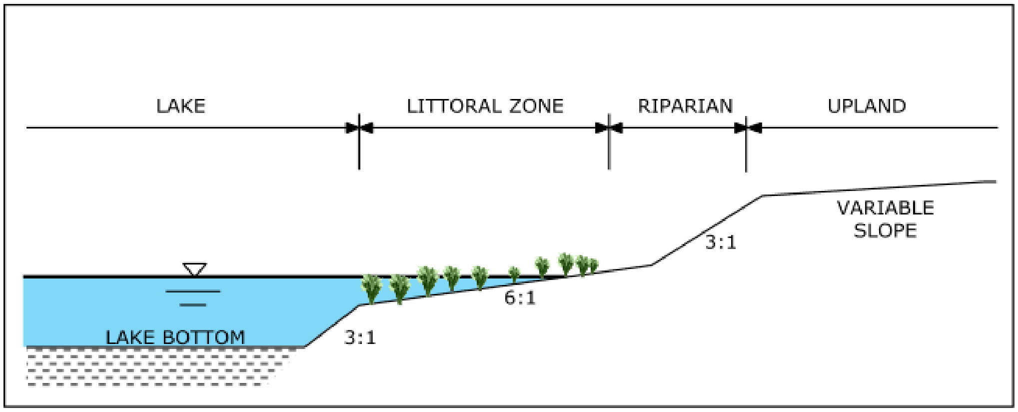


Fig 1.4 Example profile of a constructed wetland in existing guidance documents, where ratios refer to the slopes surrounding a wetland (Green Plan Ltd 2014)

If wetland landscape reclamation designs are to achieve a naturally appearing and naturally functioning landscape, topographic characteristics of natural landscapes need to be quantified to create a baseline for future landscape design guidelines.

2 Thesis Framework

Chapter 2 develops a methodology to statistically compare and quantify continuous elevation data at a landscape-scale using terrain roughness, landform element classification, and landscape metric analysis. The research develops these methods while answering the question "to what degree do topographic characteristics and variation in elevation differ by natural region and along a gradient of human disturbance?" Apart from my first goal of defining a clear method of analyzing continuous elevation data at a landscape-scale, a second goal is to define baseline topographic characteristics to improve the understanding of wetland landscape topography and improve the design of future wetland landscape reclamation projects. Chapter 3 extends the results of Chapter 2 by situating the results within existing research on landscape ecology and terrain analysis, describes how the research is useful for environmental policy development, and suggests future research directions.

Chapter 2 A Methodology to Quantify the Topographic Characteristics of Wetland Landscapes

1 Introduction

Characteristics of the surface of Earth (e.g., slope, aspect) and variation in elevation affect erosion (Martin-Duque et al. 2010), hydrology (Los Huertos and Smith 2013), and other natural processes that subsequently influence the distribution of biotic communities across local-to-regional landscapes (Hofer et al. 2008; Nellemann and Fry 1995). Through terrain analysis (Wilson and Gallant 2000; Hengl and Reuter 2009), topographic characteristics and variation in elevation are quantified to better understand how topography and landform elements underpin natural processes and the spatial distribution of ecosystems.

Wetland ecosystems are an archetype of natural systems often reliant on surrounding topography for water inputs (Los Huertos and Smith 2013). These ecosystems provide a range of services that include: habitat for a diverse range of species (Mitsch and Gosselink 2007), environmental regulation including storm water mitigation and water purification, and carbon sequestration (Zedler and Kercher 2005). Despite the benefits of wetland ecosystem services, global wetland loss is estimated at 64 – 71 % since 1900 AD (Davidson 2014) and these ecosystems are difficult to restore back to natural biological structure and function (Moreno-Mateos et al. 2012).

Ecological restoration is practiced to restore important ecosystem services to a region, of which wetlands have been a prevalent focus (Wortley et al. 2013). However, it is difficult to assess the success of restoration projects (Wortley et al. 2013) and not all projects result in healthy wetlands (Kauffman-Axelrod and Steinberg 2010) or even functional wetlands (Moreno-Mateos et al. 2012). Unsuccessful restoration projects often occur by focusing on restoring wetland biota without considering the underlying hydrology and terrain conditions (Kauffman-Axelrod and Steinberg 2010). Similarly, wetland restoration focused on individual wetlands, i.e. at the wetland scale (e.g., Newcomer et al. 2013), is likely to fail when it is not integrated into the broader landscape (Van Meter and Basu 2015).

The success of restoration projects is dependent on the degree to which the restored wetland function is integrated with the surrounding landscape (White and Fennessy 2005). A driver of wetland function is the underlying topography of the landscape as it affects hydrological processes and water availability (Los Huertos and Smith 2013). For example, the topographic position (e.g., toeslope or depression) of a wetland within a landscape can influence the source (overland flow, ground water flow, or precipitation) and amount of water received (Mitsch and Gosselink 2007). However, topography is not the only driver of wetland hydrology; soil type and associated infiltration rates (Conly and van der Kamp 2001, Hayashi et al. 1998) as well as established vegetation and associated evapotranspiration rates (Hayashi et al. 1998) can also impact the amount of water that a wetland receives and retains throughout a given year (Hayashi et al. 1998).

Where topography and ecosystems have been degraded by anthropogenic disturbance, restoration to a state identical to that which existed prior to disturbance can be an unachievable goal (Suding 2011; Rooney et al. 2015). In such cases, reclamation as opposed to restoration may represent a more attainable objective, whereby active intervention may return the wetland to a stable, productive and self-sustaining state, even if it does not resemble the pre-disturbance state (Vitt and Bhatti 2012). Reclamation commonly involves recontouring the land, commonly with the intention of reducing erosion and promoting slope stability (SER 2002). The movement of soil to reshape the landscape can also improve ecosystem function and integration with adjoining land at locations where the landscape has been completely altered and degraded (Burton 1991), as degradation typically results in the loss of topographic heterogeneity. However, reclamation guidelines for wetlands typically advise for the creation of gentle slopes surrounding a wetland at a 2:1 or 3:1 height-to-length ratio and irregular shorelines for the wetland itself (e.g., Appendix 3). These guidelines lead to the homogenization of wetland landscapes with evident anthropomorphic history that lack natural topographic variation and pattern. Instead, wetland reclamation guidelines should provide design criteria based on natural variability in topography and encourage the creation of mature landform elements that mimic natural conditions, limit erosion, and decrease sediment runoff (Martin-Duque et al. 2010). By implementing mature landforms, reclaimed landscapes can establish natural channel and surface morphology that have a greater resistance to erosion from precipitation and discharge events thereby avoiding expensive, continuous maintenance and regrading (Martin-Duque et al. 2010; McKenna 2002).

While the reference condition approach has been used to create benchmarks for indicators of biological integrity (Bailey et al. 2004), river restoration (Nestler et al. 2010), and the composition and configuration of land cover (Evans et al. 2017) to evaluate the health of ecosystems and guide ecosystem reclamation and regulations (Stoddard et al. 2006), no benchmarks have been established for topographic characteristics or variation. The adoption of topographic benchmarks by reclamation planners would increase the potential for designed landscapes, with diverse topographic features, to integrate with the surrounding natural landscape, be naturally appearing and self-sustaining, and lead to successful reclamation.

To improve our understanding of the relationship between wetlands and their surrounding landscapes and to assist resource managers and policy makers in reclaiming wetland ecosystems, I quantified the spatial pattern and characteristics of topography within wetland landscapes to answer the question: to what degree do topographic characteristics and variation in elevation differ by natural region and along a gradient of human disturbance?

2 Methodology

2.1 Study Area

Wetlands have been decreasing in number and areal extent globally (Davidson 2014) and Canada is no different (Ducks Unlimited Canada 2008). Within Canada an estimated 70 % of wetlands have been lost (Ducks Unlimited Canada 2008) and the Prairie Pothole Region, a geographical zone characterized by small, frequent depressions in the ground surface that includes the southern portion of the Province of Alberta (Shaw et al. 2013), has experienced wetland consolidation from agriculture and a loss of approximately 90 % of historic wetland area (Van Meter and Basu 2015). To ameliorate wetland loss, the Government of Alberta has developed the ‘Water for Life’ action plan, with one among several goals of ensuring healthy aquatic ecosystems, which requires the conservation and restoration of Alberta’s wetlands through an improved understanding of wetland functions (Alberta Environment 2003; Alberta Water Council 2008).

The research is situated within the Grassland, Parkland, and Dry Mixedwood subregion of the Boreal natural regions of Alberta, Canada, and more specifically within two wetland inventories that cover 27.8 percent of the province (Fig 2.1). The inventories are located within the more populated southern and central regions of the province, which is dominated by the Prairie Pothole Region of North America. This region is dominated by palustrine wetlands that are reliant on seasonal snow melt as a primary water input (Shaw et al. 2013) but can become connected to a regional surface water network through a fill and spill mechanism that occurs when a geographically isolated wetland fills with water and spills over, generating runoff that can flow into a downslope wetland, thereby connecting these depression wetlands to the local hydrologic system (Shaw et al. 2012).

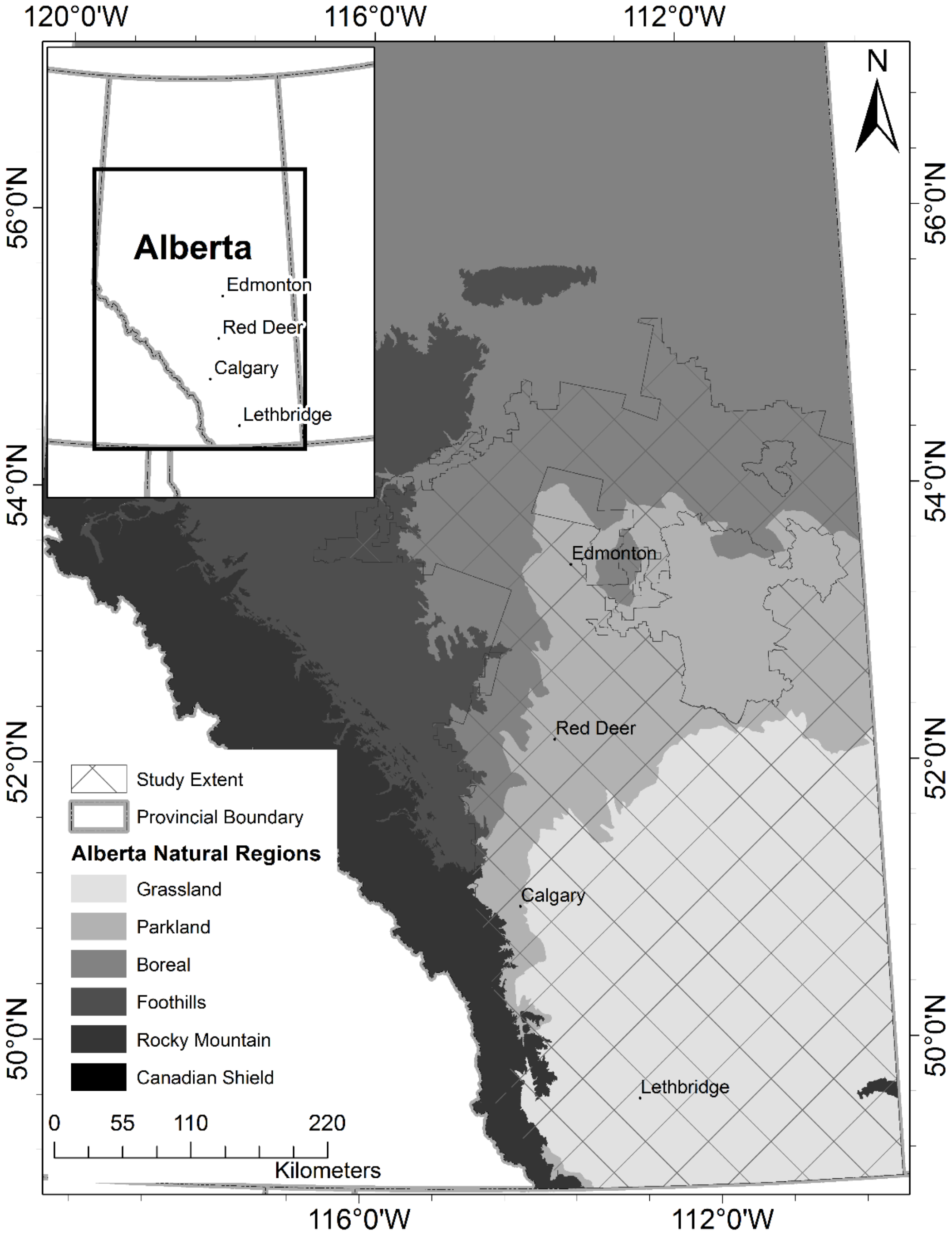
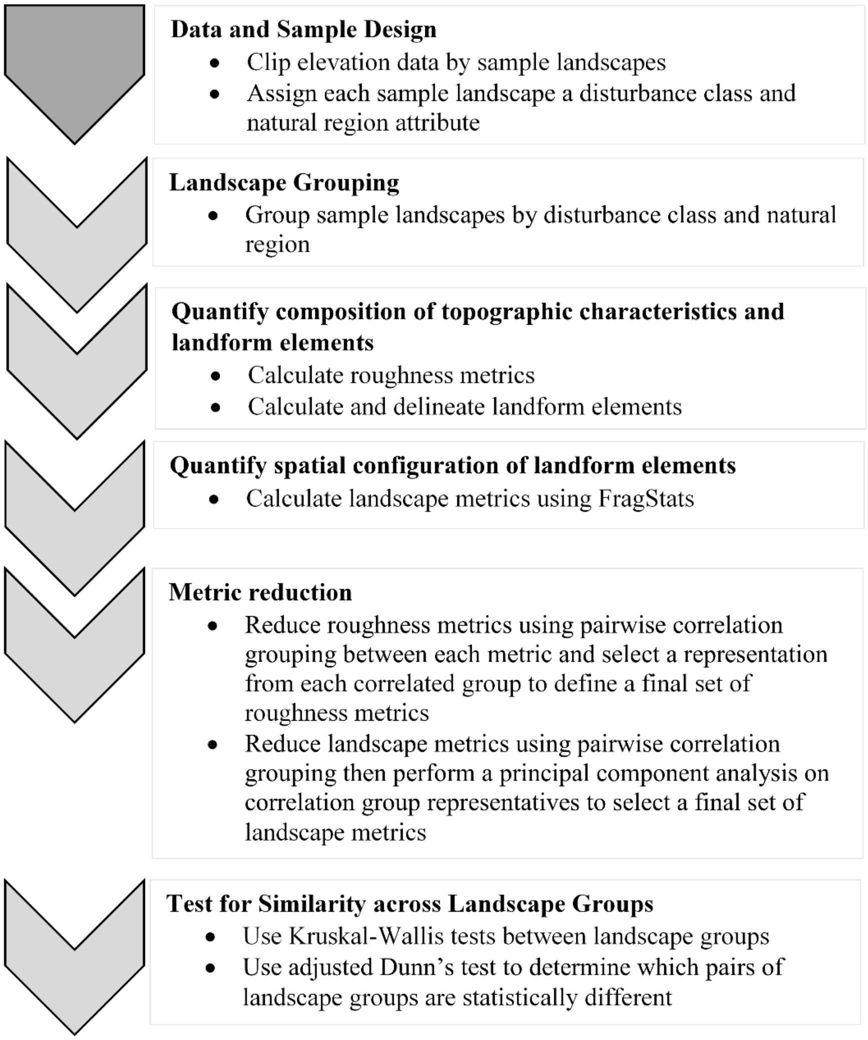


Fig 2.1 Study location in the southern Boreal, Parkland, and Grassland regions of Southern Alberta shown using a grey grid. Study area restricted by the extent of two wetland inventories in Alberta

2.2 Methodology Overview

To quantify topographic characteristics and variation in elevation, in wetland landscapes, my analysis is divided into six conceptual steps (Fig 2.2). I begin with the study site creation and subsequently group sample landscapes by natural region and proportion of disturbance. This is followed by the quantification of topographic characteristics and landform elements, calculating spatial configuration metrics, reducing the calculated metrics to a parsimonious set, and finally testing for differences in metric values across sample landscape groups (Fig 2.2).



Data and Sample Design
- Clip elevation data by sample landscapes
- Assign each sample landscape a disturbance class and natural region attribute

Landscape Grouping
- Group sample landscapes by disturbance class and natural region

Quantify composition of topographic characteristics and landform elements
- Calculate roughness metrics
- Calculate and delineate landform elements

Quantify spatial configuration of landform elements
- Calculate landscape metrics using FragStats

Metric reduction
- Reduce roughness metrics using pairwise correlation grouping between each metric and select a representation from each correlated group to define a final set of roughness metrics
- Reduce landscape metrics using pairwise correlation grouping then perform a principal component analysis on correlation group representatives to select a final set of landscape metrics

Test for Similarity across Landscape Groups
- Use Kruskal-Wallis tests between landscape groups
- Use adjusted Dunn’s test to determine which pairs of landscape groups are statistically different

Fig 2.2 Overview of key analysis steps undertaken within the thesis.

2.3 Data and Sample Design

Terrain analysis theoretically requires only elevation data. Elevation data were acquired from AltaLIS Ltd. (AltaLIS, 2015) with a 10 m spatial resolution and smoothed using two passes of a 5 X 5 cell mean filter to reduce noise in the data (e.g., Buchanan et al. 2014, MacMillan et al. 2003).

A high data resolution enabled the representation of topographic changes that may influence wetland ecosystems in the region (MacMillan et al. 2003).

Wetlands do not exist as an ecosystem in isolation from the surrounding landscape. The land cover surrounding wetlands, particularly in hydrologically 'upstream' regions, are influential to the health of wetland ecosystems (Mitsch and Gosselink 2007). Two key types of land cover, referred to as disturbance in this research, that can negatively affect wetland health are agricultural and urban lands (Mitsch and Gosselink 2007). Land cover data for Alberta from Agriculture and Agri-Food Canada were acquired and the proportion of disturbance (areas classified as 'agriculture', 'pasture', or 'urban') was calculated for each sample landscape (Evans et al. 2017).

Within the study area, 4,000 1 km^2 square sample landscapes were generated at random and only those that contained wetlands were retained, resulting in 3,434 sample landscapes (Evans et al. 2017). The 1 km^2 sample landscapes are sized to match the average size of land that impacts a wetland (i.e. 500 m radius around a wetland, Kraft 2016), as well as to facilitate future comparisons with existing research that quantified the spatial pattern of land cover in wetland landscapes using the same sample landscapes (Evans et al. 2017).

2.4 Landscape Grouping

Landscapes with similar characteristics have been shown to function similarly and understanding landscape-level ecosystem services is an important concept in landscape planning (de Groot et al. 2010). For example, landscapes with similar characteristics have similar impacts on water quality (Huang et al. 2013), can be used to predict vertebrate species abundance (Mazerolle and Villard 1999), and pest abundance (Zaller et al. 2008). To generalize these landscapes, develop a parsimonious set of criteria that can be used by regulators and industry, and simplify their application, landscapes can be grouped together based on a variety of landscape-level characteristics.

Existing research has demonstrated that the spatial composition and configuration of land cover in the same sample landscapes differed by natural region and disturbance (Evans et al. 2017). It would be useful to relate the topographic analysis undertaken in this study to previous research on the spatial pattern of land cover (Evans et al. 2017), so similar landscape groups were defined to facilitate future comparisons. Landscapes were discretized into 15 groups by partitioning the landscapes by five disturbance levels in each of three natural regions of Alberta: Grassland, Parkland, and Boreal Dry Mixedwood subregion (Table 2.1, Fig 2.3). These landscapes do not have an even distribution across the 15 groups and it is evident that there is a higher level of disturbance in the obtained sample of Parkland landscapes than in Grassland or Boreal landscapes, where 69% of Parkland landscapes are in the highest disturbance group (Table 2.1).

Table 2.1 Total number of landscapes in each landscape group, by natural region and 20 % disturbance intervals.

		Natural Region			
		Grassland	Parkland	Boreal	Total
Disturbance (%)	0-20	471	68	426	965
	>20-40	87	44	155	286
	>40-60	97	58	160	315
	>60-80	122	103	181	406
	>80-100	506	608	348	1462
	Total	1283	881	1270	3434

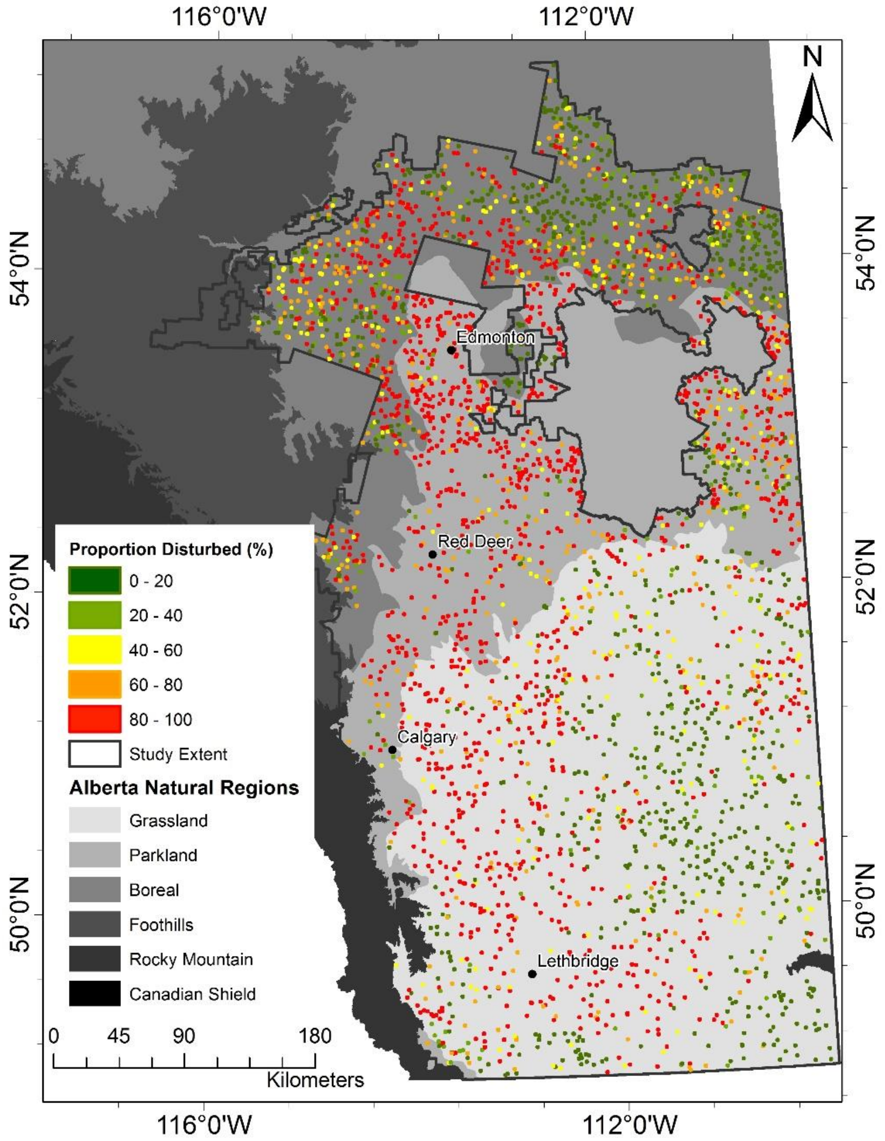


Fig 2.3 Spatial distribution of 1 km^2 landscapes across Grassland, Parkland, and southern extent of Boreal natural regions of Alberta, coloured based on proportion of disturbance in 20% intervals

2.5 Terrain Roughness

Terrain analysis methods are used for relational and descriptive purposes. Relational analyses seek to improve our understanding of the relationship between topography and environmental variables. For example, the relationship between elevation and environmental variables such as soil depth and type (Florinsky et al. 2002), soil wetness (Murphy et al. 2011), snow depth (Lapen and Martz 1996), and potential for ecosystem restoration (Kauffman-Axelrod and Steinberg 2010) have been quantified. Correlation and regression analyses are used to quantify the relationship between these two ratio datasets to test if a relationship exists between topography and an environmental variable (Murphy et al. 2011).

When the terrain analysis is conducted for descriptive purposes, a different set of methods is required to quantify the variation in topography across an area. Despite a wide range of metrics used in terrain analysis (e.g., Olaya 2009, Florinsky 2012) to quantify elements of topography, from individual cells (elevation value), to local cell windows (slope), and regional relationships (flow accumulation), none are designed specifically for a landscape scale. Quantifying the topographic characteristics of a landscape is known to be a challenge (Deng 2007, MacMillan et al. 2000), which is partly due to the continuous surface of ratio data representing elevation. To overcome this challenge, variation in elevation has been 1) described aspatially using measurements of terrain roughness (Hengl and MacMillan 2009) or 2) transformed into nominal data describing landform elements (Reuter et al. 2006).

Terrain roughness, a measure of the region's topographic complexity, is an important component and driver of ecological processes (e.g., landscape structure, McGarigal et al. 2009; vegetation growth patterns and wildlife behaviour, Nellemann and Fry 1995; plant species richness, Hofer et al. 2008). The link between terrain roughness and ecological process emphasizes the need to design heterogeneous landscapes that mimic natural surface roughness to improve the success rate of reclamation projects.

A review of terrain roughness metrics (TRMs) identified eight metrics designed to quantify the variation in elevation that could be conceptually applied at a landscape scale (Table 2.2) using spatially continuous input data (Grohmann et al. 2011). The topographic position index was removed as it has been shown to provide a less accurate representation of topographic variation than the deviation from mean elevation (DEV) metric (De Reu et al. 2013).

Table 2.2 Landscape-scale terrain roughness metrics identified through a literature review. Metrics selected and calculated in this study are designated with *.

Metric Name	Source	Calculation
*Deviation from Mean Elevation (DEV)	Lindsay et al. 2015	$\lvert \mathrm{DEM} - \mathrm{MeanDEM} \rvert^2$
*Standard Deviation of Elevation	Grohmann et al. 2011	$SD = \sqrt{\frac{\sum(DEM - MeanDEM)^2}{N}}$
*2D:3D Area Ratio	Rashid 2010	3Darea = (2Darea^3)/cos(Slp^4) Ratio = (3Darea / 2Darea^3)
*Standard Deviation of Profile Curvature	Olaya 2009	$SD = \sqrt{\frac{\sum(PrfCurv - MeanPrfCurv)^2}{N}}$
Topographic Position Index (TPI)	De Reu et al. 2013	TPI = (MeanDEM^2–MinDEM^2) / (MaxDEM^2–MinDEM^2)
*Slope Variability	Grohmann et al. 2011	SV = MaxSlp^4–MinSlp^4
*Standard Deviation of Slope	Olaya 2009	$SD = \sqrt{\frac{\sum(Slp - MeanSlp)^2}{N}}$
*Inverse Vector Dispersion	Grohmann et al. 2011, Olaya 2009	Appendix 4

^{2}DEM = elevation values, ^{3}2Darea = window area (length*width), ^{4}Slp = slope in degrees

In total, seven TRMs were used to quantify surface roughness in each sample landscape (see Appendix 4 for detailed description of metric calculations and modifications). For five of the seven metrics, DEV, standard deviation (SD) elevation, SD profile curvature, SD slope, and slope variability, two variations on the metric calculations were performed: 1) the metric was calculated based on all cells in the entire sample landscape (i.e., global), 2) the metric was calculated using a moving 5x5 focal window and then the average of the window values for the entire sample landscape was recorded. The 2D:3D Area Ratio and Inverse Vector Dispersion metrics are inherently based on focal windows and thus could not be directly calculated for the entire landscape, resulting in 12 total metrics.

Summary statistics of the average and standard deviation for each TRM were calculated by natural region and disturbance level (Appendix 5). Each landscape group's TRM distribution was tested for normality using the Shapiro-Wilks test and visually assessed using QQ plots, where it was determined that all TRMs had a non-normal distribution for all landscape groups.

Next, the 12 TRMs were reduced by grouping metrics that shared a Pearson's correlation coefficient > 0.9 with all other members of the group (Moreno-Mateos et al. 2008 Riitters et al. 1995). A representative metric was selected from each correlation group and the process repeated until all representative metrics fell below the correlation threshold (Riitters et al. 1995). Through the iterative comparison of each metric pair's correlation value, a final set of five TRMs was selected.

A Kruskal-Wallis statistic was used to test for significant differences between landscapes grouped by natural region and disturbance. In the case where a significant difference was found, a post-hoc Dunn's test was used to perform pairwise comparison tests between landscape groups. A Bonferroni correction was also applied to control for Type 1 errors, which occur when a test incorrectly reports a significant difference when none exists (Dunn 1961); to increase analytical rigor since I did not measure spatial autocorrelation; and to create statistically-sound guidelines for industry.

2.6 Landform Classification Methodology

A complementary approach to quantifying the variation in elevation using surface roughness metrics involves transforming the surface into landforms. A landform is 'a physical feature of the Earth's surface having a characteristic, recognizable shape and produced by natural causes' (pg. 228, MacMillan and Shary 2009). Landform classification has been widely applied to different regions (e.g., Turkey, Tagil and Jenness 2008; Germany, d'Oleir-Oltmanns et al. 2013) and scales (e.g., micro-topographic hummocks and hollows, Nagamatsu and Miura 1997; to continental-scale mountains and plains, Schmidt and Hewitt 2004). The purpose of the classification is, typically, to describe the composition of landforms in a study area in relation to an environmental variable of interest (e.g., Florinsky 2012). The use of landscape metrics to differentiate and quantify landform pattern across a landscape has been suggested as a promising research direction (Pike 2000) but the author is unaware of any research that has undertaken this methodology.

The use of 1 km^2 sample landscapes situate the landform classification at a scale for defining landform elements (Schmidt and Hewitt 2004) rather than traditional landforms such as drumlins, plains, or mountains. Landform elements are small regions with homogeneous terrain metric values that occur along a hillslope (Schmidt and Hewitt 2004, MacMillan et al. 2000). A hillslope can be composed of multiple landform elements, such as a peak, shoulder, toeslope, and depression (Reuter et al. 2006).

The presented research uses a discrete (or rule-based) approach to delineate landforms based on classification rules for calculated terrain metric values (Pennock et al. 1987, Reuter et al. 2006). While the classification rules need to be adapted for the region in which the landform classification is occurring (Reuter et al. 2006), their use enables 1) transparency and ease of use, 2) comparison across different regions, and 3) builds a compendium of examples for meta-analysis. The discrete landform classification used geometric terrain metrics of slope, profile curvature, plan curvature (MacMillan et al. 2000, Pennock et al. 1987) and deviation from mean elevation (DEV) (Lindsay et al. 2015). These four terrain metrics were combined to create 12 distinct landform elements, 11 that correspond to those by Reuter et al. (2006) and one taken from (MacMillan et al. 2000, Table 2.3, Appendix 6).

Table 2.3 Landform element classification criteria used to group topographic features, DEV refers to deviation from mean elevation metric (Reuter et al. 2006, * from MacMillan et al. 2000)

Landform element	Slope (Deg.)	Prof. Curv.	Plan Curv.	DEV
Divergent shoulder	>0	Convex	Convex	Any
Planar Shoulder	>0	Convex	Linear	Any
Convergent Shoulder	>0	Convex	Concave	Any
Divergent Backslope	>3.0	Linear	Convex	Any
Planar Backslope	>3.0	Linear	Linear	Any
Convergent Backslope	>3.0	Linear	Concave	Any
Divergent Footslope	>0	Concave	Convex	Any
Planar Footslope	>0	Concave	Linear	Any
Convergent Footslope	>3.0	Concave	Concave	Any
Low Level	<=3.0	Linear	Any	Low
High Level	<=3.0	Linear	Any	Mid-High
*Depression	<=3.0	Concave	Concave	Any

2.7 Quantifying topographic composition and configuration

To quantify the composition and configuration of landform elements and characterize topographic patterns by natural region and disturbance, landscape metrics were applied to the sample landscapes using FRAGSTATS (McGarigal et al. 2012). The FRAGSTATS software conceptualizes spatial pattern by measures of area-edge, shape, aggregation, and diversity, which may be applied to an individual patch, a class, or at a landscape scale (McGarigal et al. 2012). Many landscape metrics quantify a relationship between ecological processes and land cover patterns (e.g., core area and contrast, McGarigal et al. 2012). Since these relationships are irrelevant to landforms, all core area and contrast metrics were excluded from the analysis.

Thirty-three landscape metrics were deemed applicable to landform elements and were calculated at the landscape-scale (as opposed to patch- or class-scale) for each sample landscape (Appendix 7). Sample landscapes were grouped based on natural region and disturbance level (Table 1). Each landscape metric was tested, by group, for normality using the Shapiro-Wilks test and visually assessed using QQ plots, which determined that all metrics had a non-normal distribution. The thirty-two metrics were reduced to a subset of representative landscape metrics using the same correlation analysis described above for terrain roughness. In addition, a principal component analysis (PCA) was used to further reduce the subset of metrics similar to the bioclimate envelope approach (Metzger et al. 2013) used by Evans et al. (2017). The metric with the highest absolute factor loading for each principal component, with an eigenvalue greater than one, was retained.

Once the final subset of landscape metrics was defined, a Kruskal-Wallis test identified significant differences between natural regions and disturbance levels. Where significant differences were found, a post-hoc Dunn’s test with Bonferroni correction was used to perform pairwise landscape metric tests between landscape groups.

3 Results

3.1 Terrain Roughness Results

Five representative terrain roughness metrics (TRMs) were selected based on the iterative correlation analysis (Appendix 8). The correlation analysis was repeated for each natural region separately to test if different representative metrics were selected. All natural regions returned the same five representative metrics: focal slope variability, global slope variability, 2D:3D area ratio, global DEV, and focal inverse vector dispersion. For each metric, its median and standard deviation was calculated for each landscape group (e.g., natural region and disturbance level, Appendix 5) and analysis of variance tests were applied across natural regions and disturbance levels (Table 2.4 and Table 2.5).

We tested for significant differences among natural regions within the same disturbance level using a Kruskal-Wallis test for each of the five representative TRMs (Table **2.4**). Of the 25 tests, 12 (48%) were significantly different at p<0.001, 4 (16%) were significantly different at p<0.01, 3 (12%) were significantly different at p<0.05, and 6 (24%) were not significantly different. Focal slope variability, global slope variability, and area ratio metrics were significantly different among natural regions at p<0.05 for all five disturbance levels, whereas global DEV and inverse vector dispersion were significantly different for only two of the five disturbance levels (Table 2.4). The remaining two metrics, global DEV and inverse vector dispersion, were not congruent but still demonstrated sensitivity to natural region. The results, that 76% of the tests have significantly different metric values, suggest that surface roughness differs among natural regions regardless of the level of disturbance in the landscape

Table 2.4 Significant differences in representative roughness metrics (TRMs) among landscapes in different natural regions with the same disturbance level, shown using p-values obtained from a Kruskal-Wallis test. Full p-values, d.f. and chi-squared for each test provided in Appendix 9

	Disturbance (%)				
Metric	0-20	20-40	40-60	60-80	80-100
Focal Slope Var.	<0.001	0.012	<0.001	<0.001	<0.001
Global Slope Var.	0.008	0.008	<0.001	<0.001	<0.001
Area Ratio	0.003	0.03	<0.001	<0.001	<0.001
Global DEV	0.03	0.133	<0.001	0.19	0.114
Inv. Vector Dispersion	0.106	0.004	0.966	0.996	<0.001

To identify specific differences in TRMs between natural regions within different levels of disturbance a pairwise Dunn’s test was conducted. Of the five TRMs, focal and global slope variability as well as area ratio were significantly different between all three natural regions. The remaining two TRMs, global DEV and inverse vector dispersion, were only significantly different between Parkland and Grassland landscapes (Table 2.5). These results confirm that significant differences in surface roughness exist between natural regions; however, these differences are less pronounced between the Grassland and Parkland regions.

Table 2.5 Significant differences between TRMs for landscapes in different natural regions using a Bonferroni corrected Dunn's test. Significant levels of p<0.05, <0.01, and <0.001 shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

Natural Region	Boreal	Parkland
Parkland	Focal Slope Var.*** Global Slope Var.** Area Ratio*	
Grassland	Focal Slope Var.*** Global Slope Var.* Area Ratio**	Global DEV** Inv. Vector Dispersion**

To evaluate if surface roughness differed with disturbance level, a Kruskal-Wallis test was conducted separately for each natural region for the five representative TRMs based on landscapes grouped by proportion of disturbance. The Kruskal-Wallis test identified that a significant difference existed between landscapes at different disturbance levels for all five TRMs at p<0.001, except for the inverse vector dispersion metric in the Parkland (significant at p<0.01) and Grassland (not significant) regions (Appendix 9). These results suggest that landscapes with different levels of disturbance within the same natural region have significantly different surface roughness.

To identify specific differences in surface roughness between disturbance levels, a Dunn's posthoc pairwise comparison test was performed for each of the three natural regions. For the Boreal region, the test identified that high disturbance landscapes (80–100% disturbance) were significantly different than all other landscapes for all five representative TRMs (Table 2.6). There was also a significant difference between landscapes with 0–20% and 20–40% disturbance for 4 of the 5 metrics and focal slope variability was significantly different between 20–40% and 60–80% disturbance landscapes (Table 2.6).

Table 2.6 Dunn's pairwise comparison of TRMs by disturbance in Boreal with Bonferroni correction. Significance levels of p<0.05, p<0.01, and p<0.001 shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	Focal Slope Var. ** Global Slope Var.* Area Ratio** Global DEV**			
40 – 60	None	None		
60 – 80	None	Focal Slope Var. *	None	
80 – 100	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV** Inv. Vector Dispersion***	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV*** Inv. Vector Dispersion***	Focal Slope Var. *** Global Slope Var.*** Area Ratio*** Global DEV*** Inv. Vector Dispersion***	Focal Slope Var. *** Global Slope Var.*** Area Ratio*** Global DEV*** Inv. Vector Dispersion***

Results for Parkland landscapes found significant differences between high disturbance landscapes (80–100% disturbance) and all other landscapes for at least 3 of the 5 TRMs (Table **2.7**). Landscapes with 0–20% in disturbance were also found to be significantly different than 40–60% landscapes for 4 of the 5 TRMs (Table 2.7).

Table 2.7 Dunn's pairwise comparison of TRMs by disturbance in Parkland with Bonferroni correction. Significance levels of p<0.05, p<0.01, and p<0.001 shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	Focal Slope Var.* Global Slope Var.* Area Ratio** Global DEV **	None		
60 – 80	Inv. Vector Dispersion *	Inv. Vector Dispersion *	None	
80 – 100	Focal Slope Var.*** Global Slope Var.*** Area Ratio***	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV ***	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV ***	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV *** Inv. Vector Dispersion *

For the Grassland natural region, the pairwise comparisons found significant differences between high disturbance landscapes and all other landscapes at p<0.001 for all TRMs except for inverse vector dispersion (Table 2.8). There were no significant differences found for any of the other pairwise comparisons (Table 2.8).

Table 2.8 Dunn's pairwise comparison of TRMs by disturbance in Grassland with Bonferroni correction. Significance levels of $p<0.05$, $p<0.01$, and $p<0.001$ shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

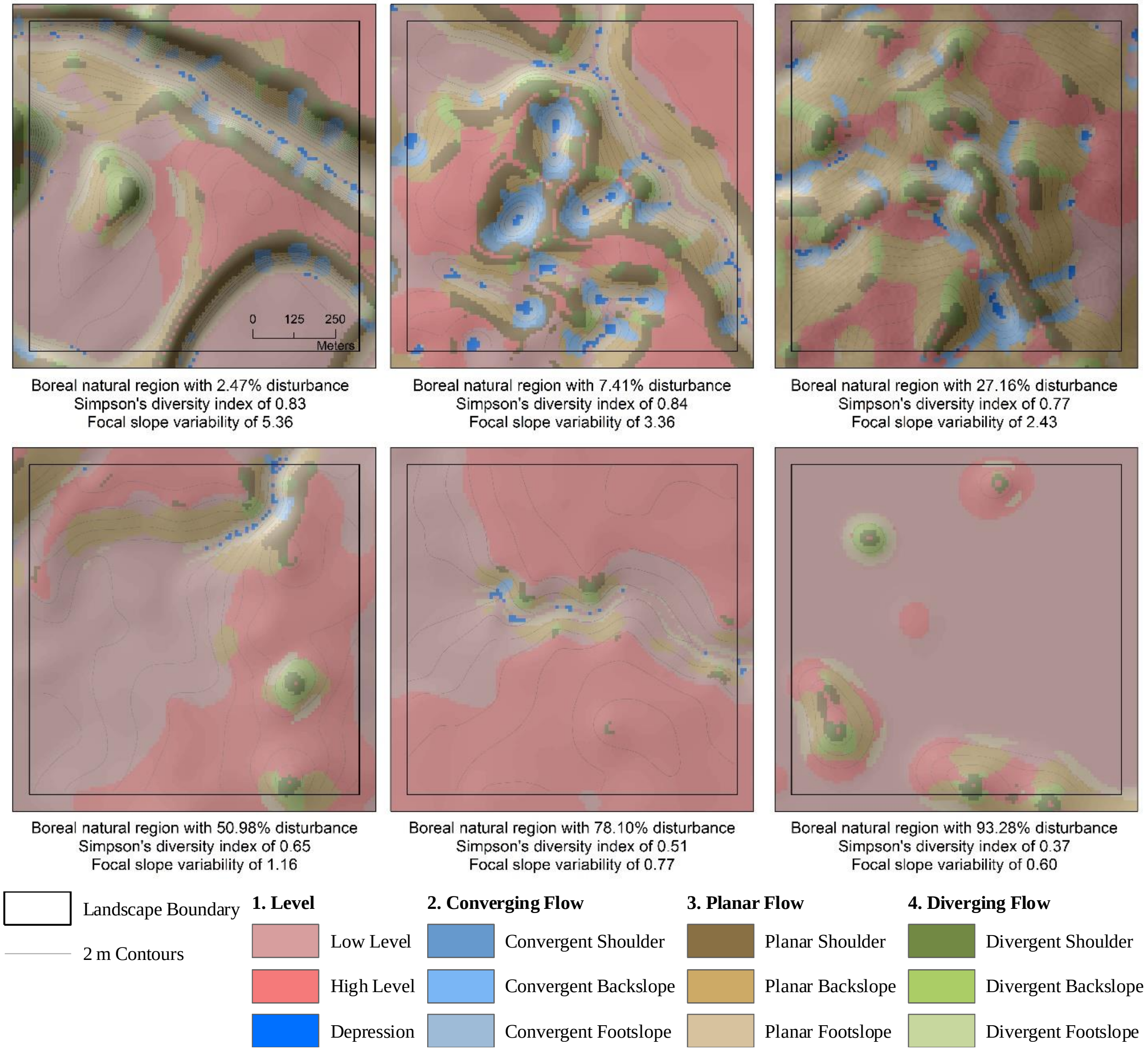
Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	None	None		
60 – 80	None	None	None	
80 – 100	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV ***	Focal Slope Var.*** Global Slope Var.** Area Ratio*** Global DEV *	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV **	Focal Slope Var.*** Global Slope Var.*** Area Ratio*** Global DEV ***

Pairwise comparison results across disturbance levels within each of the natural regions demonstrate congruence that surface roughness of 80-100% disturbance landscapes are significantly different than landscapes with other levels of disturbance. Of the three natural regions, disturbance in Grassland is the least differentiated in terms of surface roughness (Table 2.8). Among the TRMs, focal slope variability was found to be the strongest differentiator across disturbance levels, showing significant differences in 15 of the 30 comparisons, which corroborates its influence in differentiating between natural regions (Table 2.4, Table 2.6 - Table 2.8).

The results show that landscape roughness differs by measurements of slope variability and elevation variability between high disturbance landscapes and all others. In addition, the results suggest that reclamation plans should have greater slope (focal slope var. 0.69 – 1.21) and elevation variability (global DEV 2.91 – 3.35) than what is observed in high disturbance landscapes (focal slope var. 0.43 – 0.61, global DEV 2.17 – 2.50) to mimic natural landscapes (Appendix 5).

3.2 Landform Results

Each sample landscape's topography was classified into 12 discrete landform elements that represent the topographic characteristics of a landscape and were grouped based on their expected overland flow characteristics (Fig 2.4). In general, low and high level landform elements are the most prevalent across all landscapes, while convergent backslope and convergent footslope elements are the least prevalent. I quantify the composition and configuration of these landform elements across natural regions and disturbance levels using a parsimonious set of landscape metrics. Finally, I test for differences in composition and configuration by natural region and proportion of disturbance.



Boreal natural region with 2.47% disturbance
Simpson's diversity index of 0.83
Focal slope variability of 5.36

Boreal natural region with 7.41% disturbance
Simpson's diversity index of 0.84
Focal slope variability of 3.36

Boreal natural region with 27.16% disturbance
Simpson's diversity index of 0.77
Focal slope variability of 2.43

Boreal natural region with 50.98% disturbance
Simpson's diversity index of 0.65
Focal slope variability of 1.16

Boreal natural region with 78.10% disturbance
Simpson's diversity index of 0.51
Focal slope variability of 0.77

Boreal natural region with 93.28% disturbance
Simpson's diversity index of 0.37
Focal slope variability of 0.60

Fig 2.4 Example of landform element classification results across six landscapes at each disturbance level, all within the Boreal natural region. Landscapes increase in disturbance from left-to-right, starting at the top left square, and exemplifies how level landform elements dominate landscapes with a high proportion of disturbance while low disturbance landscapes have greater landform diversity.

3.2.1 Metric Reduction

Thirty-two landscape metrics were reduced using an iterative correlation analysis, which grouped all metrics with a paired Pearson correlation coefficient greater than 0.9 and then a representative from each group was selected. The correlation analysis resulted in 15 representative landscape metrics for the Boreal and Grassland regions, 14 metrics for the Parkland region, and 16 metrics when considering the entire region (Appendix 10).

To further refine the landscape metrics, a Principal Component Analysis (PCA) was performed on the representative metrics identified in the correlation analysis for each natural region (Table 2.9). The PCA identified a set of five landscape metrics for the entire study area, four landscape metrics for each natural region, and a total of seven unique metrics. Each natural region retained the same two metrics (SHEI and ENN_AM), while Boreal and Parkland both retained GYRATE_AM and Parkland and Grassland both retained PROX_AM (Table 2.9)

Table 2.9 Representative landscape metrics for each natural region based on PCA. Metric name is given in capitals. Metric conceptual grouping is given below each metric.

	Principal Component				
Natural Region	1	2	3	4	5
All	SIDI	SHEI	SHAPE_AM	ENN_AM	CONNECT
	Diversity/ Evenness	Diversity/ Evenness	Shape	Aggregation	Aggregation
Boreal	GYRATE_AM	SHEI	SHAPE_AM	ENN_AM	N/A
	Area/Edge	Diversity/ Evenness	Shape	Aggregation	
Parkland	GYRATE_AM	SHEI	PROX_AM	ENN_AM	N/A
	Area/Edge	Diversity/ Evenness	Aggregation	Aggregation	
Grassland	SIDI	SHEI	PROX_AM	ENN_AM	N/A
	Diversity/ Evenness	Diversity/ Evenness	Aggregation	Aggregation	

Out of the seven unique representative landscape metrics identified, three landscape metrics measured landform element aggregation, two metrics measured landscape diversity or evenness, one measured landform element area or edge, and one measured landform element shape

(Appendix 7). The seven representative metric's mean and standard deviation values were calculated to compare the distribution of metric values across landscapes based on both natural region and proportion of disturbance (Appendix 5).

3.2.2 Relating Metrics to Natural Region and Human Disturbance

The representative landscape metrics for each sample landscape group were tested for normality using a Shapiro-Wilks test and visually compared using QQ-plots; each landscape category reported a p-value of <0.01, rejecting the null hypothesis that the data followed a normal distribution. A Kruskal-Wallis test was conducted to determine if significant difference existed among the three natural regions for landscapes with the same proportion of human disturbance (Table 2.10). Of the 35 total comparisons made, 17 (48.6%) were significant at p<0.001, 5 (14%) were significant at p<0.01, 5 (14%) were significant at p<0.05, and 8 (22.9%) had no significant difference (Table 2.10). Two of the seven metrics were significantly different for all five disturbance groups (GYRATE_AM and SIDI) (Table 2.10).

Table 2.10 Kruskal-Wallis test results for significant difference between landscape metrics in different natural regions with the same proportion of disturbance. Full p-values, d.f., and chi-squared statistics provided in Appendix 9

	Disturbance (%)				
Metric	0-20	20-40	40-60	60-80	80-100
GYRATE_AM	<0.001	0.026	<0.001	<0.001	<0.001
PROX_AM	<0.001	0.655	<0.001	0.003	<0.001
SIDI	<0.001	0.014	<0.001	<0.001	<0.001
SHEI	<0.001	0.019	0.095	0.943	0.054
SHAPE_AM	<0.001	0.383	<0.001	<0.001	<0.001
ENN_AM	<0.001	0.33	0.034	0.002	0.073
CONNECT	0.001	0.007	0.027	0.002	0.715

Landscapes in different natural regions were statistically compared using Dunn's pairwise comparison test for the seven representative landscape metrics. The test found significant differences in landscape metrics between all three natural regions, and the greatest number of differences was found between Parkland and Boreal where six out of the seven representative metrics were significantly different (Table 2.11). Parkland and Grassland had the least number of differences, with three out of the seven representative metrics significantly different (Table 2.11). These results suggest that the configuration of landscape elements differ significantly between natural regions.

Table 2.11 Pairwise comparison between landscapes in different natural regions for each landscape metric. Significance levels p<0.005, p<0.01, and p<0.001 shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

Natural Region	Boreal	Parkland
Parkland	GYRATE_AM*** PROX_AM*** SIDI*** SHAPE_AM*** ENN_AM* CONNECT**	
Grassland	GYRATE_AM*** PROX_AM*** SIDI*** SHEI* SHAPE_AM***	SHAPE_AM*** ENN_AM** CONNECT**

Given significant differences between natural regions, I tested for significant difference between landscape disturbance levels within each natural region. Results showed significant differences between landscapes with different proportions of disturbance for all seven representative metrics, with the exception of the CONNECT metric in the Boreal and Grassland regions and the SHEI metric in the Grassland region (Table 2.12).

Table 2.12 Kruskal-Wallis test results for significant differences between landscape metrics values among disturbance levels by natural region, all tests have 4 degrees of freedom

	Metric	Chi-squared (*H*)	p	Significance
Boreal	GYRATE_AM	41.504	<0.001	***
	PROX_AM	15.757	0.003	**
	SIDI	53.126	<0.001	***
	SHEI	15.926	0.003	**
	SHAPE_AM	25.983	<0.001	***
	ENN_AM	20.039	<0.001	***
	CONNECT	3.618	0.46	
Parkland	GYRATE_AM	88.756	<0.001	***
	PROX_AM	23.018	<0.001	***
	SIDI	103.509	<0.001	***
	SHEI	12.465	0.014	*
	SHAPE_AM	33.289	<0.001	***
	ENN_AM	33.336	<0.001	***
	CONNECT	32.213	<0.001	***
Grassland	GYRATE_AM	59.356	<0.001	***
	PROX_AM	33.406	<0.001	***
	SIDI	71.437	<0.001	***
	SHEI	6.681	0.154	
	SHAPE_AM	37.954	<0.001	***
	ENN_AM	16.113	0.003	**
	CONNECT	3.757	0.44	

Pairwise comparisons between disturbance classes in the Boreal using an adjusted post-hoc Dunn’s test found significant difference between high disturbance landscapes and all other landscape groups for the GYRATE_AM and SIDI metrics. Furthermore, six of the seven representative metrics are significantly different between landscapes with 0–20% and 80–100% disturbance (Table 2.13). Significant differences were also found for three of the seven metrics between 0–20% and 20–40% landscapes (Table 2.13).

Table 2.13 Pairwise comparison of disturbance levels in Boreal region using a Bonferroni corrected Dunn's test. Significance levels p<0.05, p<0.01, and p<0.001 shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	GYRATE_AM*** PROX_AM** SIDI**			
40 – 60	None	None		
60 – 80	ENN_AM**	SHAPE_AM*	None	
80 – 100	GYRATE_AM* SIDI*** SHEI*** SHAPE_AM** ENN_AM**	GYRATE_AM*** PROX_AM*** SIDI*** SHAPE_AM***	GYRATE_AM** SIDI***	GYRATE_AM** SIDI***

The Parkland natural region results also found that the high disturbance landscapes are significantly different from landscapes at all other disturbance levels (Table 2.14). At least four of the seven representative landscape metrics were significantly different between high disturbance landscapes and all other landscapes and six of the seven metrics were significantly different between landscapes with 60–80% and 80–100% disturbance. The only other difference detected was for the SIDI metric at p<0.05 between 0–20% and 40–60% disturbance landscapes (Table 2.14).

Table 2.14 Pairwise comparison of disturbance levels in the Parkland region using a Bonferroni corrected Dunn's test. Significance levels p<0.05, p<0.01, and p<0.001 shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	SIDI*	None		
60 – 80	None	None	None	
80 – 100	GYRATE_AM** SIDI*** ENN_AM*** CONNECT	GYRATE_AM*** SIDI*** SHEI* CONNECT*	GYRATE_AM*** PROX_AM*** SIDI*** SHAPE_AM**	GYRATE_AM*** PROX_AM* SIDI*** SHAPE_AM*** ENN_AM* CONNECT*

Our comparison between levels of disturbance within the Grassland region identified significant differences between high disturbance landscapes and all other landscapes, with no other significant differences found. Between three and five representative landscape metrics were significantly different between 80–100% disturbance landscapes and all other landscapes (Table 2.15). Three metrics, GYRATE_AM, SHAPE_AM, and SIDI were significantly different across all four comparisons for high disturbance landscapes (Table 2.15)

Table 2.15 Pairwise comparison of disturbance levels in the Grassland region using a Bonferroni corrected Dunn's test. Significance levels p<0.05, p<0.01, and p<0.001 shown by *, **, and ***. Full p-values, chi-squared, and Z statistics provided in Appendix 9

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	None	None		
60 – 80	None	None	None	
80 – 100	GYRATE_AM*** PROX_AM* SIDI*** SHAPE_AM*** ENN_AM***	GYRATE_AM*** PROX_AM** SIDI*** SHAPE_AM**	GYRATE_AM*** PROX_AM** SIDI*** SHAPE_AM**	GYRATE_AM*** SIDI*** SHAPE_AM**

The results of the landform element analysis were similar to the results of the surface roughness analysis. Specifically, landscapes with 80-100% disturbance differed significantly from all other landscapes while the Grassland region showed the least difference across disturbance levels. This suggests that similar spatial patterns of landform elements exist in Grassland regions with medium to low levels of disturbance. Of the 30 total comparisons (Table 2.13 to Table 2.15), 14 showed SIDI to be significantly different, and the most pronounced differentiator of landform pattern, across disturbance levels and natural regions.

The differences observed between high disturbance landscapes and landscapes with low disturbance show that landscape designs for wetland reclamation should use a diverse set of landform elements (SIDI 0.51 – 0.60) that are small (GYRATE 251.84 - 277.04), irregularly shaped (SHAPE_AM 1.92 – 2.12), and located close to other landform elements of the same type (ENN_AM 42.65 – 69.29) to more closely mimic the topographic pattern of natural landscapes (Appendix 5).

4 Discussion

4.1 Terrain Roughness

The presented results show that the representative roughness metrics were statistically different between natural regions in Alberta, Canada, with a tendency for Parkland landscapes to have greater topographic roughness than Boreal and Grassland landscapes. Results were less systematic when comparing landscape roughness among landscapes with different disturbance levels. However, high disturbance landscapes (80-100% disturbed) were significantly different from all other disturbance levels in each natural region and tended to have the lowest TRM values across all three natural regions. The low TRM values illustrate that high disturbance landscapes were significantly flatter, and had less elevation variability and topographic complexity than less disturbed landscapes.

Across all three natural regions, highly disturbed landscapes are primarily in cropland (73.9 %). Flat land is more suitable for agriculture (Yeh and Li 1998), which, when combined with conventional tillage practices in this study area, reduces the topographic variation. Similarly, development, and land-use change in general, decreases topographic variability (Lóczy and Gyenizse 2010). This flattening of topography by anthropogenic land-uses reaches a threshold that significantly differs for highly disturbed landscapes relative to all other disturbance levels, illustrated by the lower TRM values in highly disturbed landscapes when compared to all other landscapes.

Within the three natural regions, Grassland was the only region that did not have significant differences in TRMs between landscapes with less than 80 % disturbance (Table 2.8). High disturbance landscapes in the Grassland region are primarily affected by crop-based disturbance (87.14% of landscape area) whereas landscapes with less than 80 % disturbance have that disturbance more evenly distributed between agriculture (avg. 59%) and pasture (avg. 37%). The preference for flat land, or the levelling of land, prior to the development of cropland may account for the significant difference between landscapes with high disturbance relative to landscapes with all other levels of disturbance.

While low-to-medium disturbance landscapes in all natural regions have no systematic difference in terrain roughness, it is important to note that the entire study region had low terrain roughness values comprising a small range (Appendix 5). For example, average values for the Area Ratio TRM, which measure elevation change within a 5x5 cell window, ranged from a median of 1.001 in low disturbance Grassland landscapes to 1.000 in high disturbance landscapes (Appendix 5) with a maximum elevation range of 200 m. This value range is a minute difference when compared to other studies. For example, a mountainous study area with ~1,200 m of elevation change had Area Ratio values between 1.000 and 1.300 (Grohmann 2004), which emphasizes that our Alberta study area, located in a region known for its low relief, had an overall flat topography. Other TRMs, such as focal slope variability, demonstrate wider value ranges. Regardless of the small range in TRMs across the sample landscapes (e.g., 0.43 to 1.68 for focal slope variability), an interesting finding is that there is a clear tendency for high disturbance landscapes to have the lowest TRM values (e.g., 0.43 to 0.61 for focal slope variability; Appendix 5).

4.2 Landscape Metrics

The characterization of landscape topography showed different patterns in landform elements across natural regions and disturbance levels. From 32 metrics, I identified a parsimonious set of seven unique landscape metrics that can be used to quantify landform patterns. Comparing these results with previous research that used a landscape metric reduction approach to reduce landscape metrics calculated for land cover data within the same 1 km^2 sample landscapes used in my study (Evans et al. 2017), three of the seven landscape metrics were selected in both studies, SHAPE_AM, ENN_AM, and SIDI. In addition, a comparison with Evans et al. (2017) suggests that a single data analysis for all landscapes results in less variability in landscape metric selection. For example, Evans et al. (2017) were required to use two separate data layers with different data accuracy for the landscape metric reduction analysis, which resulted in ten unique representative metrics for six landscape subsets (Evans et al. 2017). Conversely, this study reduced the landscape metrics to seven unique representative metrics and required only three landscape subsets based on natural region.

Of the seven metrics selected, three represent measures of aggregation, two represent measures of diversity/evenness, and the remaining two were measures of area/edge and shape, which totals to five measures of spatial configuration and two measures of spatial composition. The aggregation metrics measured how disperse or connected each landform element is within a landscape and how similar adjacent landform elements are to each other (McGarigal 2012), which is useful to determine how landform elements are arranged within a landscape. Diversity/evenness metrics describe the variability of landform elements, which can inform reclamation planners about how many different landform elements should be created in each landscape. Area/edge metrics describe landform element size within a landscape and the metric selected does this by measuring the spatial reach of each landform element (McGarigal 2012). Finally, shape metrics measure the average shape of landform elements, where the shape metric selected measures how much a landform element deviates from a square shape (McGarigal 2012).

The seven representative landscape metrics were systematically different amongst natural regions, with only GYRATE_AM and SIDI statistically different across all five disturbance levels (Table 2.10). Within natural regions, high disturbance landscapes had significantly different landform element spatial pattern from landscapes at all other disturbance levels and no significant differences were observed between landscapes with less than 80 % disturbance in the Grassland and Parkland, with one exception. Landscapes in the Boreal region followed a similar trend, where landscapes with greater than 80 % disturbance had significant differences in landscape metrics when compared to landscapes with less than 80 % disturbance. Boreal landscapes had the greatest number of differences in landscapes with less than 80 % disturbance, where three disturbance comparisons were significantly different (Table 2.13). The differences observed in the Boreal comparisons versus Parkland or Grassland comparisons by disturbance may be due to differences in disturbance types in these natural regions (Downing and Pettapiece 2006), where Boreal has a more even split between pasture and agricultural disturbance in high disturbance landscapes, whereas Grassland and Parkland are dominated by agricultural disturbance in high disturbance landscapes (Fig 2.5).

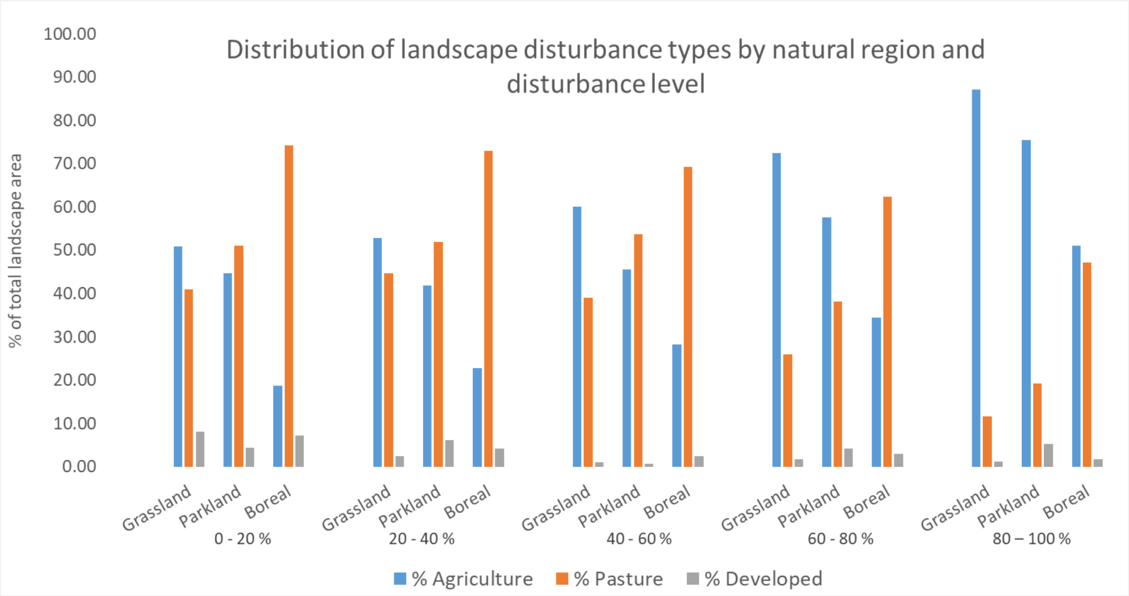


Fig 2.5 Proportion of disturbance type at each disturbance level, separated by natural region. Figure shows that high disturbance landscapes in the Grassland and Parkland are dominated by agricultural disturbance with a more even split between agriculture and pasture in lower disturbance landscapes

A landscape diversity metric measuring landform element composition (SIDI) and an area/edge metric measuring landform element configuration (GYRATE_AM) were the only two metrics that were significantly different between high disturbance landscapes and all other landscapes across all natural regions. High disturbance landscapes were likely dominated by ‘level’ landform elements which results in a low number of large landform elements and less landform element diversity. This is shown by higher radius of gyration values (e.g., in Parkland landscapes, GYRATE_AM had a median of 276.59 for high disturbance and 251.84 for low disturbance, Appendix 5) and lower average landform element SIDI values in high disturbance landscapes (e.g., in Parkland landscapes, average SIDI equaled 0.50 for high disturbance and 0.60 for low disturbance, Appendix 5). The landform element spatial pattern analysis corroborates the findings from the roughness analysis that high disturbance have less topographic variability, less complexity, and overall flatter landscapes.

4.3 Use of Terrain Analysis for Reclamation

The presented research identified a parsimonious set of five surface roughness metrics and seven landform element pattern metrics that can statistically differentiate the terrain of landscapes in different natural regions and between high disturbance landscapes from those with less than 80 % disturbance. Given that, one roughness metric, focal slope variability, and two landform element pattern metrics, SIDI and GYRATE_AM, were shown to be sensitive to topographic differences between natural regions and along a gradient of disturbance, they may be used as a simplified set to quantify and compare terrain roughness and spatial pattern of landscape elements.

The observed values for each metric (by natural region and disturbance level; Appendix 5) can be used as a lookup table to guide reclamation planning and design by industry or to guide the evaluation of reclamation closure plans to ensure reclamation landscapes fall within the range of topographic characteristics found in natural landscapes. The results from low disturbance landscapes can be summarized to provide clear recommendations for how to use roughness and landscape metrics to quantify the topography of landscapes and mimic natural topographic characteristics (Table 2.16). However, oversight is required to ensure that the aggregation of reclaimed landscapes applying the presented topographic characteristic benchmarks represents the distribution of the metric values. If these benchmarks are used (e.g., just the median value) to generate a collection of homogeneous landscapes then my efforts have not advanced upon the height-to-length ratio guidelines (e.g., Appendix 3) for wetland reclamation that fail to represent natural topographic variability.

Table 2.16: Overview of recommendations for landscape-scale reclamation from both roughness and landform element analysis

Recommendation	Associated Metrics	Metric Ranges
Wide slope variability	Focal Slope Var.	FclSlpVar 0.69 – 1.21
	Global Slope Var.	GblSlpVar. 5.04 – 7.09
	2D:3D Area Ratio	AreaRatio 1.0004 – 1.0007
Wide elevation variability	Global DEV	GblDEV 2.91 – 3.35
	Inverse Vector Dispersion	InvVectDisp $1.05\text{x}10^{-2}$ – $1.07\text{x}10^{-2}$
Diverse range of landform elements	Simpson's Diversity Index	SIDI 0.51 – 0.60
Small landform elements	Radius of Gyration	GYRATE_AM 251.84 – 277.04
Irregularly shaped landform elements	Shape Index	SHAPE_AM 1.92 – 2.12
Near landform elements of the same type	Euclidean Nearest Neighbour Index	ENN_AM 42.65 – 69.29

Incorporating natural topographic characteristics into wetland reclamation projects would likely improve upon ecohydrologic function reclaimed wetlands. A disturbed landscape has a greater potential for erosion (Martin-Duque et al. 2010) and disturbed wetlands have less vegetation richness than natural wetlands (Trites and Bayley 2009). Attempting reclamation without mimicking natural topography can cause reclaimed landscapes to have less topographic stability (Martin-Duque et al. 2010) and an inability to mimic natural hydrologic processes (Price et al. 2010). Thus, incorporating a more natural topography into reclamation plans would likely yield more success in achieving reclamation objectives of natural ecosystem appearance, landscape integration, and sustainability.

Quantification of topography is one of many characteristics that affect wetland function and subsequently reclamation planning and acquisition of closure permits, e.g., soil and hydrological characteristics (McKenna 2002). Identifying the covariation among these different biophysical components remains a research gap and opportunity (de Groot et al. 2010) since the dependencies among topography and hydrology (Shaw et al. 2013), solar radiation (Mei et al. 2015; Hofer et al. 2008), and vegetation diversity (Hofer et al. 2008) are strong. Incorporating covariation among the components of reclamation will improve the probability of reclamation success.

4.4 Limitations

Terrain analysis results have some dependency on the resolution of the input elevation data used (Deng et al. 2007; Thompson et al. 2001). For example, a coarser resolution can cause lower slope values in steep slope regions and higher slope values in flat slope regions while also decreasing the range in topographic curvature values (Thompson et al. 2001). While the presented research uses a 10 m resolution digital elevation model (DEM), the degree to which this resolution captures the true topographic variation within the study area is unknown. Terrain analysis in geographically similar landscapes have used elevation data with resolutions ranging from 1 m (Van Meter and Basu 2015) to 10 m (MacMillan et al. 2003). Recent advances in unmanned aerial vehicle (UAV) technology equipped with light detecting and ranging (LiDAR) or used in structure for motion derivation of surface elevation models may provide a cost-effective approach for quantifying the effects of spatial resolution on topographic representation. Comparison of the presented benchmarks across a range of spatial resolutions would add value to the presented research by quantifying the relative change in metric values by spatial resolution while also validating landform classification.

The elevation data used in this analysis, or that of others (e.g., MacMillan et al. 2000), does not include bathymetry of hydrological features within the sample landscapes. To more accurately capture the topographic variation in natural wetland landscapes, future research could replicate the presented methodology with the inclusion of bathymetric measurements within the wetland boundary (CEMA 2014). While costly, incorporating bathymetric measurements would increase information about the water holding capacity, bank profiles, and shape of natural wetlands, which would further assist reclamation planners in designing wetland landscapes that are naturally appearing and self sustaining.

A greater understanding of how each representative roughness and landscape metric relates to landscape disturbance, natural region, and how these metrics interact with each other could have been attained through using multivariate analysis rather than the multiple single analysis of variance tests used in this thesis. Multivariate analysis would treat each metric as an independent variable (Carey 1998) and would have allowed the study to determine how each roughness and landscape metric interacts with each other by quantifying their covariation, as well as measure how that interaction changes by disturbance or natural region (Warne 2014). Multivariate analysis would have allowed the results to quantify the relationship between each metric, which is useful when there are correlated continuous response variables, which occurs in this thesis (Warne 2014).

Finally, the proportion of disturbance used in this study was calculated using AAFC annual crop inventory (land cover) data, which has a 56 m spatial resolution (Fisette et al. 2014). At this spatial resolution it is likely that I have both overestimated disturbance and the rectilinear representation of land cover patches in wetland landscapes. The degree to which the results are affected by spatial resolution remains an avenue for future research.

5 Conclusion

Successful reclamation of wetland landscapes requires integrating reclamation projects with surrounding landscapes, of which topography is a key component. Topography is a driver of ecological processes such as water availability and sunlight potential (Los Huertos and Smith 2013), which are components in the health and location of wetland ecosystems (Mitsch and Gosselink 2007). I have developed a methodology to quantify and describe the topographic characteristics of wetland landscapes and set of topographic metrics that quantify baseline topographic characteristics of wetland landscapes in Alberta.

A parsimonious set of terrain roughness metrics and landform pattern metrics have been defined that can quantify the topographic variability of wetland landscapes and describe the spatial pattern of topographic landform elements across natural regions and at a gradient of disturbance. These metrics can be applied to landscapes to statistically compare topographic characteristics and to define baseline topographic characteristics for different landscapes. Significant differences in topographic characteristics between landscapes in different natural regions and between high disturbance landscapes and all other landscapes illustrates that reclamation plans can define baseline topographic characteristics within the same natural region and with <80% human disturbance.

Chapter 3 – Context, Contributions, and Future Research

1 Implications of Metric Selection

Our research defined a parsimonious set of roughness and landscape metrics that describe the topographic variability of landscapes as well as landform element spatial composition and configuration. These metrics can be used to quantify and characterize wetland landscapes to define baseline topographic conditions to better understand wetland systems and create guidelines for future reclamation. The content within this chapter builds off the results of Chapter 2 by providing greater depth on the conceptual differences between each representative metric, defines environmental properties that the representative metrics measure, and provides recommendations for how these metrics should be used in landscape reclamation.

1.1 Topographic Roughness Metrics

A parsimonious set of 5 TRMs were defined in the research, focal and global slope variability, 2D:3D area ratio, global DEV, and inverse vector dispersion. All five metrics were found to be statistically different across landscape groups in different natural regions and across a gradient of disturbance, but a clear trend was observed. When comparing solely by natural region, global DEV and inverse vector dispersion were the only two metrics significantly different between Parkland and Grassland, while the other three metrics (focal and global slope variability, 2D:3D area ratio) were significantly different when comparing Boreal to Parkland/Grassland but were not different between Parkland and Grassland. This leads us to conclude that there is a topographic characteristic occurring that is captured by one of these groups of TRMs that is not measured by the other group. While it is not presently possible to concretely determine what is setting these TRMs apart, it is possible to delve into their conceptual underpinnings to fully understand what aspects of topographic roughness each metric measures.

Slope variability measures the range in slope values in the landscapes, either using the focal version calculated by taking the landscape-average of the slope range of a moving 5x5 window (focal slope variability) or the global version based on the direct slope range of each landscapes (global slope variability). A focal approach is likely to report less slope variability than the global approach since slope measurements near each other are likely to have similar values. This is apparent when comparing the median focal and global slope variability values across landscape groups, where median focal slope variability ranges from 0.43 to 1.68 and median global slope variability ranges from 3.12 to 9.47 (Appendix 5). Given the generally flat topography of the study area, global slope variability is primarily quantifying the maximum slope value in each landscape (since the minimum slope value is close to 0 degrees), whereas focal slope variability is reporting if large slope changes occur in close proximity.

2D:3D area ratio was significantly different between the same natural regions as slope variability, which may be caused by these metrics measuring similar topographic characteristics. 2D:3D area ratio calculates the ratio between the 2D surface area of each 5x5 window and its 3D area. Landscapes with low (0 – 20 %) disturbance had higher median 2D:3D area ratio (1.0004 – 1.0007) than high (80 – 100 %) disturbance landscapes (1.0002) and had a median range across all landscapes of 1.0002 to 1.0013 (Appendix 5), highlighting the general flat topography of the study area and, similar to focal slope variability, measuring regions where large slope changes occur within close proximity.

All three metrics that found significant differences between Boreal and Parkland/Grassland measure large slope changes in either close proximity (focal slope variability, 2D:3D area ratio) or large slope ranges in a landscape (global slope variability), which suggests that the topographic characteristic that these three metrics are capturing is directly related to the slope within a landscape. A landscape’s slope has direct impacts on the distribution of vegetation (Bennie et al. 2006, Wilson and Gallant 2000), soil moisture (Murphy et al., 2011), solar radiation (Dubayah and Rich 1995), and can directly impact wetland location (Stein et al. 2004). These three metrics were lower in the southern Boreal subregion than in the Parkland or Grassland (Appendix 5), which suggests that Boreal landscapes were slightly flatter with less slope variability.

When comparing solely by natural region, global DEV and inverse vector dispersion were the only two metrics significantly different between Parkland and Grassland landscapes, which suggests that Parkland and Grassland had more similarities in topographic roughness than the southern Boreal subregion. Global DEV calculates the deviation from mean elevation for each landscape, which measures if a landscape’s topography is flat with low deviation from the mean or if there are significant topographic variations. However, global DEV cannot determine if a large deviation is the result of one significant topographic feature surrounded by flat land or a series of undulating hills that vary about a mean elevation. Global DEV was on average lower in the

Grassland (2.50 – 3.54) than in the Parkland (2.14 – 5.12) and was lower in high disturbance landscapes (2.17 – 2.50) than low disturbance landscapes (2.91 – 3.35), reinforcing that high disturbance landscapes had lower topographic variability than less disturbed landscapes (Appendix 5).

Inverse vector dispersion measures a landscape's topographic roughness by defining a unit vector perpendicular to each cell in a landscape, based on both slope degree and aspect. The variability in unit vector direction is used to define the topographic roughness of a landscape. Significant differences in inverse vector dispersion between low (0 – 20 %) disturbance and high (80 – 100 %) disturbance landscapes were only apparent in the Boreal region, where low disturbance had higher inverse vector dispersion (1.07×10^{-2}) than landscapes with high disturbance (Avg. 1.04×10^{-2}, Appendix 5), which is due to the flatter high disturbance landscapes observed in the Boreal than what is observed in the Parkland or Grassland (Appendix 5).

Our research has shown that quantifying landscape roughness requires measurements of slope variability as well as elevation variability when assessing landscape roughness. In addition, the results suggest that reclamation plans have greater slope (focal slope var. 0.69 – 1.21) and elevation variability (global DEV 2.91 – 3.35) than what is observed in high disturbance landscapes to mimic natural landscapes (Appendix 5).

1.2 Configuration and Composition of Landform Elements

The spatial composition and configuration of the 12 landform elements was quantified using seven representative landscape metrics, radius of gyration, shape index, Euclidean nearest neighbour, proximity index, connectance index, Simpson's diversity index, and Shannon's evenness index. Chapter 2 discusses the aspects of landform spatial pattern that each metric measures and I build on that here by more thoroughly describing how landscape metrics can be used to design landscapes for reclamation. The seven representative landscape metrics can be grouped into four metric types based on the aspect of landform element spatial pattern that each metric measures (e.g., area/edge, shape, aggregation, diversity/evenness) and this section will provide an overview of how landscape metrics within each type can guide wetland reclamation designs.

Landform element area/edge quantifies the average landform element size within a landscape by measuring how far a landform element extends from its central point (McGarigal 2012). If a landscape has high area/edge metric values, quantified in this study by radius of gyration, then it can be determined that the landform elements in the landscape are large. One would expect landscapes with high area/edge to have low diversity as the landscape is likely dominated by a few large landform elements rather than a multitude of smaller landform elements. Since this study found that low disturbance landscapes had lower area/edge values (251.84 - 277.04) than high disturbance landscapes (276.59 – 287.58, Appendix 5), the results suggest that reclamation designs should incorporate multiple smaller landform elements into the design rather than dominating the landscape with a few large landform elements, which would provide landscapes with greater ecological and topographic diversity.

Shape landscape metrics measure how much the landform elements in a landscape deviate from a defined geometric shape (McGarigal 2012), quantified by deviation from a square using the shape index. Natural landform elements would likely have greater variability in their shape and this study corroborates this hypothesis by finding that high disturbance landscapes have lower shape values (1.80 – 1.94) than low disturbance landscapes (1.92 – 2.12, Appendix 5). The results suggest that a shape metric should be utilized in reclamation planning, rather than solely relying on the existing height-to-length ratios in current guidelines (Green Plan Ltd 2014), to ensure that landform element designs use unique and varied shapes to better mimic natural landscapes.

Landform element aggregation is measured using the proximity index, Euclidean nearest neighbour index, and connectance index, which all measure isolation, or how close landform elements of the same class occur in a landscape (McGarigal 2012). Landscapes with high proximity or connectance and low Euclidean nearest neighbour would have clusters of the same landform element near each other. While not as clear of a trend as other landscape metric types, generally high disturbance landscapes with 80 – 100 % disturbance have greater isolation (ENN_AM 74.95 – 83.13) than natural landscapes with 0 to 20 % disturbance (ENN_AM 42.65 – 69.29, Appendix 5), suggesting that landscape designs should place landform elements of the same type close together.

Finally, diversity/evenness metrics quantify how many different landform elements there are and how evenly the landform elements are spread across a landscape (McGarigal 2012), measured using Simpson’s diversity index and Shannon’s evenness index. A landscape with low diversity would likely be dominated by one or two large landform elements and have high area/edge metric values. This trend is observed in this study where high disturbance landscapes had higher area/edge values (GYRATE_AM 276.59 – 287.58) and lower diversity values (SIDI 0.49 – 0.50) compared to landscapes with 0 - 20 % disturbance (GYRATE 251.84 - 277.04, SIDI 0.51 – 0.60, Appendix 5). While a few landscapes had statistically different evenness values, there was not a consistent trend across compared landscapes by disturbance or natural region. To mimic natural landscapes, reclamation plans should ensure designed landscapes have a diverse range of landform elements.

To summarize, I recommend that landscape designs for wetland reclamation use a wide range (SIDI 0.51 – 0.60) of small (GYRATE 251.84 - 277.04), irregularly shaped (SHAPE_AM 1.92 – 2.12) landform elements near (ENN_AM 42.65 – 69.29) elements of the same type, to more closely mimic the topographic pattern of natural landscapes (Appendix 5).

2 Future Research Recommendations

While the research has been able to provide recommendations for how to better mimic natural landscapes when designing reclamation plans, two existing terrain analysis and topographic modelling methods have been identified that could improve the findings. Wet areas mapping and landscape evolution models are two existing methods that would be beneficial additions to this research and could create a more robust topographic characterization of wetland landscapes.

2.1 Wet-areas mapping

Wet areas mapping is a terrain analysis process used to identify locations with saturated soils and, given the academic evidence relating landforms and soil types (e.g., Florinsky et al. 2002, Böhner and Selige 2006, Dobos and Hengl 2009), would be a useful addition to quantify the relationship between landform elements and ‘wet areas’. Wet areas mapping estimates regions in a landscape that are likely to have saturated soil using the depth-to-water metric (Murphy et al. 2009), which is based on a location’s proximity to a known surface water body and the slope between those two points. This analysis method has been used to delineate regions susceptible to soil erosion and rutting (Ågren et al. 2014), locate ephemeral streams (White et al. 2012), estimate wetland locations (Murphy et al. 2007), and model forest soil properties (Murphy et al. 2011). The results from wet areas mapping are validated using either field surveys to collect data on soil type, drainage, and vegetation cover (Ågren et al. 2014, Murphy et al. 2011, Murphy et al. 2009) or results are compared to existing soil data sets (Murphy et al. 2007, White et al. 2012).

Incorporating existing wet-areas mapping techniques into the landscape-scale analysis would allow the quantification of the relationship between each landform element and its likelihood to have saturated soils, which would determine which landform elements have the greatest association with hydric soils and, potentially, wetlands. It would be beneficial to identify landform elements with a high proportion of saturated soils to improve where these landform elements are placed in wetland reclamation plans and could create more robust guidelines for how to design wetland landscapes.

In addition, wet areas mapping has been shown to be a useful tool to delineate wetland locations (Murphy et al. 2007) and it would be beneficial to test if this process could improve the accuracy of wetland inventories in Alberta. Alberta's wetland inventory has been identified as having inconsistent accuracy across its extent (Evans et al. 2017), which limits the research that can be conducted on relating topographic characteristics with specific wetland location. If wet areas mapping could improve the accuracy of Alberta's wetland inventory, it would allow this research to be extended to not just the topographic characteristics of wetland landscapes as a whole, but also quantify the topographic characteristics both within and surrounding wetland sites.

2.2 Landscape Evolution Models

Natural landscapes and their landform elements are assumed to be mature features that are less prone to erosion and landscape change than constructed landscapes (Martin-Duque et al. 2010, Thiffault et al. 2017, Ayres et al. 2006). The spatial pattern and composition of landform elements have been defined for landscapes along a gradient of disturbance, which provides an opportunity to test the assumption that natural landscapes are less prone to erosion (Martin-Duque et al. 2010) by using landscape erosion models. Existing soil erosion models could be applied to landscapes at each disturbance level and individually to each landform element to estimate the volume of sediment that would erode in each scenario. In addition to testing a landscape's resilience to erosion, this method would also provide a useful summary of landform elements that are least likely to experience erosion, which may assist in limiting soil erosion in future reclamation projects (Ayres et al. 2006).

Soil erosion is an important factor to consider when designing wetland landscapes for reclamation because soil loss can alter the created landscape shape and anticipated surface water flow paths (Hancock et al. 2008, Martin-Duque et al. 2010), decrease downstream water quality

(Martin-Duque et al. 2010), and impact the soil's nutrient availability and productive capability (Erwin 2009, Wall et al. 2002). To anticipate how resilient each landform element is to erosion and to model how a designed landscape's shape will evolve over time, traditional soil erosion models and more robust landscape evolution models, which simulate how a landscape's surface will change following years of erosion and deposition (Ayres et al. 2006), can be applied to landscapes with defined topographic characteristics.

Traditional soil erosion models estimate the erosion processes of soil detachment and deposition along a single hillslope based on set of input parameters that typically include slope length and angle, rainfall, soil type, and vegetation cover (Wall et al. 2002). These models, such as the Revised Universal Soil Loss Equation (RUSLE) and Water Erosion Prediction Program (WEPP), typically calculate erosion along a two-dimensional hillslope and multiple model iterations are often linked together to estimate landscape-scale erosion (Taylor et al. 2016). While these soil erosion models are useful for estimating rill erosion along a hillslope or in a watershed, they are not able to simulate how a landscape will evolve with continuous erosion and deposition over geomorphic time scales (Ayres et al. 2006). To simulate the future erosion of natural and disturbed landscapes, landscape evolution models could be used.

Landscape evolution models quantify the erosion response of a landscapes over long time scales and model the changes to a landscape's topography as erosion or deposition occurs (Ayres et al. 2006, Coulthard 2001). Two popular landscape evolution models are SIBERIA, which requires annual precipitation, a calibrated fluvial sediment transport equation, soil particle size, and topography parameters to simulate annual topographic evolution and erosion (Ayres et al. 2006, Willgoose, 2005), and CAESAR, which has a greater emphasis on hydrology and requires hourly rainfall, soil particle size, and topography to simulate a landscape's hourly erosion response (Hancock et al. 2010). While these two models have been shown to produce similar results after 1,000 years (Hancock et al. 2010), SIBERIA requires greater effort to set up and calibrate due to its dependence on a fluvial sediment transport equation than the CAESAR model (Hancock et al. 2010).

Landscape evolution models have been used in landform design and modelling for reclamation planning but have been limited to individual sites and projects (e.g., Taylor et al. 2006). If this research was extended by applying landscape evolution models to the thousands of different landscapes analyzed in this study, it would define a unique classification of the erosion response of landscapes along a gradient of disturbance and natural region. However, CAESAR and SIBERIA are sensitive to the accuracy of input parameters (Hancock et al. 2010), which limits the applicability of landscape evolution models to regions that have soil particle and hydrology data available at a high enough resolution to accurately model sediment transport and landscape evolution.

Applying a landscape evolution model to the study landscapes would provide insight on how each landform element responds to erosion and provide a clear example of how topographic baseline characteristics can be implemented in landscape design simulations. Running multiple iterations of a landscape evolution model using a range of landscapes with varying topographic roughness and landform element composition and configuration would allow us to determine what topographic characteristics are most resilient to erosion.

3 Expected Contributions and Broader Implications

This thesis has made contributions to wetland management and policy while also contributing to the academic terrain analysis and landscape ecology communities. The contributions and implications of the research have been divided into these two key areas: management and policy, and academic.

3.1 Management and Policy

As identified in Chapter 1, a goal of this thesis was to define baseline topographic characteristics of natural wetland landscapes to improve our understanding of these landscapes and improve the design of future wetland landscape reclamation projects. I have defined a set of terrain metrics that have been statistically proven to capture differences in topographic variation and spatial structure of wetland landscapes across natural regions and increasing levels of disturbance (Appendix 5).

The terrain roughness and landform element results can be utilized as a quantitative baseline in reclamation design of wetland landscapes since it has been shown that topographic variability and spatial pattern differs by natural region and between high-disturbance landscapes and landscapes with less than 80 % disturbance. While there were some exceptions, the research also shows that reclamation planners can establish baseline roughness and spatial pattern characteristics for landscapes within the same natural region as long less than 80 % of the landscape is disturbed.

In addition, the quantified topographic characteristics will contribute to ongoing research on characterizing wetland landscapes that will culminate in the creation of a tool to assist wetland reclamation at a landscape scale in Alberta. Future research will work to develop a wetland reclamation tool using a combination of topographic roughness and landform metrics, biologic features, land cover metrics (Evans et al. 2017), and future climate scenarios. The tool will be used to inform stakeholders involved in wetland reclamation on the necessary biophysical and geophysical characteristics that should exist within a reclaimed wetland ecosystem based on the characterization of existing, healthy wetlands.

We hope that the quantified topographic characteristics will assist the Government of Alberta to achieve their Water for Life goals, through which the province is striving to better understand wetland landscapes and improve wetland reclamation (Alberta Environment, 2003; Alberta Water Council, 2008). As was stated in Chapter 1, natural topographic characteristics have not been clearly defined in wetland reclamation guidelines and, by defining these characteristics, I hope to contribute to future wetland reclamation policy by outlining clearer guidelines to incorporate natural topographic characteristics into reclamation plans.

3.2 Academic

A second goal of this thesis was to define a clear methodology to analyze continuous landscape-scale elevation data and by doing so, I hope to contribute to the academic disciplines of landscape ecology and terrain analysis. The research methodology describes a process to quantify and compare the spatial pattern and roughness of topography in wetland landscapes at various disturbance levels and within three different natural. I believe this to be a unique method that has not previously been completed in terrain analysis or landscape ecology literature.

While the research was applied to a specific geographic region, southern Alberta, the methodology could be replicated and applied to other locations and the baseline topographic characteristics quantified can be used as a comparison for future studies.

References

Ågren AM, Lidberg W, Strömgren M et al (2014) Evaluating digital terrain indices for soil wetness mapping – a Swedish case study. Hydrology and Earth System Sciences Discussions, 11(4):4103–4129

Alberta Environment (2003) Water for life. Alberta Environment (Vol. 123). http://www.ncbi.nlm.nih.gov/pubmed/15296155

Alberta Environment and Sustainable Resource Development (ESRD) (2015) Alberta Wetland Classification System. Water Policy Branch, Policy and Planning Division, Edmonton, AB

Alberta Transportation (2014) General Design Guidelines for a Constructed 'Habitat' Wetland – Grasslands Natural Region of Alberta. Report prepared by Green Plan Lrd. http://www.transportation.alberta.ca/Content/docType29/production/DGfCHW_GrasslandsNaturalRegionofAlberta.pdf

Alberta Water Council (2008) Water for Life: A renewal. Government of Alberta.

AltaLIS (2015) Digital Elevation Model (DEM) Support Document

Ayres B, Dobchuk B, Christensen D, Kane MO, Fawcett M (2006) Incorporation of natural slope features into the design of final landforms for waste rock stockpiles. In 7th International Conference on Acid Rock Drainage. St. Louis MO

Bailey RC, Norris RH, Reynoldson TB (2004) Bioassessment of freshwater ecosystems: using the reference condition approach. Springer US, Boston

Bennie J, Hill MO, Baxter R, Huntley B (2006) Influence of slope and aspect on long-term vegetation change in British chalk grasslands. Journal of Ecology, 94:355–368

Böhner J, Selige T (2006) Spatial prediction of soil attributes using terrain analysis and climate regionalisation. Göttinger Geographische Abhandlungen, 115:13–28

Buchanan BP, Fleming M, Schneider RL et al (2014) Evaluating topographic wetness indices across central New York agricultural landscapes. Hydrology and Earth System Sciences, 18(8):3279–3299

Buckley BA (2010) Understanding curvature rasters https://blogs.esri.com/esri/arcgis/2010/10/27/understanding-curvature-rasters/

Burrough PA, Van Gaans PFM, Macmillan RA (2000) High-resolution landform classification using fuzzy k-means. Fuzzy Sets and Systems, 113:37–52

Burton PJ (1991) Ecosystem restoration versus reclamation: The value of managing for biodiversity (pp. 17–26). Kamloops, BC: The Technical and Research Committee on Reclamation

CH2MHILL (2013) Wetland Design Guidelines. Report prepared for City of Saskatoon. https://www.saskatoon.ca/sites/default/files/documents/transportation-utilities/construction-design/new-neighbourhood-design/wetlands_design_guidelines.pdf

Cohen MJ, Creed IF, Alexander L et al (2016) Do geographically isolated wetlands influence landscape functions?. Proceedings of the National Academy of Sciences, 113(8):1978-1986

Conly F, van der Kamp G (2001) Monitoring the hydrology of Canadian prairie wetlands to detect the effects of climate change and land use changes. Environmental Monitoring and Assessment, 67:195–215

Coulthard TJ (2001) Landscape evolution models: a software review. Hydrological Processes, 15:165–173

Cumulative Environmental Management Association (CEMA) (2014) Guidelines for Wetlands Establishment on Reclaimed Oil Sands Leases. Third Edition. Cumulative Environmental Management Association

Cushman SA, Huettmann F (2010) Spatial complexity, informatics, and wildlife conservation. Spatial Complexity, Informatics, and Wildlife Conservation 1–458

Davidson NC (2014). How much wetland has the world lost? Long-term and recent trends in global wetland area. Marine and Freshwater Research, 65:934–941

De Reu J, Bourgeois J, Bats M et al (2013) Application of the topographic position index to heterogeneous landscapes. Geomorphology, 186:39–49

de Groot RS, Alkemade R, Braat L et al (2010) Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity, 7(3):260–272

Deng Y, Wilson JP, Bauer BO (2007) DEM resolution dependencies of terrain attributes across a landscape. International Journal of Geographical Information Science, 21(2):187–213

Deng YX, Wilson JP (2006) The role of attribute selection in GIS representations of the biophysical environment. Annals of the Association of American Geographers, 96(1):47–63

Dobos E, Hengl T (2009) Soil Mapping Applications. In Hengl T, Reuter HI (Eds) Geomorphometry - Concepts, Software, Applications, Vol. 33. Elsevier, Amsterdam pp 461–479

D'Oleire-Oltmanns S, Eisank C, Drăgut L, Blaschke T (2013) An object-based workflow to extract landforms at multiple scales from two distinct data types. IEEE Geoscience and Remote Sensing Letters, 10(4):947–951

Drăguţ L, Blaschke T (2006) Automated classification of landform elements using object-based image analysis. Geomorphology, 81(3–4):330–344

Dubayah R, Rich PM (1995) Topographic solar radiation models for GIS. International Journal of Geographic Information Systems, 9(4):405–419

Ducks Unlimited Canada (2008). The Impacts of Wetland Loss.

Dunn OJ (1961) Multiple comparisons among means. Journal of American Statistical Association, 56(293):52-64

EPA (2013) A handbook of constructed wetlands (Vol. 1). Bibliogov. https://www.epa.gov/sites/production/files/2015-10/documents/constructed-wetlands-handbook.pdf

EPA (2000) Guiding Principles for Constructed Treatment Wetlands: Providing for Water Quality and Wildlife Habitat. https://nepis.epa.gov/Exe/ZyPDF.cgi/2000536S.PDF?Dockey=2000536S.PDF

Erwin KL (2009) Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and Management, 17:71–84

Evans IS (2012) Geomorphometry and landform mapping: What is a landform? Geomorphology, 137(1):94–106

Evans IS, Robinson DT, Rooney RC (2017) A methodology for relating wetland configuration to human disturbance in Alberta. Landscape Ecology, 32(10):2059–2076

Fang X, Pomeroy JW (2008) Drought impacts on Canadian prairie wetland snow, Hydrological Processes, 22:2858–2873

Fisette T, Davidson A, Daneshfar B et al (2014) Annual space-based crop inventory for Canada: 2009-2014. IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2014) 5095–5098

Florinsky IV (2012) Digital Terrain Analysis in Soil Science and Geology. Academic Press (First). Elsevier, Amsterdam

Florinsky IV, Eilers RG, Manning GR, Fuller LG (2002) Prediction of soil properties by digital terrain modelling. Environmental Modelling Software, 17(3):295–311

Carey G (1998) Multivariate Analysis of Variance (MANOVA): I. Theory. University of Colorado, Boulder, pp 14 http://ibgwww.colorado.edu/~carey/p7291dir/handouts/manova1.pdf

Gessler PE, Chadwick OA, Chamran F, Althouse L, Holmes K (2000) Modeling Soil–Landscape and Ecosystem Properties Using Terrain Attributes. Soil Science Society of America Journal, 64(6):2046-2056

Gleason RA, Laubhan MK, Euliss NH Jr (2008) Ecosystem services derived from wetland conservation practices in the United States Prairie Pothole Region with an emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs: U.S. Geological Professional Paper 1745

Grabs T, Seibert J, Bishop K, Laudon H (2009) Modeling spatial patterns of saturated areas: A comparison of the topographic wetness index and a dynamic distributed model. Journal of Hydrology, 373(1–2):15–23

Green Plan Ltd (2014) General Design Guidelines for a Constructed “Habitat” Wetland – Grasslands Natural Region of Alberta. Alberta Transportation, Edmonton

Grohmann CH (2004) Morphometric analysis in geographic information systems: Applications of free software GRASS and R. Computers and Geosciences, 30(9–10):1055–1067

Grohmann CH, Smith MJ, Riccomini C (2011) Multiscale analysis of topographic surface roughness in the Midland Valley, Scotland. IEEE Transactions on Geoscience and Remote Sensing, 49(4):1200–1213

Gruber S, Peckham S (2009) Land-surface parameters and objects in hydrology. In Hengl T, Reuter HI (Eds), Geomorphometry: Concepts, Software, Applications, Vol. 33 Elsevier, Amsterdam, pp 171–194

Hancock GR, Crawter D, Fityus SG, Chandler J, Wells T (2008) The measurement and modelling of rill erosion at angle of repose slopes in mine spoil. Earth Surface Processes and Landforms, 33:1006–1020

Hancock GR, Lowry JBC, Coulthard TJ, Evans KG, Moliere DR (2010) A catchment scale evaluation of the SIBERIA and CAESAR landscape evolution models. Earth Surface Processes and Landforms, 35:863–875

Hayashi M, van der Kamp G, Rosenberry DO (2016) Hydrology of prairie wetlands: understanding the integrated surface-water and groundwater processes. Wetlands, 36(2):237-254

Hayashi M, van der Kamp G, Rudolph DL (1998) Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. Journal of Hydrology, 207:42–55

Hengl T, MacMillan RA (2009) Geomorphometry - a key to landscape mapping and modelling. In Hengl T, Reuter HI (Eds) Geomorphometry: Concepts, Software, Applications, Vol. 33 Elsevier, Amsterdam, pp 433-460

Hengl T, Reuter HI (2009). Geomorphometry - Concepts, Software, Applications. Developments in Soil Science (Vol. 33). Elsevier, Amsterdam

Herzog F, Lausch A, Müller E, Thulke HH, Steinhardt U, Lehmann S (2001) Landscape metrics for assessment of landscape destruction and rehabilitation. Environmental Management, 27(1):91–107

Hiraishi T, Krug T, Tanabe K et al (2014) 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, IPCC, Switzerland

Hoechstetter, S, Walz U, Dang LH, Thinh NX (2008) Effects of topography and surface roughness in analyses of landscape structure - A proposal to modify the existing set of landscape metrics. Landscape Online, 3(1):1–14

Hofer G, Wagner HH, Herzog F, Edwards PJ (2008) Effects of topographic variability on the scaling of plant species richness in gradient dominated landscapes. Ecography, 31(1):131–139

Huang J, Li Q, Pontius R et al (2013) Detecting the dynamic linkage between landscape characteristics and water quality in a subtropical coastal watershed, Southeast China. Environmental management, 51(1):32-44

Huggett, RJ (1975) Soil landscape systems: A model of soil genesis. Geoderma, 13(1):1–22

Kauffman-Axelrod JL, Steinberg SJ (2010) Development and application of an automated GIS based evaluation to prioritize wetland restoration opportunities. Wetlands, 30(3):437–448

Keddy PA (2010) Wetland Ecology: Principles and Conservation, 2nd edn, Cambridge University Press, New York

Kheir RB, Wilson J, Deng Y (2007) Use of terrain variables for mapping gully erosion susceptibility in Lebanon. Earth Surface Processes and Landforms, 32:1770–1782

Klemas V (2013) Using Remote Sensing to Select and Monitor Wetland Restoration Sites: An Overview. Journal of Coastal Research, 29(4):958–970

Lang M, McCarty G, Oesterling R, Yeo IY (2013) Topographic Metrics for Improved Mapping of Forested Wetlands. Wetlands, 33(1):141–155

Lapen DR, Martz LW (1996) An investigation of the spatial association between snow depth and topography in a Prairie agricultural landscape using digital terrain analysis. Journal of Hydrology, 184(3–4):277–298

Lindsay JB, Cockburn JMH, Russell HAJ (2015) An integral image approach to performing multi-scale topographic position analysis. Geomorphology, 245(15):51–61

Lóczy D, Gyenizse P (2010) Human impact on topography in an urbanised mining area: Pécs, Southwest Hungary. Géomorphologie: relief, processus, environnement, 16(3):287-300

Los Huertos M, Smith D (2013) Wetland Bathymetry and Mapping. In Anderson JT, Davis CA (Eds) Wetland Techniques, Volume 1, pp 181–227

Martín-Duque JF, Sanz MA, Bodoque JM et al (2010) Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes. Earth Surface Processes and Landforms, 35(5):531-548

MacMillan RA, Martin TC, Earle TJ, McNabb DH (2003) Automated analysis and classification of landforms using high-resolution digital elevation data: Applications and issues. Canadian Journal of Remote Sensing, 29(5):592–606

MacMillan R, Pettapiece WW, Nolan SC, Goddard TW (2000) A generic procedure for automatically segmenting landforms into landform elements using DEMs, heuristic rules and fuzzy logic. Fuzzy Sets and Systems, 113(1):81–109

MacMillan RA, Shary PA (2009) Landforms and landform elements in geomorphometry. In Hengl T, Reuter HI (Eds) Geomorphometry - Concepts, Software, Applications, Vol. 33. Elsevier, Amsterdam pp 227-254

Martín-Duque JF, Sanz MA, Bodoque JM et al (2010) Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes. Earth Surface Processes and Landforms, 35(5):531-548

Mazerolle MJ, Villard MA (1999) Patch characteristics and landscape context as predictors of species presence and abundance: a review. Ecoscience, 6(1):117-124

McBratney AB, De Gruijter JJ, Brus DJ (1992) Spatial prediction and mapping of continuous soil classes. Geoderma, 54(1–4):39–64

McCauley LA, Anteau MJ, van der Burg MP, Wiltermuth MT (2015) Land use and wetland drainage affect water levels and dynamics of remaining wetlands. Ecosphere, 6(6):1–22

McGarigal K (2012) Landscape Pattern Metrics. In Encyclopedia of Environmetrics, 2nd edn. John Wiley & Sons

McGarigal K, Cushman SA, Ene E (2012) FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps. [Computer software] University of Massachusetts, Amherst http://www.umass.edu/landeco/research/fragstats/fragstats.html

McGarigal K, Tagil S, Cushman SA (2009) Surface metrics: An alternative to patch metrics for the quantification of landscape structure. Landscape Ecology, 24(3):433–450

McKenna G (2002) Sustainable mine reclamation and landscape engineering. Dissertation, University of Alberta

Mei X, Fan W, Mao X (2015) Analysis of impact of terrain factors on landscape-scale solar radiation. International Journal of Smart Home, 9(10):107–116

Metzger MJ, Bunce RGH, Jongman RHG et al (2013) A high-resolution bioclimate map of the world: A unifying framework for global biodiversity research and monitoring. Global Ecology and Biogeography, 22(5):630–638

Milne G (1947) A Soil Reconnaissance Journey Through Parts of Tanganyika Territory December 1935 to February 1936. Journal of Ecology, 35(1/2):192–265

Mitsch WJ, Gosselink JG (2007) Wetlands, 4th edn. John Whiley Sons, Hoboken

Moreno-Mateos D, Mander Ü, Comın FA et al (2008) Relationships between Landscape Pattern, Wetland Characteristics, and Water Quality in Agricultural Catchments. Journal of Environmental Quality, 37:2170–2180

Moreno-Mateos D, Power ME, Comin FA et al (2012) Structural and Functional Loss in Restored Wetland Ecosystems. PLoS Biology, 10(1):1-8

Murphy PNC, Ogilvie J, Arp PA (2009) Topographic modelling of soil moisture conditions: A comparison and verification of two models European Journal of Soil Science, 60(1):94–109

Murphy PNC, Ogilvie J, Connor K, Arp PA (2007) Mapping Wetlands: A Comparison of Two Different Approaches for New Brunswick, Canada. Wetlands, 27(4):846–854

Murphy PNC, Ogilvie J, Meng FR et al (2011). Modelling and mapping topographic variations in forest soils at high resolution: A case study. Ecological Modelling, 222(14):2314–2332

Nagamatsu D, Miura O (1997) Soil disturbance regime in relation to micro-scale landforms and its effects on vegetation structure in a hilly area in Japan. Plant Ecology, 133:191–200

Nellemann C, Fry G (1995) Quantitative analysis of terrain ruggedness in reindeer winter grounds. Arctic, 48(2):172–176

Nestler JM, Theiling CH, Lubinski KS, Smith DL (2010) Reference Condition Approach to Restoration Planning. River Research and Applications, 26:1199–1219

Natural Regions Committee (2006) Natural Regions and Subregions of Alberta. Compiled by Downing DJ, Pettapiece WW. Government of Alberta

Newcomer ME, Kuss AJM, Ketron T et al (2013) Estuarine sediment deposition during wetland restoration: A GIS and remote sensing modeling approach. Geocarto International, 29(4):451–467

Nwaishi F, Petrone RM, Price JS, Andersen R (2015) Towards Developing a Functional-Based Approach for Constructed Peatlands Evaluation in the Alberta Oil Sands Region, Canada. Wetlands, 35(2):211–225

Olaya V (2009) Basic land-surface parameters. In Hengl T, Reuter HI (Eds) Geomorphometry - Concepts, Software, Applications, Vol. 33. Elsevier, Amsterdam pp 141–169

Pennock DJ, Zebarth BJ, De Jong E (1987) Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. Geoderma, 40(3–4):297–315

Piehler MF, Smyth AR (2011) Habitat-specific distinctions in estuarine denitrification affect both ecosystem function and services. Ecosphere, 2(1):1-17

Pike RJ (2000) Geomorphometry – diversity in quantitative surface analysis. Progress in Physical Geography, 24(1):1–20

Price JS, McLaren RG, Rudolph DL (2010) Landscape restoration after oil sands mining: conceptual design and hydrological modelling for fen reconstruction. International Journal of Mining, Reclamation and Environment, 24(2):109–123

Rains MC, Leibowitz SG, Cohen MJ et al (2016) Geographically isolated wetlands are part of the hydrological landscape. Hydrological Processes, 30(1):153-160

Rashid H (2010) 3-D Surface-area computation of the state of Jammu Kashmir using Shuttle Radar Topographic Mission (SRTM) data in Geographical Information System. Journal of Geomatics, 4:77–82

Reuter HI, Wendroth O, Kersebaum KC (2006) Optimisation of relief classification for different levels of generalisation. Geomorphology, 77(1–2):79–89

Riitters KH, O'Neill RV, Hunsaker CT et al (1995) A factor analysis of landscape pattern and structure metrics. Landscape Ecology, 10(1):23–39

Rooney RC, Robinson DT, Petrone R (2015) Megaproject reclamation and climate change. Nature Clim. Change, 5(11):963–966

Rudy ACA, Lamoureux SF, Treitz P, van Ewijk KY (2016) Transferability of regional permafrost disturbance susceptibility modelling using generalized linear and generalized additive models. Geomorphology, 264:95–108

Schmidt J, Hewitt A (2004) Fuzzy land element classification from DTMs based on geometry and terrain position. Geoderma, 121(3–4):243–256

Shaw DA, Pietroniro A, Martz LW (2013) Topographic analysis for the prairie pothole region of Western Canada. Hydrological Processes, 27(22):3105–3114

Shaw DA, Vanderkamp G, Conly FM, Pietroniro A, Martz L (2012) The Fill-Spill Hydrology of Prairie Wetland Complexes during Drought and Deluge. Hydrological Processes, 26(20):3147–3156

Society for Ecological Restoration Science & Policy Working Group (SER) (2002) The SER Primer on Ecological Restoration. www.ser.org/

Sørensen R, Seibert J (2007) Effects of DEM resolution on the calculation of topographical indices: TWI and its components. Journal of Hydrology, 347(1-2):79–89

Sørensen R, Zinko U, Seibert J (2006) On the calculation of the topographic wetness index: Evaluation of different methods based on field observations. Hydrology and Earth System Sciences, 10(1):101–112

Stein ED, Mattson M, Fetscher AE, Halama KJ (2004) Influence of geologic setting on slope wetland hydrodynamics. Wetlands, 24(2):244–260

Stewart RE, Kantrud HA (1971) Classification of natural ponds and lakes in the glaciated prairie region. United States Department of the Interior (Vol. 92)

Stoddard JL, Larsen DP, Hawkins CP et al (2006) Setting Expectations for the Ecological Condition of Streams: The Concept of Reference Condition. Ecological Applications, 16(4):1267–1276

Suding KN (2011) Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution, and Systematics, 42:465-487

Summerell GK, Vaze J, Tuteja NK, Grayson RB, Beale G, Dowling TI (2005) Delineating the major landforms of catchments using an objective hydrological terrain analysis method. Water Resources Research, 41(12):1–12

Tagil S, Jenness J (2008) GIS-based automated landform classification and topographic, landcover and geologic attributes of landforms around the Yazoren Polje, Turkey. Journal of Applied Sciences, 8(6):910–921

Taylor I, Kemp A, O'Kane M, Walker S, Barteaux M, Laurencont T (2016) Designer waste landform modelling and design - Rum Jungle Mine. In Proceedings of the 11th International Conference on Mine Closure, Australian Centre for Geomechanics, pp 405-417

Thiffault E, Webster K, Lafleur B, Wilson S, Mansuy N (2017) Biophysical indicators based on spatial hierarchy for informing land reclamation: The case of the Lower Athabasca River. Ecological Indicators, 72:173–184

Thompson JA, Bell JC, Butler CA (2001) Digital elevation model resolution: Effects on terrain attribute calculation and quantitative soil-landscape modeling. Geoderma, 100(1–2):67–89

Trites M, Bayley SE (2009) Vegetation communities in continental boreal wetlands along a salinity gradient: Implications for oil sands mining reclamation. Aquatic Botany, 91(1):27–39

van der Kamp G, Hayashi M (2009) Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America. Hydrogeology Journal, 17:203–214

Van Meter KJ, Basu NB (2015) Signatures of human impact: size distributions and spatial organization of wetlands in the Prairie Pothole landscape. Ecological Applications, 25(2):451–465

Vitte D, Bhatti J (2012) Restoration and Reclamation of Boreal Ecosystems: Attaining Sustainable Development. Cambridge University Press

Wall GJ, Coote DR, Pringle EA, Shelton IJ (2002) RUSLEFAC - Revised Universal Soil Loss Equation for Application in Canada: A handbook for estimating soil loss from water erosion in Canada. Research Branch, Agriculture and Agri-Food Canada, Ottawa

Warne RT (2014) A Primer on Multivariate Analysis of Variance (MANOVA) for Behavioral Scientists. Practical Assessment, Research & Evaluation, 19(17):1-10

White D, Fennessy S (2005) Modeling the suitability of wetland restoration potential at the watershed scale. Ecological Engineering, 24:359–377

White B, Ogilvie J, Campbell DMHH et al (2012) Using the Cartographic Depth-to-Water Index to Locate Small Streams and Associated Wet Areas across Landscapes. Canadian Water Resources Journal, 37(4):333–347

Willgoose G (2005) User Manual for SIBERIA, Version 8.30

Wilson JP (2012) Digital terrain modeling. Geomorphology, 137(1):107–121

Wilson JP, Gallant JC (2000) Terrain Analysis: Principles and Applications. Terrain Analysis. John Wiley & Sons

Winter TC, Rosenberry DO (1998) Hydrology of prairie pothole wetlands during drought and deluge: A 17-year study of the Cottonwood Lake wetland complex in North Dakota in the perspective of longer term measured and proxy hydrological records. Climatic Change

Wood, J (1996) Geomorphological Characterisation of Digital Elevation Models. Dissertation, University of Leicester

Wortley L, Hero JM, Howes M (2013) Evaluating ecological restoration success: A review of the literature. Restoration Ecology, 21(5):537–543

Wu J (2013) Landscape Ecology. In Leemans R (Ed) Ecological Systems: Selected Entries from the Encyclopedia of Sustainability Science and Technology. Springer, New York pp 179–200

Wu J, Jelinski DE, Luck M, Tueller PT (2000) Multiscale Analysis of Landscape Heterogeneity: Scale Variance and Pattern Metrics. Geographic Information Sciences, 6(1):6-19

Yeh AG, Li X (1998) Sustainable land development model for rapid growth areas using GIS. International Journal of Geographic Information Science, 12(2):169–189

Zaller JG, Moser D, Drapela T et al (2008) Insect pests in winter oilseed rape affected by field and landscape characteristics. Basic and applied ecology, 9(6):682-690

Zedler JB, Kercher S (2005) Wetland Resources: Status, Trends, Ecosystem Services, and Restorability. Annu. Rev. Environ. Resour. 30:39–74

Zevenbergen LW, Thorne CR (1987) Quantitative Analysis of Land Surface Topography. Earth Surface Processes and Landforms, 12:47–56

Zhang B, Schwartz FW, Liu G (2009) Systematics in the size structure of prairie pothole lakes through drought and deluge, 45:1–12

Zhiming Z, Van Coillie F, De Wulf R, De Clercq EM, Xiaokun O (2012) Comparison of Surface and Planimetric Landscape Metrics for Mountainous Land Cover Pattern Quantification in Lancang Watershed , China. Mountain Research and Development, 32(2):213–225.

Zhou Q, Lees B, Tang G (2008) Advances in Digital Terrain Analysis. Springer

Appendix 1 - Primary Terrain Metrics

Table 1.1 Frequently used primary terrain metrics. Sources that have used or referenced a terrain metric are marked using an ‘x’ under the authors’ name

Name	Description	Agren et al. 2014	Florinsky et al. 2002	Florinsky 2012	Gessler,et al. 2000	Gruber and Peckham 2009	Lang et al. 2013	Murphy et al. 2007	Murphy et al. 2009	Murphy et al. 2011	Olaya 2009	Wilson and Gallant 2000	Wilson 2012	White et al. 2012
Upslope Height	Average height of upslope area											x		
Aspect	The azimuth angle of the slope	x	x	x		x				x	x	x	x	
Slope	The gradient of the land surface	x	x	x	x	x		x	x	x	x	x	x	x
Upslope slope	The mean gradient of the upslope area			x								x	x	
Dispersal slope	The mean gradient of the dispersal area			x								x	x	
Catchment slope	The average gradient over the whole catchment			x								x		
Upslope area	The catchment area above a short length of contour	x		x		x		x	x	x		x	x	
Dispersal Area	The area downslope from a short length of contour			x								x		
Catchment Area	The area draining to a catchment outlet	x	x	x		x					x	x		
Specific Catchment area	Upslope area per unit width of contour			x								x		
Flow path length	The maximum distance of water flow to a given point in the catchment		x	x		x		x		x		x	x	x

Name	Description	Agren et al. 2014	Florinsky et al. 2002	Florinsky 2012	Gessler,et al. 2000	Gruber and Peckham 2009	Lang et al. 2013	Murphy et al. 2007	Murphy et al. 2009	Murphy et al. 2011	Olaya 2009	Wilson and Gallant 2000	Wilson 2012	White et al. 2012
Upslope length	Mean length of flow paths to a point in the catchment			x								x		
Dispersal length	Distance from a point in the catchment to the outlet point			x								x		
Catchment length	Distance from the highest elevation point to the outlet point			x								x		
Profile curvature	The profile curvature of the slope, which influences the rate of water flow	x	x	x	x						x	x	x	
Plan curvature	The contour curvature, which influences the convergence on divergence of water flow	x	x	x							x	x	x	
Mean Curvature	An average of the calculated profile and plan curvature values		x											
Topographic Position Index	The difference between a cell's elevation and the average elevation of the surrounding cells	x		x									x	
Flow Routing	The cell-by-cell direction which water would flow on the landscape.	x		x	x		x	x	x	x	x	x		x

Table 1.2 Ecological significance of primary terrain metrics (Ågren et al. 2014, Wilson 2012, White et al. 2012, Olaya 2009, Wilson and Gallant 2000)

Terrain Metric Name	Ecological or Geophysical Significance
Aspect	Can be used to determine the direction of flow, ground latent and sensible heat flux, and distribution of flora or fauna
Catchment Area	In combination with catchment slope, determines the total runoff volume of the study area
Catchment length	Impacts the overland flow that will be attenuated into local storage
Catchment slope	In combination with catchment area, the average slope helps determine total runoff volume of the area
Depth to Water (D_{TW})	Can be used to determine the location and extent of wet areas on a landscape, including wetlands, ponds, and streams, and can calculate the water table elevation
Dispersal Area	In combination with dispersal slope, determines the rate of soil drainage
Dispersal length	The total distance from a point to the outflow of the catchment would describe the impedance to soil drainage of the point
Dispersal slope	In combination with dispersal area, the average slope helps determine the rate at which wetland would drain
Flow path length	The total distance that water flows to a given point influences the erosion rates and total sediment yield at that point
Flow Routing	The path that overland water would flow impacts the volume of water that accumulates and the location of saturated land
Mean Curvature	The average of both plan and profile curvature can be used to estimate both the acceleration and divergence of water flow
Plan curvature	Influences whether water flow is diverging or converging and the soil water content
Profile curvature	Influences the acceleration or deceleration of flowing water and the erosion or deposition rate
Roughness	The roughness of the landscape can be used to characterize the exposure of the landscape to wind and wind directions
Slope	A key component in the calculation of the rate of overland and subsurface flow, soil moisture content, and is an input in many other terrain metrics
Specific Catchment area	The catchment area for a specific elevation region impacts runoff volume, soil-water content, and runoff rate for that region
Strahler Stream Order	Calculating the presence of streams in the landscape can be used to indicate presence of saturated soil. The closer a cell is a to a higher order stream, the more likely the ground will be saturated.
Stream-power indices	Its output provides a measure of the erosive power of certain reach of flowing water, with influences sediment yield of the stream and erosion potential

Topographic Depression Status	The value of this metric describes the ability of surface water to accumulate in an area of lower elevation than the surrounding area, a high value designates an area with a topographic depression and would be a likely area for a wetland
Topographic Position Index	Its measurement of the ridges, valleys, and flat areas of a region can be used to find regions that would likely contain wetter soil and potentially wetland ecosystems
Topographic Wetness Index	Used to predict the location and extent of zones of saturation, which can contribute to runoff generation and surface water ponding and is an indication of a wetland ecosystem
Upslope area	In combination with upslope slope, determines the runoff volume of an upslope area, which influences the water availability for the point of interest and downslope regions
Upslope Height	It can be used to estimate the potential energy of the system, since it is based on the height of the local topographic high
Upslope length	Influences flow acceleration and the rate of erosion above a certain point of interest, can be used to determine the water flow and sediment load into a wetland
Upslope slope	Average slope of upslope area would determine the speed of runoff into the wetland

Appendix 2 - Secondary Terrain metrics

Table 2.1 Commonly used secondary terrain metrics. Sources that have used or referenced a terrain metric are marked with an ‘x’ under the authors’ name

Name	Description	Agren et al 2014	Florinsky 2012	Gessler et al. 2000	Grabs et al. 2009	Gruber and Peckham 2009	Lang et al. 2013	Murphy et al. 2007	Murphy et al. 2009	Murphy et al. 2011	Sorensen et al. 2006	Sorensen and Seibert 2007	Tang et al. 2012	White and Fennessy 2005	White et al. 2012	Wilson and Gallant 2000	Wilson 2012
Roughness	The complexity or variability in the catchment terrain					x									x		x
Topographic Depression Status	Calculates the ability of surface water to accumulate in depressions in the surface												x		x		
Strahler Stream Order	Calculates the strahler stream order of the local stream network to determine the distance of each cell to a higher order stream		x			x								x			
Topographic Wetness Index	Quantifies the topographic control on hydrologic processes, variations in the calculation are based on different flow routing algorithms	x	x	x	x	x	x	x	x	x	x	x		x		x	x
Depth to Water	The elevation difference between a point and the closest open water feature	x	x					x	x	x					x		
Stream-power indices	A measure of the erosive power of flowing water		x			x	x									x	x

Appendix 3 - Wetland Reclamation Design Guidelines

Table 3.1 Overview of wetland reclamation design guidelines

Organization	Guidelines	Shoreline Slope Ratio
Alberta Transportation (Alberta Transportation 2014)	Gentle slopes surrounding a wetland at a 2:1 or 3:1 height to length ratio that will guide runoff into a wetland and irregular shorelines for the wetland itself	3:1 adjacent to open water; 6:1 in the littoral zone; variable slopes after.
United States Environmental Protection Agency (EPA 2015)	Recommends selecting sites for reclamation that have gradual slopes and can be easily altered. Primarily recommends finding sites with natural topography rather than constructing a landscape to mimic natural topography.	N/A
United States Environmental Protection Agency (EPA 2000)	Use existing natural landforms and gravity when designing wetlands. Ensure wetland and adjacent land have topographic variability and diversity.	N/A
City of Saskatoon (CH2MHILL 2013)	Design should have the goal of attaining 'naturalistic' features that mimic existing natural wetlands, including undulating boundaries and natural landform shapes. Wetland itself should have a length to width ratio greater than 1:1 with some consensus of ideal ratio between 2:1 < L:W < 4:1.	3.5:1 or lower slope angle directly adjacent to the wetland.

Appendix 4 - Roughness Metric Calculation

The DEV metric calculates a value for each cell that describes the cell's deviation from the mean elevation of a surrounding region of a user-defined size (Lindsay et al. 2015; De Reu et al. 2013). This metric was adapted for this study by using the mean elevation of each sample landscape and subtracting this average value from each elevation value in the landscape. The result was a measure of each cell's deviation from the mean landscape elevation and the absolute value of the deviation was then calculated. Finally, the average of the absolute deviation from mean elevation was calculated for each landscape. This calculation methodology for the DEV metric results in each landscape having a single value for average deviation from mean elevation while ensuring that a true representation of the elevation variation is retained.

Three standard deviation based metrics were all calculated using a similar formula but with three different inputs: elevation, profile curvature, or slope. Each metric is calculated by finding the standard deviation of the input values within a defined region, either focally using a moving window then obtaining the average value for each landscape or globally using the entire distribution of values in a landscape. Standard deviation is calculated by squaring the result of subtracting the mean value of a region from a given cell within the region, this is repeated for each cell in the region and all resultant values are summed together. Finally, the summed values are divided by the number of cells in the region and the square root is then taken. Standard deviation is a straight forward method of quantifying elevation variation occurring within a region (Grohmann 2011).

A cell's area in a digital elevation model is not the true area of the surface since it does not incorporate the additional area created by a sloping land surface (Rashid 2010). A proxy for a region's surface roughness can be quantified by finding the ratio between a region's 2-Dimensional surface area and its true 3-Dimensional surface area. The area ratio metric is calculated by first finding 3D area by dividing the 2D area, simply the length multiplied by the width of each 5x5 window (2,500 m^2), by the cos of the slope (Equation 1). The 3D area is then divided by the 2D area to find the area ratio value, where a value of 1 would indicate a flat surface and a moderately hilly region would have a value of 1.3 (Rashid 2010). For example, a region with a maximum slope of 11 degrees would have a 3D surface area equal to 2,546.86 m^2 (2,500 / cos (11)) or 2,500 / 0.9816), which would result in an area ratio of 1.0187

Equation 1: 3D area calculation

$$3Darea = (2Darea)/\cos(slope)$$

Slope variability is a measure of the range in slope values that occur within a defined region. It is calculated by subtracting a region's minimum slope value from the same region's maximum slope value (Grohmann 2011). The simplicity of this equation allows slope variability to be implemented at a variety of scales and was calculated directly for each landscape as well as focally with a moving 5X5 window then averaged across each landscape.

Vector dispersion is quantified by defining unit vectors normal to the cell plane based on each cell's slope and aspect. Vector strength and dispersion are then calculated using a series of equations (Equation 2) and can be used to understand the roughness of a surface. Areas with high roughness will result in low vector strength and high vector dispersion, with the opposite occurring in regions with a smooth surface.

Equation 2: Vector Dispersion Calculation.

$$\text{Colatitude} = 90.0 - \text{Slope}$$

$$x_i = \sin(Colatitude) * \cos(Aspect) \quad \mathrm{y}_i = \sin(Colatitude) * \sin(Aspect) \quad z_i = \cos(Colatitude)$$

$$\overline{x_i} = \sum_{i=1}^{m_1} \mathrm{x}_i \qquad \overline{y_i} = \sum_{i=1}^{m_1} \mathrm{y}_i \qquad \overline{z_i} = \sum_{i=1}^{m_1} z_i$$

$$VectStrength = \sqrt{\overline{x_i}^2 + \overline{y_i}^2 + \overline{z_i}^2}$$

$$Vector\ Dispersion = 1/\left(\frac{N-1}{N - VectStrength}\right)$$

Note: m_1 is a 5x5 cell window centered on cell i, N = number of cells in window (15)

Appendix 5 - Representative Metrics Summary Statistics and Boxplots

Table 5.1 Mean and Standard deviation values for representative TRMs for each natural region and disturbance group. Values are rounded to two decimal places for visual clarity, except for Area Ratio, which required four decimal places, and Inverse Vector Dispersion, which was best shown using scientific notation.

	Disturbance (%)	0 - 20		20 - 40		40 - 60		60 - 80		80 - 100	
	Metric Name	median	SD	median	SD	median	SD	median	SD	median	SD
Boreal	FclSlpVar	0.69	0.79	0.89	0.86	0.67	0.78	0.67	0.67	0.43	0.47
	GblSlpVar	5.04	4.82	6.44	5.42	4.87	4.80	5.00	4.65	3.12	3.18
	AreaRatio	1.0004	0.002	1.0006	0.002	1.0004	0.001	1.0003	0.001	1.0002	0.001
	GblDEV	2.91	3.91	3.50	4.98	3.33	3.00	3.14	3.32	2.41	2.11
	FclInvVecDisp	1.07E-02	7.17E-04	1.08E-02	6.80E-04	1.07E-02	8.17E-04	1.08E-02	7.64E-04	1.04E-02	7.44E-04
Parkland	FclSlpVar	1.21	1.13	1.49	1.50	1.68	1.04	1.26	1.01	0.61	0.57
	GblSlpVar	7.09	5.90	7.40	8.01	9.47	7.08	6.76	5.81	3.99	3.71
	AreaRatio	1.0007	0.002	1.0011	0.005	1.0013	0.003	1.0007	0.002	1.0002	0.001
	GblDEV	3.15	3.90	4.35	9.28	5.12	6.20	3.61	4.09	2.17	2.50
	FclInvVecDisp	1.05E-02	4.67E-04	1.05E-02	4.88E-04	1.08E-02	4.27E-04	1.08E-02	6.07E-04	1.06E-02	7.68E-04
Grassland	FclSlpVar	0.83	1.19	0.80	0.95	1.00	1.05	0.90	0.81	0.53	0.47
	GblSlpVar	5.58	6.80	5.29	6.09	5.74	7.09	5.85	6.30	3.54	3.90
	AreaRatio	1.0005	0.004	1.0004	0.002	1.0006	0.003	1.0005	0.001	1.0002	0.001
	GblDEV	3.35	5.39	3.51	3.51	3.39	4.32	3.54	3.36	2.50	2.48
	FclInvVecDisp	1.07E-02	6.65E-04	1.06E-02	6.62E-04	1.08E-02	5.89E-04	1.08E-02	7.35E-04	1.07E-02	8.04E-04

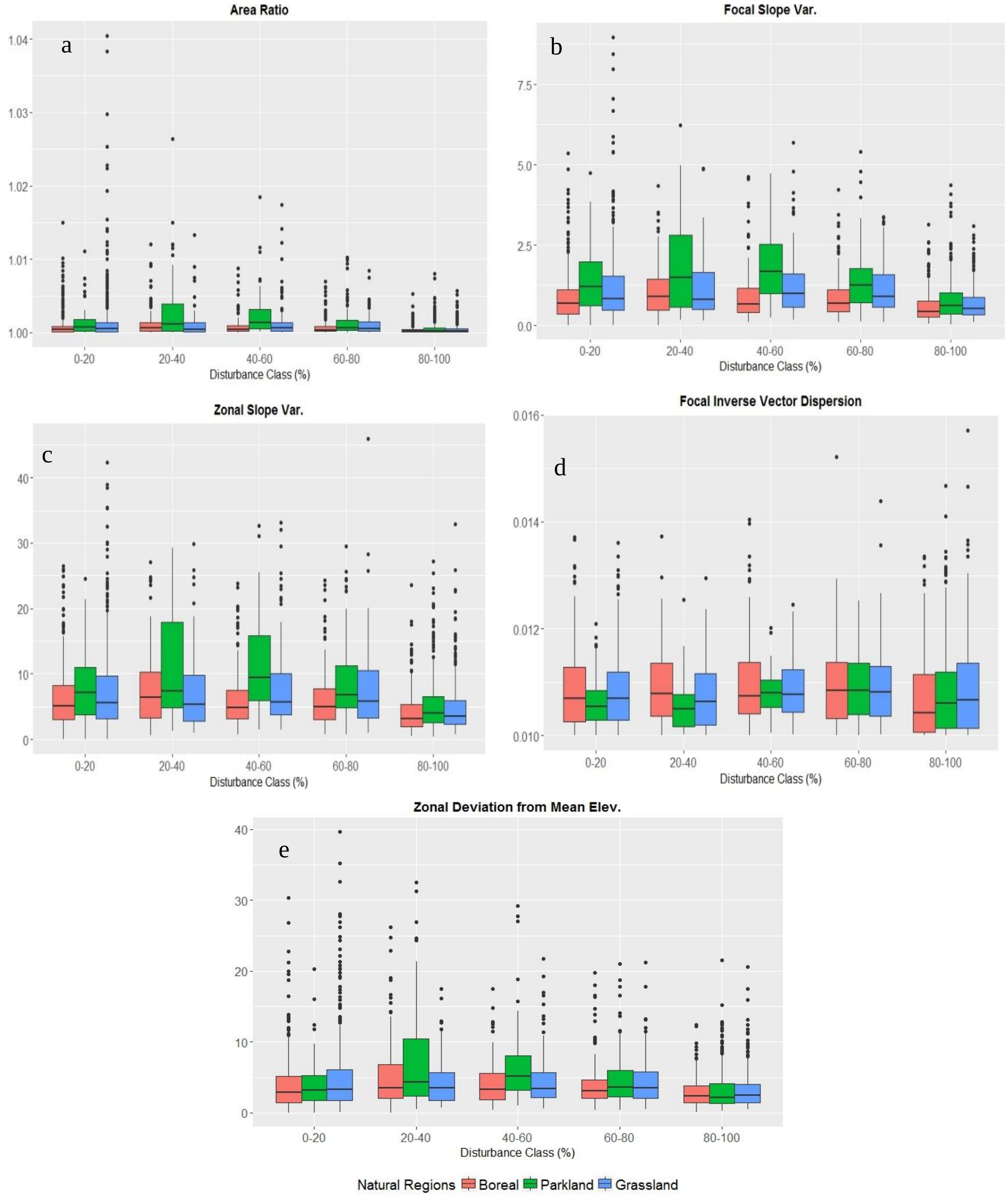


Fig. 5.1 Boxplots of representative TRMs: Area Ratio (a), focal slope variability (b), global slope variability (c), focal inverse vector dispersion (d), and global deviation from mean elevation (e).

Table 5.2 Median and standard deviation values for representative landscape metrics for each natural region and disturbance class. Values are rounded to two decimal places for visual clarity.

	Disturbance (%)	0 - 20		20 - 40		40 - 60		60 - 80		80 - 100	
	Metric Name	median	SD	median	SD	median	SD	median	SD	median	SD
Boreal	GYRATE_AM	277.04	62.53	258.20	63.76	272.48	57.23	274.39	53.21	287.58	44.53
	PROX_AM	2.11	32.28	5.33	23.48	2.47	19.59	2.59	40.41	1.62	32.40
	SIDI	0.51	0.18	0.56	0.16	0.51	0.14	0.50	0.12	0.49	0.12
	SHEI	0.51	0.21	0.54	0.17	0.52	0.18	0.52	0.19	0.55	0.24
	SHAPE_AM	1.92	1.02	1.96	0.46	1.83	0.40	1.87	0.44	1.80	0.39
	ENN_AM	65.18	65.90	66.87	55.06	65.80	67.26	85.90	73.43	83.13	83.79
	CONNECT	13.64	15.25	14.98	14.99	14.29	16.89	15.15	14.31	15.30	16.09
Parkland	GYRATE_AM	251.84	89.06	211.55	83.84	214.58	67.47	241.01	68.76	276.59	48.38
	PROX_AM	6.06	20.48	6.46	17.14	10.43	18.82	7.89	17.06	3.61	40.51
	SIDI	0.60	0.22	0.69	0.18	0.69	0.14	0.60	0.14	0.50	0.11
	SHEI	0.58	0.24	0.63	0.19	0.61	0.16	0.53	0.17	0.50	0.22
	SHAPE_AM	2.12	0.52	2.08	0.47	2.20	0.42	2.21	0.45	1.94	0.44
	ENN_AM	42.65	56.29	51.58	52.97	53.11	48.53	53.13	53.53	74.95	67.33
	CONNECT	8.96	8.42	9.43	12.92	10.45	7.76	11.04	11.67	14.47	12.83
Grassland	GYRATE_AM	262.28	68.38	256.65	66.78	254.04	58.67	259.62	62.09	276.85	43.47
	PROX_AM	5.41	31.55	5.76	24.01	6.33	22.95	4.99	23.01	1.96	30.98
	SIDI	0.54	0.15	0.54	0.14	0.57	0.14	0.54	0.14	0.50	0.10
	SHEI	0.56	0.19	0.59	0.19	0.53	0.16	0.52	0.18	0.51	0.22
	SHAPE_AM	2.01	0.42	2.01	0.39	1.97	0.41	1.99	0.45	1.85	0.38
	ENN_AM	69.29	61.33	70.18	52.96	81.92	57.38	71.20	71.27	79.77	78.12
	CONNECT	13.44	13.03	14.44	14.34	13.64	11.87	14.62	11.89	15.98	16.23

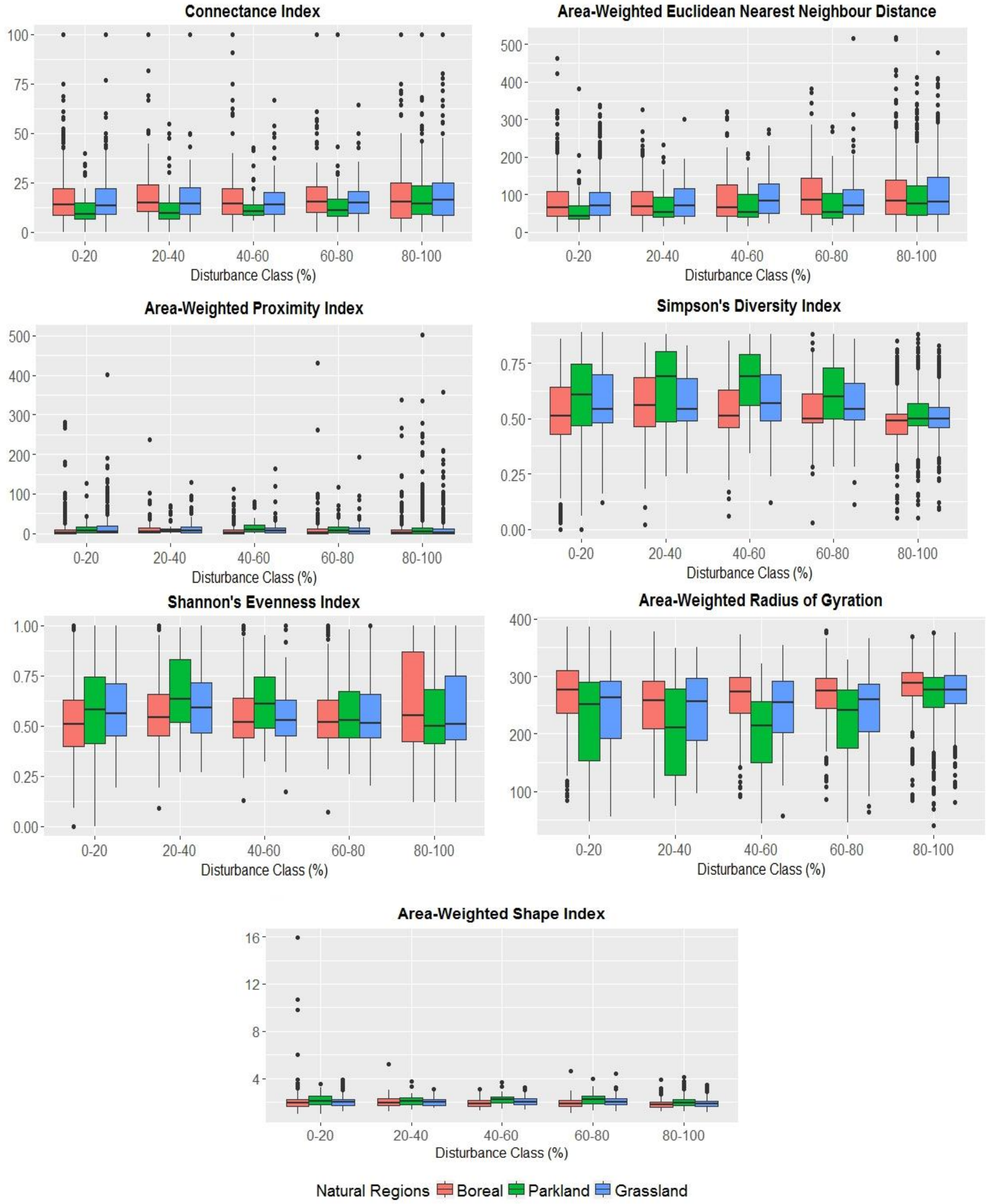


Fig. 5.2 Boxplots of representative landscape metrics. Colour gradient denotes natural region and each boxplot's x-axis denotes the proportion of disturbance

Appendix 6 - Landform Classification Calculation

The slope metric was calculated using the D8-algorithm and was classified into three classes to designate flat regions (zero degree slopes), low slope regions (greater than zero and less than three degrees slopes), and high slope regions (greater than three degrees slopes) (Table 4.1). Classification ranges were selected based on the understanding that a three-degree slope threshold value corresponds with a change in hydrologic activity (Macmillan et al. 2000).

Profile curvature was calculated based on Zeverbergen and Thorne's (1987) algorithm, which produces profile curvature signs opposite to alternative algorithms (Pennock et al. 1987, MacMillan et al. 2000) and requires care to ensure congruence with literature-derived landform classification criteria. Threshold values for each profile curvature class varies from 0.1 Deg/100 m (Pennock et al. 1987, Reuter et al. 2006) to 10 Deg/100 m (MacMillan et al. 2000). Iterative geovisualization of threshold values at 0.01, 0.05, 0.1, 1, and 10 resulted in the selection of a +/- 0.05 Deg/100 m profile curvature threshold value based on its ability to best visually represent the elevation contours in this study area. The profile curvature was reclassified to define convex (water shedding), linear, and concave (water ponding) regions (Table 4.1).

Plan curvature was also calculated based on Zeverbergen and Thorne's (1987) algorithm but produced plan curvature signs in agreement with existing landform literature (Pennock et al. 1987, MacMillan et al. 2000). Following an iterative process similar to the profile curvature process, a threshold value of +/- 0.05 was selected for plan curvature. Negative values (< -0.05) designate horizontally concave surfaces that would experience converging flow while positive values (> 0.05) designate horizontally convex surfaces that would experience diverging flow. Zero values (- 0.05 - + 0.05) designate horizontally linear surfaces (Table 4.1).

A deviation from mean elevation (DEV) metric was calculated that quantified each cell’s deviation from a landscape’s mean elevation to quantify high and low elevation regions in each landscape. The DEV metric calculation followed a similar methodology to the DEV metric outlined in the roughness analysis section but with small modifications to ensure the metric output was suitable for landform classification. This study’s use of the DEV metric differs from existing DEV calculations (e.g., Lindsay et al. 2015, De Reu et al. 2013) by using the mean elevation of each 1 km sq landscape, whereas existing studies calculate the mean elevation surrounding each cell using a moving window. The mean elevation of the entire landscape was used to ensure that the metric output highlighted the high and low elevation regions of each landscape, rather than localized elevation extremes in a moving window. Each cell’s elevation value was subtracted from the mean elevation of the landscape and then divided by the standard deviation of each landscape’s elevation. Dividing the elevation deviation by the standard deviation improves the interpretation of the DEV metric and allowed most of the metric values to fall between -1 and 1 (De Reu et al. 2013). The DEV metric was then reclassified to create three distinct classes of low elevation position (< -0.5), middle elevation position (-0.5 – 0.5), and high elevation position (> 0.5) (Table 4.1).

Table 6.1 Value ranges used to reclassify input terrain metrics for landform element classification (Pennock et al. 1987, MacMillan et al. 2000, Reuter et al. 2006).

Metric	Class Range	Class Value	Description
Deviation from mean elevation (DEV)	< -0.5	1000	Low Elevation Regions
	-0.5 – 0.5	2000	Mid Elevation Regions
	>0.5	3000	High Elevation Regions
Slope (Degrees)	0	100	No Slope
	0 – 3	200	Low Slope
	>3	300	High Slope
Profile Curvature (1/100 m)	< - 0.05	10	Convex (Shedding)
	-0.05 – 0.05	20	Linear
	>0.05	30	Concave (Ponding)
Plan Curvature (1/100 m)	< - 0.05	1	Concave (Converging)
	-0.05 – 0.05	2	Linear
	>0.05	3	Convex (Diverging)

The reclassified terrain metrics (Table 4.1) were summed together to generate distinct topographic features with unique class codes that describe the range of each input terrain metric. For example, topographic feature 1231 would refer to a feature in the low elevation position with a low slope (0 – 3 Degrees), concave profile curvature (> 0.05 1/100 m), and concave plan curvature (< - 0.05 1/100 m). The class creation process generated 57 unique topographic features from which landform elements were defined by grouping features (In text Table 3) based on established landform classification criteria (MacMillan et al. 2000, Reuter et al. 2006).

Appendix 7 - Landscape Metric Calculation

Area-weighted mean was calculated for each metric that used distribution statistics. The following equations display how the distribution statistics are calculated, where X designates the specific metric of interest, and a_{ij} is the area of patch ij.

Area-weighted mean equation:

$$AM = \sum_{i=1}^{m} \sum_{j=1}^{n} \left[X_{ij} \quad \left(\frac{a_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}} \right) \right]$$

Table 7.1 Calculations and descriptions for the seven representative landscape metrics

Type	Metric	Acronym	Description	Formula	Units	Range
Area/Edge	Radius of Gyration	GYRATE	Describes how far a landform element reaches, measured by the distance between each cell in an element and the element's centroid	$\frac{\sum_{r=1}^{Z} h_{ijr}}{Z}$	Metres	GYRATE ≥ 0
Shape	Shape Index	SHAPE	Measures how irregular the shape of each landform element patch is, with 1 representing a square patch	$\frac{p_{ij}}{\min p_{ij}}$	None	SHAPE ≥ 1
Aggregation	Euclidean Nearest Neighbour	ENN	Measures the distance from the edge of each landform element to the nearest patch of the same element, describes how isolated each landform element is within a landscape	h_{ij}	Metres	ENN > 0

Type	Metric	Acronym	Description	Formula	Units	Range
Aggregation	Proximity Index	PROX	Measures how close landform elements of the same type are by dividing the patch area by the distance to the edge of a patch of the same landform element type	$\sum_{s=1}^{n} \frac{a_{ijs}}{h_{ijs}2}$	None	PROX ≥ 0
Aggregation	Connectance Index	CONNECT	Describes how connected the landform element patches are by searching for the same landform element within 100 m of each element	$\left[\frac{\sum_{j\neq k}^{n} c_{ijk}}{\frac{n_i(n_i-1)}{2}}\right](100)$	Percent	0 ≤ CONNECT ≤ 100
Diversity/ Evenness	Simpson's Diversity Index	SIDI	A measure of how diverse landform elements are within a sample landscape, based on the probability that two randomly selected pixels would be from different landform elements	$1-\sum_{i=1}^{m} {P_i}^{2}$	None	0 ≤ SIDI < 1
Diversity/ Evenness	Shannon's Evenness Index	SHEI	Describes the distribution of landform elements in a landscape, a SHEI value close to 1 indicates that landform elements within a landscape have an even distribution of area	$\frac{-\sum_{i=1}^{m}(P_i * \ln P_i)}{\ln m}$	None	0 ≤ SHEI < 1

a_{ij}= area of landform element ij

h_{ij} = distance from element ij to nearest element of the same type

h_{ijr} = distance between cell ijr and centroid of element ij

Z = number of cells in element ij

P_i = proportion of landscape occupied by element i

p_{ij} = perimeter of element ij

a_{ijs}= area of element ijs within defined neighbourhood (m) of element ij

c_{ijk} = joining between element j and k of element type i where 0 = unjoined and 1 = joined

h_{ijs} = edge-to-edge distance between element ijs and element ijs

m = number of element types in the landscape

n_i = number of elements in the landscape of the same type

Appendix 8 - Correlation Grouping for Roughness Metrics

Table 8.1 TRM groups based on correlation analysis, where the prefix Fcl designates the focal calculation method and the prefix Gbl designates the global calculation method.

Representative	Other Group Members				
Focal Slope Variability	FclPrfCrv	GblPrfCrv	FclDEV	FclSDSlp	FclSDElev
Global Slope Variability	GblSDSlp				
Area Ratio					
Global DEV	GblSDElev				
Focal Inv. Vector Dispersion					

Appendix 9 – Full Tables for Roughness and Landform Analysis Results

Table 9.1 Differences between landscapes with different proportions of disturbance for each TRM by natural region, calculated using a Kruskal-Wallis test. Chi-squared, degrees of freedom and p-value reported

	Metric	Chi-squared (*H*)	d.f.	*p*
Boreal	Focal Slope Var.	88.26	4	3.09E-18
	Global Slope Var.	97.14	4	4.01E-20
	Area Ratio	85.48	4	1.20E-17
	Global DEV	42.95	4	1.06E-08
	Inv. Vector Dispersion	36.65	4	2.13E-07
Parkland	Focal Slope Var.	145.34	4	2.03E-30
	Global Slope Var.	131.73	4	1.66E-27
	Area Ratio	127.53	4	1.32E-26
	Global DEV	84.70	4	1.76E-17
	Inv. Vector Dispersion	15.59	4	3.62E-03
Grassland	Focal Slope Var.	112.39	4	2.25E-23
	Global Slope Var.	87.45	4	4.59E-18
	Area Ratio	83.81	4	2.71E-17
	Global DEV	38.79	4	7.69E-08
	Inv. Vector Dispersion	6.63	4	1.57E-01

Table 9.2 Differences in landscapes in different natural regions with the same disturbance level by TRM, calculated using Kruskal-Wallis. P-values shown first followed by H statistic in brackets, all tests have 2 degrees of freedom

	Disturbance (%)				
Metric	0-20	20-40	40-60	60-80	80-100
Focal Slope Var.	<0.001 (29.64)	0.012 (8.85)	<0.001 (48.04)	<0.001 (37.25)	<0.001 (38.01)
Global Slope Var.	0.008 (9.75)	0.008 (9.78)	<0.001 (30.65)	<0.001 (19.56)	<0.001 (21.91)
Area Ratio	0.003 (11.96)	0.030 (6.98)	<0.001 (32.87)	<0.001 (16.83)	<0.001 (16.4)
Global DEV	0.030 (7.02)	0.133 (4.03)	0.001 (14.17)	0.190 (3.32)	0.114 (4.34)
Inv. Vector Dispersion	0.106 (4.49)	0.004 (11.19)	0.966 (0.07)	0.996 (0.01)	0.001 (14.35)

Table 9.3 Differences in landscapes in different natural regions by TRM, calculated using a Bonferroni corrected Dunn's Test. P-values shown first followed by H statistic and Z value in brackets

Natural Region	Boreal	Parkland
Parkland	Focal Slope Var. <0.001 (36.12, -5.4) Global Slope Var. 0.010 (7.12, -2.31) Area Ratio 0.040 (7.85, -1.75)	
Grassland	Focal Slope Var. <0.001 (36.12, -4.81) Global Slope Var. 0.013 (7.12, -2.24) Area Ratio 0.003 (7.85, -2.74)	Global DEV 0.004 (6.89, 2.61) Inv. Vector Dispersion 0.009 (5.57, 2.35)

Table 9.4 Differences in landscapes with different levels of disturbance in the Boreal natural region by TRM. Significant TRMs are displayed in the matrix followed by their respective p-value first then H statistic and Z value in brackets, calculated using a Bonferroni corrected Dunn's Test

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	Focal Slope Var. 0.002 (88.26, -3.57) Global Slope Var. 0.027 (97.13, -2.78) Area Ratio 0.005 (85.47, -3.27) Global DEV 0.008 (42.95, -3.14)			
40 – 60	None	None		
60 – 80	None	Focal Slope Var. 0.044 (88.26, 2.62)	None	
80 – 100	Focal Slope Var. <0.001 (88.26, 6.47) Global Slope Var. <0.001 (97.13, 7.57) Area Ratio <0.001 (85.47, 6.55) Global DEV 0.004 (42.95, 3.38) Inv. Vector Dispersion <0.001 (36.65, 3.95)	Focal Slope Var. <0.001 (88.26, 8.32) Global Slope Var. <0.001 (97.13, 8.37) Area Ratio <0.001 (85.47, 8.08) Global DEV <0.001 (42.95, 5.58) Inv. Vector Dispersion <0.001 (36.65, 4.39)	Focal Slope Var. <0.001 (88.26, 5.62) Global Slope Var. <0.001 (97.13, 5.73) Area Ratio <0.001 (85.47, 5.64) Global DEV <0.001 (42.95, 4.53) Inv. Vector Dispersion <0.001 (36.65, 4.36)	Focal Slope Var. <0.001 (88.26, 5.63) Global Slope Var. <0.001 (97.13, 6) Area Ratio <0.001 (85.47, 5.55) Global DEV <0.001 (42.95, 4.13) Inv. Vector Dispersion <0.001 (36.65, 4.61)

Table 9.5 Differences in landscapes with different levels of disturbance in the Parkland natural region by TRM. Significant TRMs are displayed in the matrix followed by their respective p-value and H statistic in brackets, calculated using a Bonferroni corrected Dunn's Test

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	Focal Slope Var. 0.023 (145.34, -1.12) Global Slope Var. 0.024 (131.73, -1.65) Area Ratio 0.005 (127.53, 1.63) Global DEV 0.001 (84.7, -2.51)	None		
60 – 80	Inv. Vector Dispersion 0.037 (15.59, -2.68)	Inv. Vector Dispersion 0.02 (15.59, -2.88)	None	
80 – 100	Focal Slope Var. <0.001 (145.34, 5.05) Global Slope Var. <0.001 (131.73, 4.47) Area Ratio <0.001 (127.53, 4.17)	Focal Slope Var. <0.001 (145.34, 5.52) Global Slope Var. <0.001 (131.73, 5.71) Area Ratio <0.001 (127.53, 5.43) Global DEV <0.001 (84.7, 4.89)	Focal Slope Var. <0.001 (145.34, 8.39) Global Slope Var. <0.001 (131.73, 7.83) Area Ratio <0.001 (127.53, 8.19) Global DEV <0.001 (84.7, 6.83)	Focal Slope Var. <0.001 (145.34, 7.67) Global Slope Var. <0.001 (131.73, 7.33) Area Ratio <0.001 (127.53, 6.88) Global DEV <0.001 (84.7, 5.40) Inv. Vector Dispersion 0.03 (15.59, 2.74)

Table 9.6 Differences in landscapes with different levels of disturbance in the Grassland natural region by TRM. Significant TRMs are displayed in the matrix followed by their respective p-value and H statistic in brackets, calculated using a Bonferroni corrected Dunn's Test

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	None	None		
60 – 80	None	None	None	
80 – 100	Focal Slope Var. <0.001 (112.39, 8.75) Global Slope Var. <0.001 (87.45, 7.95) Area Ratio <0.001 (83.81, 7.70) Global DEV <0.001 (38.79, 5.16)	Focal Slope Var. <0.001 (112.39, 4.83) Global Slope Var. 0.002 (87.45, 3.52) Area Ratio 0.001 (83.81, 3.81) Global DEV 0.012 (38.79, 3.04)	Focal Slope Var. <0.001 (112.39, 6.45) Global Slope Var. <0.001 (87.45, 5.57) Area Ratio <0.001 (83.81, 5.48) Global DEV 0.001 (38.79, 3.63)	Focal Slope Var. <0.001 (112.39, 6.70) Global Slope Var. <0.001 (87.45, 5.94) Area Ratio <0.001 (83.81, 5.82) Global DEV <0.001 (38.79, 3.94)

Table 9.7 Differences between landscapes with different proportions of disturbance for each landscape metric by natural region, calculated using a Kruskal-Wallis test. Chi-squared, degrees of freedom and p-value reported

	Metric	Chi-squared (*H*)	d.f.	*p*
Boreal	GYRATE_AM	41.50	4	2.11E-08
	PROX_AM	15.76	4	3.36E-03
	SIDI	53.13	4	8.02E-11
	SHEI	15.93	4	3.12E-03
	SHAPE_AM	25.98	4	3.19E-05
	ENN_AM	20.04	4	4.91E-04
	CONNECT	3.62	4	4.60E-01
Parkland	GYRATE_AM	88.76	4	2.42E-18
	PROX_AM	23.02	4	1.26E-04
	SIDI	103.51	4	1.76E-21
	SHEI	12.46	4	1.42E-02
	SHAPE_AM	33.29	4	1.04E-06
	ENN_AM	33.34	4	1.02E-06
	CONNECT	32.21	4	1.73E-06
Grassland	GYRATE_AM	59.36	4	3.96E-12
	PROX_AM	33.41	4	9.86E-07
	SIDI	71.44	4	1.13E-14
	SHEI	6.68	4	1.54E-01
	SHAPE_AM	37.95	4	1.15E-07
	ENN_AM	16.11	4	2.87E-03
	CONNECT	3.76	4	4.40E-01

Table 9.8 Differences in landscapes in different natural regions with the same disturbance level by landscape metric, calculated using Kruskal-Wallis. P-values shown first followed by H statistic in brackets, all tests have 2 degrees of freedom

	Disturbance (%)				
Metric	0-20	20-40	40-60	60-80	80-100
GYRATE_AM	<0.001 (38.13)	0.026 (7.33)	<0.001 (31.1)	<0.001 (25.85)	<0.001 (27.27)
PROX_AM	<0.001 (27.27)	0.655 (0.85)	<0.001 (24.11)	0.003 (11.55)	0.001 (15.13)
SIDI	<0.001 (26.51)	0.014 (8.47)	<0.001 (31.78)	<0.001 (19.98)	<0.001 (27.3)
SHEI	<0.001 (17.88)	0.019 (7.93)	0.095 (4.7)	0.943 (0.12)	0.054 (5.84)
SHAPE_AM	<0.001 (15.94)	0.383 (1.92)	<0.001 (23.14)	<0.001 (30.81)	0 (38.73)
ENN_AM	<0.001 (18.19)	0.33 (2.22)	0.034 (6.77)	0.002 (12.66)	0.073 (5.24)
CONNECT	0.001 (13.74)	0.007 (9.93)	0.027 (7.2)	0.002 (12.27)	0.715 (0.67)

Table 9.9 Differences in landscapes in different natural regions by landscape metric, calculated using a Bonferroni corrected Dunn's Test. P-values shown first followed by H statistic and Z value in brackets

Natural Region	Boreal	Parkland
Parkland	GYRATE_AM <0.001 (48.66, 6.01) PROX_AM <0.001 (35.04, -5.46) SIDI <0.001 (29.85, -4.64) SHAPE_AM <0.001 (56.59, -7.38) ENN_AM 0.018 (8.93, 2.09) CONNECT 0.002 (9.58, 2.84)	
Grassland	GYRATE_AM <0.001 (48.66, 5.88) PROX_AM <0.001 (35.04, -4.51) SIDI <0.001 (29.85, -4.67) SHEI 0.023 (4.52, -1.99) SHAPE_AM <0.001 (56.59, -4.64)	SHAPE_AM 0.001 (56.59, -3.2) ENN_AM 0.002 (8.93, 2.96) CONNECT 0.004 (9.58, 2.67)

Table 9.10 Differences in landscapes with different levels of disturbance in the Boreal natural region by landscape metric. Significant landscape metrics are displayed in the matrix followed by their respective p-value first then H statistic and Z value in brackets, calculated using a Bonferroni corrected Dunn's Test

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	GYRATE_AM <0.001 (41.5, 3.93) PROX_AM 0.009 (15.76, -3.14) SIDI 0.002 (53.13, -3.49)			
40 – 60	None	None		
60 – 80	ENN_AM 0.002 (20.04, -3.53)	SHAPE_AM 0.041 (25.98, 2.65)	None	
80 – 100	GYRATE_AM 0.019 (41.5, -2.89) PROX_AM 1 (15.76, 1.11) SIDI <0.001 (53.13, 4.2) SHEI 0.001 (15.93, -3.76) SHAPE_AM 0.002 (25.98, 3.58) ENN_AM 0.002 (20.04, -3.59)	GYRATE_AM <0.001 (41.5, -5.97) PROX_AM 0.001 (15.76, 3.88) SIDI 0 (53.13, 6.53) SHAPE_AM <0.001 (25.98, 4.77)	GYRATE_AM 0.001 (41.5, -3.63) SIDI <0.001 (53.13, 4.32)	GYRATE_AM 0.001 (41.5, -3.67) SIDI <0.001 (53.13, 4.66)

Table 9.11 Differences in landscapes with different levels of disturbance in the Boreal natural region by landscape metric. Significant landscape metrics are displayed in the matrix followed by their respective p-value first then H statistic and Z value in brackets, calculated using a Bonferroni corrected Dunn's Test

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	SIDI 0.046 (103.51, -2.61)	None		
60 – 80	None	None	None	
80 – 100	GYRATE_AM 0.002 (88.76, -3.58) SIDI <0.001 (103.51, 4.06) ENN_AM <0.001 (33.34, -4.99) CONNECT <0.001 (32.21, -4.25)	GYRATE_AM <0.001 (88.76, -4.57) SIDI <0.001 (103.51, 5) SHEI 0.011 (12.46, 3.05) CONNECT 0.031 (32.21, -2.74)	GYRATE_AM <0.001 (88.76, -6.54) PROX_AM <0.001 (23.02, 4.02) SIDI <0.001 (103.51, 7.17) SHAPE_AM 0.001 (33.29, 3.63)	GYRATE_AM <0.001 (88.76, -6.01) PROX_AM 0.029 (23.02, 2.76) SIDI <0.001 (103.51, 6.22) SHAPE_AM <0.001 (33.29, 4.39) ENN_AM 0.043 (33.34, -2.63) CONNECT 0.015 (32.21, -2.97)

Table 9.12 Differences in landscapes with different levels of disturbance in the Boreal natural region by landscape metric. Significant landscape metrics are displayed in the matrix followed by their respective p-value first then H statistic and Z value in brackets, calculated using a Bonferroni corrected Dunn's Test

Disturbance Class (%)	0 – 20	20 – 40	40 – 60	60 – 80
20 – 40	None			
40 – 60	None	None		
60 – 80	None	None	None	
80 – 100	GYRATE_AM <0.001 (59.36, -6.78) PROX_AM <0.001 (33.41, 5.09) SIDI <0.001 (71.44, 7.01) SHAPE_AM <0.001 (37.95, 5.14) ENN_AM 0.001 (16.11, -3.72)	GYRATE_AM <0.001 (59.36, -3.9) PROX_AM 0.004 (33.41, 3.36) SIDI <0.001 (71.44, 4.25) SHAPE_AM 0.005 (37.95, 3.32)	GYRATE_AM <0.001 (59.36, -4.11) PROX_AM 0.008 (33.41, 3.17) SIDI <0.001 (71.44, 5.16) SHAPE_AM 0.002 (37.95, 3.6)	GYRATE_AM <0.001 (59.36, -4.38) SIDI <0.001 (71.44, 5.01) SHAPE_AM 0.002 (37.95, 3.6)

Appendix 10 - Correlation Grouping for Landscape Metrics

Table 10.1 Parkland landscape metric groups where Pearson's correlation coefficient |>0.9|

Group	Representative	Other Group Members
1	Number of patches	Patch density; Total edge; Landscape shape index; Area-weighted perimeter-area ratio; Area-weighted contiguity index; Proportion of like adjacencies; Patch cohesion index; Aggregation index
2	Largest patch index	Area-weighted patch area; Landscape division index; Effective mesh size
3	Radius of gyration	Shannon's diversity index; Simpson's diversity index; Modified Simpson's diversity index
4	Area-weighted shape index	Area-weighted fractal dimension index
5	Related circumscribing circle	
6	Perimeter-Area fractal dimension	
7	Area-weighted proximity index	
8	Area-weighted Euclidean nearest neighbor distance	
9	Contagion	
10	Interspersion juxtaposition index	
11	Connectance index	
12	Splitting index	
13	Patch richness	Patch richness density; Relative patch richness
14	Shannon's evenness index	Simpson's evenness index; Modified Simpson's evenness index

Table 10.2 Grassland landscape metric groups where Pearson's correlation coefficient |>0.9|

Group	Representative	Other Group Members
1	Number of patches	Patch density; Total edge; Landscape shape index; Area-weighted perimeter-area ratio; Area-weighted contiguity index; Proportion of like adjacencies; Patch cohesion index; Aggregation index
2	Largest patch index	Area-weighted patch area; Landscape division index; Effective mesh size
3	Radius of gyration	Shannon's diversity index; Modified Simpson's diversity index
4	Area-weighted shape index	Area-weighted fractal dimension index
5	Related circumscribing circle	
6	Perimeter-Area fractal dimension	
7	Area-weighted proximity index	
8	Area-weighted Euclidean nearest neighbor distance	
9	Contagion	
10	Interspersion juxtaposition index	
11	Connectance index	
12	Splitting index	
13	Patch richness	Patch richness density; Relative patch richness
14	Simpson's diversity index	
15	Shannon's evenness index	Simpson's evenness index; Modified Simpson's evenness index

Table 10.3 Boreal landscape metric groups where Pearson's correlation coefficient |>0.9|

Group	Representative	Other Group Members
1	Number of patches	Patch density; Total edge; Landscape shape index; Area-weighted perimeter-area ratio; Area-weighted contiguity index; Proportion of like adjacencies; Patch cohesion index; Aggregation index
2	Largest patch index	Area-weighted patch area; Landscape division index; Effective mesh size; Simpson's diversity index
3	Radius of gyration	Shannon's diversity index; Modified Simpson's diversity index
4	Area-weighted shape index	
5	Area-weighted fractal dimension index	
6	Related circumscribing circle	
7	Perimeter-Area fractal dimension	
8	Area-weighted proximity index	
9	Area-weighted Euclidean nearest neighbor distance	
10	Contagion	
11	Interspersion juxtaposition index	
12	Connectance index	
13	Splitting index	
14	Patch richness	Patch richness density; Relative patch richness
15	Shannon's evenness index	Simpson's evenness index; Modified Simpson's evenness index

Table 10.4 All landscape metric groups where Pearson's correlation coefficient |>0.9|

Group	Representative	Other Group Members
1	Number of patches	Patch density; Total edge; Landscape shape index; Area-weighted perimeter-area ratio; Area-weighted contiguity index; Proportion of like adjacencies; Patch cohesion index; Aggregation index
2	Largest patch index	Area-weighted patch area; Landscape division index; Effective mesh size
3	Radius of gyration	Shannon's diversity index; Modified Simpson's diversity index
4	Area-weighted shape index	
5	Area-weighted fractal dimension index	
6	Related circumscribing circle	
7	Perimeter-Area fractal dimension	
8	Area-weighted proximity index	
9	Area-weighted Euclidean nearest neighbor distance	
10	Contagion	
11	Interspersion juxtaposition index	
12	Connectance index	
13	Splitting index	
14	Patch richness	Patch richness density; Relative patch richness
15	Simpson's diversity index	
16	Shannon's evenness index	Simpson's evenness index; Modified Simpson's evenness index