Assessing the potential of integrating distribution and structure of permanent open-water wetlandscapes in reclamation design: a case study of Alberta, Canada

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Abstract Wetlands are multi-functional systems that provide a disproportionate number of ecosystem services given the spatial extent they occupy both nationally and globally. The ecological functioning of these wetlands is dependent on the structure of the landscape, which poses unique challenges when reclaiming wetlands in areas where resource extraction is occurring. Resource extraction mega-projects require that entire wetlandscapes be reclaimed and often involve timelines that necessitate the consideration of climate projections to create self-sustaining, naturally appearing wetlandscapes that meet policy objectives. To understand wetland structure and guide reclamation planning and closure permitting evaluation, a random sample of 13,676 1-km²

landscapes were subselected to identify 1684 permanent open-water wetlandscapes. A parsimonious set of landscape metrics were applied and compared across levels of anthropogenic disturbance and across natural regions (i.e., Grassland, Parkland and Boreal). Results demonstrated that permanent open-water wetlands are relatively rare (12.3% of our total random sample) and typically occupy less than 8% of wetlandscapes when present. The majority of wetlands in the study area are less permanent and more variable in nature than the permanent open water wetlandscapes created by megaproject reclamation, which has the potential to alter the distribution and size of open-water wetlands beyond their natural occurrence. Comparison across disturbance levels and natural regions yield statistical differences among landscape structure. General wetland landscapes representing a combination of disturbance level and natural region can be created for each metric to guide reclamation design and closure planning approval.

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Introduction

Resource megaprojects (e.g., oil sands mining, Appalachian coalfields) present a unique reclamation challenge due to the massive spatial extents and timeframes of their operations (Bernhardt et al. 2012;

Rooney et al. 2015). Entire ecosystems, landforms, and hydrologic catchments must be recreated and integrated with the surrounding landscape. In addition to the engineering challenge associated with reclamation, meeting the goals of key stakeholders (e.g., government, industry, and citizens) is difficult to achieve (Rooney and Bayley 2010) as post-disturbance landscape reclamation is expensive (Lemphers et al. 2010) and stakeholders are unlikely to have consensus about the goals for reclamation (Hirsch and Dukes 2014; Parlee 2015). Furthermore, reclaimed landscapes create novel ecosystems with different biotic assemblages and abiotic components that alter the hydrological connectivity within (Devito et al. 2012; Laarmann et al. 2015).

While restoring a disturbed landscape (i.e., returning a landscape back to its original state) is ideal, it is more common that disturbed landscapes are reclaimed, particularly in areas where resource extraction has occurred (Lima et al. 2016) or where it may be impossible to restore a landscape back to its original state (Johnson et al. 2016) due to the establishment of permanent infrastructure, climate change, or other factors. Legal definitions of reclamation vary across governments and countries, but typically disturbed lands are required to be reclaimed upon project closure and returned to a naturally appearing, self-sustaining state of equivalent land capability (e.g., Alberta, Canada; Kompanizare et al. 2018; Alam et al. 2018).

With an extensive history of megaprojects (Maxwell et al. 1997; Jergeas 2008) and reclamation efforts (Scheider et al. 1975; Powter et al. 2012; Rooney et al. 2015), Canada, and more specifically the province of Alberta is undertaking significant wetland reclamation. This is because wetlands are a defining feature of the landscape in Alberta, from the prairie potholes of the grasslands and parklands in the arid south, to the expansive peatland complexes of the boreal in the sub-humid north (Downing and Pettapiece 2006). Wetlands are valuable at-risk ecosystems (Woodward and Wui 2001) that have an estimated loss of 33–50% world-wide in the last century (Davidson 2014; Hu et al. 2017). These multi-functional systems provide a range of valued ecosystem services (Finlayson and van der Valk 1995; Brander et al. 2006) that is disproportionate to the spatial extent they occupy both nationally and globally (Zedler and Kercher 2005; Molnar and Kubiszewski 2012). As a result of their economic, ecological, and cultural importance, wetlands are

often the focus of conservation, restoration, and reclamation efforts (Mitsch and Wilson 1996; Chimner et al. 2017). They can be considered keystone ecosystems in larger landscape-level reclamation plans.

Over the next century, hundreds of wetlands are expected to be reclaimed in Alberta's oil sands region (CEMA 2014), representing the largest wetland reclamation project in Canadian history (Rooney and Bayley 2010; Foote 2012). Most of these will be permanent open-water marshes with mineral substrate and open water that persists throughout the growing season (Wells and Price 2015). Reclamation and closure plans in this region often include designs to fill open quarries and pits with water, thereby creating a permanent open-water wetland ecosystem (Slingerland and Beier 2016) and avoiding the costs associated with reshaping topography. However, replacing native peatland-rich landscapes with open-water wetlandscapes may (1) not replicate natural ecosystems in the region, (2) result in novel ecosystems more susceptible to failure, and (3) fail to meet policy objectives under future climate scenarios, which predict increased temperatures (Schneider 2015), sporadic precipitation (Kompanizare et al. 2018), and reduced snow pack depth and earlier spring melt (Adam et al. 2009).

The critical role of landscape interactions in key primary ecological processes such as hydrology, nutrient cycling, and community assembly has long been recognized (e.g., Whisenant 1999). However, the current reclamation and closure planning approval process for oil sands operations is focused on individual habitat patches and does not consider the cumulative long-term sustainability of patches at the landscape-level (AESRD 2013; Timoney 2015). Failure to integrate reclamation projects at the landscape-level may jeopardize their success. For example, recent advances challenge the assumption that wetlands should be restricted to low-lying areas, where they act as a hydrologic sink. Studies are beginning to recognize the key role of wetlands as a hydrologic source, providing water to surrounding forestlands (Hokanson et al. 2020).

Inadequate integration of wetlands into landscape-level reclamation can result in greater sensitivity to cycles of drought, deterioration of water quality, and reduced resilience to climate change (Rooney et al. 2015; Ketcheson et al. 2016; Kessel et al. 2018; Biagi et al. 2019). Poor landscape-level integration can also

lead to reduced biodiversity, as habitat isolation limits dispersal and propagule sources, leading to reduced species (e.g., Brederveld et al. 2011, Kettenring and Galatowitsch 2011) and genetic diversity (e.g., Aavik and Helm 2018) in reclaimed ecosystems. More, failure to consider landscape context can impact wildlife foraging and breeding site selection (Jones and Davidson 2016). Importantly, the spatial arrangement of habitats and their composition within a landscape also has implication for threats like invasive species (e.g., Glen et al. 2013), wildfire (e.g., Weir and Johnson 1998), and disease (e.g., Huang et al. 2015). A recent review of 472 restoration projects concluded that fewer than one in eight considered landscape context in site selection, suggesting this is a broader issue in ecological restoration (Gilby et al. 2018). Of the restoration projects that Gilby et al. (2018) reviewed, most of those that did consider landscape context showed better outcomes for wildlife, emphasizing the importance of landscape integration for long-term success and sustainability.

Landscape-level reclamation planning would result in the careful arrangement of reclaimed habitats within reclaimed landscapes but would also need to consider the integration of reclaimed lands within the surrounding natural habitat. The integration of reclamation projects into the surrounding landscape must consider not just appropriate transitions in topography (e.g., Branton and Robinson 2020) and hydrologic connections (e.g., Ketcheson et al. 2016), but also the ecological connectivity among land covers. Connectivity between reclaimed habitat patches and natural patches of the same type is one of the few spatial metrics regularly considered in restoration and reclamation projects (Gilby et al. 2018). However, the cost-surface or permeability of other habitats in the landscape (e.g., Koen et al. 2012) and the availability of habitats necessary for wildlife to meet their full life-cycle needs should also be considered (Bortoleto et al. 2016; Gilby et al. 2018). As an example, reclamation of wetlands should consider not only whether the surrounding landscape will contribute sufficient water to meet the wetland's water budget (Ketcheson et al. 2016), but also whether it provides sufficient adjoining overwintering habitat for amphibians (e.g., Sawatzky et al. 2019), riparian and swampland to support beaver (e.g., Scrafford et al. 2020), roosting and nesting structures and foraging habitat for wetland-dependent birds (e.g., Anderson and Rooney 2019), and sufficient

open water to support breeding waterfowl (e.g., Holopainen et al. 2014) but not to boost their predator populations (e.g., Krapu et al. 2004).

To pursue reclamation with a landscape-integration perspective, planners must account for the climate-driven water budget, hydrologic connectivity both in terms of surface and ground water (e.g., Devito et al. 2012; Kompanizare et al. 2018), the topographic configuration (e.g., Branton and Robinson 2020), and the proportion and spatial arrangement of land covers (e.g., Evans et al. 2017) within the reclamation area and its surroundings. Due to its hydrologic and ecologic importance, the extent and spatial arrangement of open water is of particular importance in this endeavor. Hence, this research draws on the emerging concept of wetlandscapes (*sensu* Thorslund et al. 2017)—landscapes comprising multiple aquatic habitats, with aggregate and emergent ecohydrologic effects exceeding those of individual wetlands—to place focus on the distribution and cover of open water in integrating reclaimed lands with their surrounding wetlandscapes.

The search for and creation of guidelines and parameters to facilitate reclamation design and assessment for wetlandscapes remains a continued focus of academia, industry, and regulators. The presented research furthers this effort by quantifying the spatial patterns in permanent open-water wetlandscapes to determine what is the landscape structure associated with permanent open-water wetlandscapes and how does that landscape structure vary with disturbance and across the natural regions? To answer these questions, the distribution of permanent open-water wetlandscapes was assessed across three natural regions in Alberta, Canada, and a method is outlined for quantifying the composition and configuration of these wetlandscapes along levels of anthropogenic disturbance using landscape metrics. By quantifying the composition and configuration of wetlandscapes, this research contributes to an overarching goal of establishing reclamation design targets that may vary by natural region and level of disturbance, to enhance reclamation success. Specifically, the presented research contributes to understanding about how patterns of permanent open-water wetlands, situated in wetlandscapes, can sustain hydrological wetland requirements, despite fluctuations in the water budget resulting from climate change.

Reclamation of whole landscapes following megaprojects tend to increase the abundance of permanent open-water wetlands (e.g., Rooney and Bayley 2011). Consequently, to model reclaimed wetlandscapes off of naturally occurring wetlandscapes, and thereby meet reclamation criteria that they be naturally appearing and self-sustaining, there is a need to characterize the composition and configuration of natural wetlandscapes that are rich in permanent open-water. This research can facilitate reclamation and closure planning by providing metrics and the range of their values that describe how the spatial patterns of wetlands and land cover types in open-water wetlandscapes vary with increasing levels of disturbance and across Boreal, Parkland, and Grassland natural regions.

Methods

Study area

Natural regions in Alberta are uniquely defined based on soils, vegetation, and physiographic features, and their distribution is the result of influences from topography, climate and geology (Downing and Pettapiece 2006) (see Appendix 1 for a description of natural regions). The study area covers the Grassland, most of the Parkland and southern Boreal regions and is constrained by two non-overlapping wetland inventories (Fig. 1). Note, while both inventories cover a portion of the Parkland, neither cover the central area of this region.

Wetlandscape analysis

The approach taken in this research builds on the seminal work of Evans et al. (2017), which quantified distributions of composition and configuration of land cover types in randomly selected wetland-rich landscapes spanning across five levels of disturbance and three natural regions. The presented research expanded this initiative to inform reclamation and closure plan design, which is constrained by the water budget, and hence by the extent of open-water habitat in the landscape. The process used involved first randomly selecting landscapes throughout the study area and filtering these down to a sample of 1684 wetlandscapes (Fig. 2). Then a parsimonious set of

landscape metrics were applied to each sample to quantify wetlandscape structure.

Differences in composition and configuration (i.e., landscape metric values) were statistically tested across natural regions and levels of disturbance. Differences in wetlandscape structure by natural region was investigated to determine if patterns varied in relationship to geomorphology and climate. Differences in wetlandscape structure by disturbance level was investigated because (1) it may not be possible to use a reference condition for biological integrity and other disturbed or best attainable conditions may only be achievable (Stoddard et al. 2006), and (2) identifying when metric values differ by disturbance level provides more information for regulators assessing closure permits and those undergoing reclamation. The combination of results by natural region and disturbance quantify a set of metric values that describe spatial patterns of open-water wetlands and land cover that can be used to guide reclamation design and closure permitting approval.

Prepare data

Two wetland inventories (i.e., Central and Southern) were acquired from Alberta Sustainable Resource Development (ASRD). These inventories delineate marshes based on hydroperiod: temporary, seasonal, semi-permanent, permanent open-water or alkali (see Online Appendix 2; Stewart and Kantrud 1971; ASRD 2010). The Central and Southern inventories both augment the Alberta Grassland Vegetation Inventory classification system; however, different methods were employed in their development. The Central inventory covers a portion of the southern Boreal and north-west of the Parkland region (Fig. 1) and was created with a combination of SPOT 5 imagery (2006–2009), a 25 m resolution digital elevation model (DEM), and ancillary data (e.g., roads and hydrography) (ASRD 2011). Object-based image classification was performed on image segments to delineate land cover types and a predictive ecosystem decision-tree model was used to produce the final wetland classes. Classification accuracy was assessed using 100 random two-kilometre zones. Orthorectified and SPOT 5 imagery were manually interpreted for each zone and compared to the classification with an observed accuracy of 83% (ASRD 2011).

Fig. 1 The Central and Southern wetland inventories comprising Grassland and portions of the Parkland and Boreal natural regions of Alberta, Canada. Within the inset, the study area is shown in red

The Southern inventory was also created with SPOT 5 imagery but used orthoimagery (2005–2006) and SPOT 4 images where cloud cover inhibited classification (Alberta Terrestrial Imaging Centre 2009). Images were stacked temporally and classified with a support vector machine algorithm to identify wetland boundaries. A second classification was then performed to classify the wetlands by permanence class and the majority class identified over the image stack was assigned to represent that wetland feature.

The accuracy of the Southern inventory was assessed within five township boundaries where wetlands were manually digitized and classified by aerial imagery with cell sizes between 0.5 and 2.5 m. The range of accuracy among the five townships was 51%–68% (ASRD 2011).

Land cover data were acquired from Agriculture and Agri-Food Canada (AAFC) annual crop inventory for 2009 to match the temporal period of the wetland inventories. The AAFC data were created from a

Fig. 2 Methodological steps of wetlandscape analysis

combination of RADARSAT-2 and LANDSAT-8 imagery and classified using a decision-tree method at a 30 m resolution. An accuracy of $\sim 90\%$ was ground-truthed by crop-insurance companies (Fisette et al. 2013; AAFC 2014). The AAFC data were aggregated into eight general land use and land cover classes: developed, agriculture, exposed, water, shrubland, wetland, grassland, and forest (see Online Appendix 2).

Disturbance was represented as the combined percent of developed and agriculture area within each sample landscape. These anthropogenic land use and land cover types include a combination of impervious and pervious surfaces that restrict or alter biogeochemical (e.g., nutrient cycling; DuPont et al. 2009; Mattsson et al. 2005; Ye et al. 2009), biogeophysical (e.g., latent and sensible heat fluxes, albedo; Ban-Weiss et al. 2011; de Noblet-Ducoudré et al. 2012), and biogeographical (e.g., species distribution and migration; Ficken et al. 2019; Morissette et al. 2019;

Thuiller et al. 2008; Zhang et al. 2012) processes relative to undisturbed natural landscapes. Furthermore, the combination of these alterations to the surface of the earth affect local, and cumulatively across large regions, global climate (Stohlgren et al. 1998; Kalnay and Cai 2003). While land management also affects the intensity of disturbance at a location, land management activities are highly variable within and among different land uses and these data are not available across large spatial extents.

Select wetlandscape samples

The spatial extent of sample wetlandscapes was fixed at 1 km^2 to reflect the typical disturbance footprint associated with in-situ oil extraction sites in Alberta, i.e., the area typically disturbed by bitumen treatment plants, well pads, roads, gravel pits, steam generators, water treatment plants, and housing units for workers (Evans et al. 2017). A total of 13,676 points were

randomly generated across both inventories (Central and Southern) in the study area, with a minimum distance of 1.5 km between points. Kraft et al. (2019) demonstrated that spatial autocorrelation and concordance among physicochemical conditions and vegetation communities with land use and land cover dropped from 500 m to 1000 m, after which there was no statistical relationship. A 1 km² sample landscape was generated around each point as the polygon centroid. This step ensured spatial independence among sample landscapes.

From these 13,676 sample landscapes, 9833 contained ASRD wetlands. Samples that did not include permanent open-water wetlands (LenW) or had 100% disturbance based on AAFC data were also removed, yielding 1,981 sample wetlandscapes with LenW (Online Appendix 3). Approximately 82% of these wetlandscapes contained less than 20% of their area in LenW. Wetlandscapes with greater than 20% of their area in LenW had a misclassification rate of 93% (n = 60). Therefore, all landscapes with > 20% of their area in LenW were removed to yield a final sample size of 1,684 wetlandscapes comprising at least one LenW wetland and a total landscape area of 20% or less in LenW (Online Appendix 4). When broken down by inventory and natural region, the final sample of wetlandscapes contained 984 in the Central inventory, with 632 in the Boreal and 352 in the Parkland; and 700 in the Southern inventory, with 141 in the Parkland and 559 in the Grassland.

Percent land cover and the percent of the wetlandscapes containing permanent open-water wetlands (LenW) was determined. These results were interrogated by wetland inventory (Central and Southern) and natural region (Boreal, Parkland and Grassland), for a total of six datasets (Central All, Central Boreal, Parkland Boreal, Southern All, Southern Parkland, and Southern Grassland), through a series of frequency plots and boxplots based on percent of permanent open-water wetland (LenW) (see Online Appendices 5 and 6 for boxplots). These samples were then grouped in twenty-percent disturbance classes for further analysis. Other methods of identifying breaks were explored, but equal breaks with five classes in twenty percent bins was chosen to make results comparable across natural regions and inventories, to previous and on-going research (Evans et al. 2017; Branton and Robinson 2020), and to increase the

usability of the results by non-academics involved in wetlandscapes reclamation.

Quantify spatial patterns

The quantification of landscape structure has been used to acquire understanding about relationships between landscape pattern and ecological processes (Turner 1989; Wei et al. 2017). In wetlandscapes, ecological processes such as the propagation of seeds, energy and nutrient exchange (Galatowitsch and van der Valk 1996), and the presence or absence of avian species, invertebrates, and fish are affected by the aggregation of wetland patches within a landscape (Haig et al. 1998; Fairbairn and Dinsmore 2001; Stephens et al. 2005). Furthermore, landscape configuration affects hydrological processes and the delivery of water necessary to sustain a wetland (Ketcheson et al. 2016) that, when combined with topography and climate, is a key determinate of wetland type (Mitsch and Gosselink 2000, 2007).

In addition to their role in natural systems, wetlands provide an array of services to humans (see Zedler and Kercher 2005). The sustainability of the provision of these services is reliant on the integration of wetlands within a broader landscape (Zedler 2000; CEMA 2014). However, the link between wetland reclamation and landscape integration is rarely operationalized in reclamation (Rooney et al. 2012; Timoney 2015) and standardized wetland guidelines, like height-to-length and length-to-width ratios (e.g., Davis 1995, NRCS 2008), could lead to the homogenization of wetlands throughout a region. Furthermore, the continued creation of permanent open-water wetlandscapes in megaproject reclamation will change the distribution of wetland types and have ecological (Galatowitsch and van der Valk 1996) and hydrological implications (Cohen et al. 2016) that require consideration.

Landscape structure, the spatial pattern of wetlandscapes, is composed of two components: composition and configuration (McGarigal and Marks 1995; Gustafson 1998). Composition encompasses the non-spatial aspects and integration of patches (e.g., patch diversity) (McGarigal 2014), while configuration refers to the spatial arrangement, position, and orientation of elements within the landscape (McGarigal and Marks 1995; Wei et al. 2017). These components can be quantified using statistical measurements

known as landscape metrics (*sensu* McGarigal and Marks 1995), which have been used in a myriad of management applications ranging from analyzing land cover change, to urban planning and studies of biodiversity (Uuemaa et al. 2009). A variety of software packages exist to aid researchers in calculating landscape metrics (see Turner 2005). Within such packages, landscape metrics are relatively simple to calculate and compare (Lausch and Herzog 2002), making them ideal for government and industry partners to use when quantifying landscape features and for evaluating the success of large-scale reclamation efforts (e.g., Evans et al. 2017).

A number of steps were taken to derive a parsimonious and independent set of landscape metrics (Evans et al. 2017). First, collinearity was removed by conducting pairwise correlation comparisons among 47 candidate landscape metrics. Metrics that were correlated at 0.9 or greater were grouped (Riitters et al. 1995) and a representative metric was qualitatively selected based on interpretability. The process was repeated to minimize collinearity among landscape metrics. To ensure patch sizes would not affect metric values, regressions were conducted (linear, quadratic, and cubic) between area and metric values. If R^2 values from any regression was greater than 0.2, then the metric was removed. Then, a principal components analysis was conducted on the remaining metrics to identify those metrics that explained a large proportion of the variance in landscape patterns. Landscape metrics with the highest factor loadings were retained, a process that is similarly used in bioclimate envelop modelling (Metzger et al. 2013).

Nine landscape metrics were identified and used to quantifying landscape structure in the 1,684 wetland-scapes (Table 1). These nine metrics were calculated using the FRAGSTATS software and can be organized conceptually into three groups: Shape, Aggregation, and Diversity metrics (Table 1; McGarigal et al. 2012). The shape, aggregation and diversity of wetland metrics were derived from the ASRD wetland data and the diversity of land cover from the AAFC data. While these metrics were chosen to reduce collinearity and their sensitivity to patch size, the diversity metrics are influenced by the proportion of wetlandscape 1 km² samples that are disturbed. The values of the nine metrics were then analyzed across disturbance levels and natural region to determine the range of composition and configuration pattern values

that could be used to guide reclamation activities in areas of ongoing resource extraction (see Online Appendix 7 for metric descriptions).

Statistical analysis

To determine if landscape metric values of wetland-scapes differed significantly across disturbance levels, inventories, or natural regions, results were qualitatively compared using boxplots and their distributions were further analyzed quantitatively. The data were determined to be non-parametric both quantitatively with a Shapiro-Wilk's test (Shapiro and Wilk 1965) and graphically with Q-Q plots (Wilk and Gnanadesikan 1968). A Brown-Forsythe test identified that some landscape metrics within the six datasets (Central All, Central Boreal, Central Parkland, Southern All, South Parkland, South Grassland), had unequal variances (Brown and Forsythe 1974). Where unequal variances were revealed, the Kolmogorov–Smirnov (K–S) test was applied within and between groups manually to conduct pairwise comparisons (Darling 1957; see Online Appendix 8).

The Kruskal–Wallis (K–W) test was applied to all comparisons of landscape metrics where their distributions were equal in variance across subsets to determine if wetlandscape composition and configuration differed by level of disturbance and natural region (Kruskal and Wallis 1952). In cases where significant differences were found, a Dunn's pairwise comparison was used to determine where significant differences were occurring among disturbance classes (Dunn 1964). The results of both K–S and K–W pairwise tests were combined into a final table to illustrate where significant differences in wetlandscape composition and configuration reside.

All Dunn's tests were conducted with and without Bonferroni correction. Inclusion of Bonferroni correction did not alter results qualitatively and all metrics found significant without Bonferroni correction remained significant with Bonferroni correction. A Wilcox pairwise comparison was also conducted as an alternative to the Dunn's test, which yielded the same qualitative results and nearly identical quantitative results with and without Bonferroni correction. Since the Wilcox tests were more sensitive to small sample sizes, results were reported using the Dunn's

Table 1 Nine parsimonious landscape metrics representing the spatial configuration of wetlandscapes independent of the proportion of those landscapes comprising wetlands

Type	Metric	Abbreviation
Shape	Area-weighted mean related circumscribing circle of wetland patches	CIRCLE_WET
	Area-weighted mean shape index of wetland patches	SHAPE_WET
Aggregation	Aggregation index for wetlands	AI_WET
	Patch Cohesion index for wetlands	COHES_WET
	Contagion index for wetlands	CONTAG_WET
	Euclidean nearest neighbor of wetland patches	ENN_WET
	Splitting index for wetlands	SPLIT_WET
Diversity	Simpson's diversity index for wetlands	SIDI_WET
	Simpson's diversity for land cover	SIDI_LAND

Metrics adapted from Evans et al. (2017). Metrics abbreviated by the suffix _WET were applied to all wetland patches regardless of type, while SIDI_LAND was applied to the AAFC land cover data

test without Bonferroni correction to avoid being overly conservative (Moran 2003).

Results

While wetlands are numerous throughout the study area, wetlandscapes containing permanent open-water wetlands are rare. Of the 13,676 randomly sampled landscapes, 9833 (71.89%) contained one or more ASRD wetlands (see Online Appendix 3), while just 1684 (12.3%) samples contained one or more permanent open-water wetlands (LenW; $n = 984$ in the Central inventory and $n = 700$ in Southern inventory; Fig. 3). These results indicate that the majority of wetlands in the study area are less permanent and more variable in nature (i.e., semi-permanent, seasonal, temporary, alkaline wetlands; Online Appendix 2). Additionally, 85.19% of the 1,684 sample wetlandscapes had just 8% (0.08 km²) or less of their total area classified as permanent open-water wetland, suggesting that not only are permanent open-water wetlands rare, they are relatively small. Further interrogation of these samples determined that wetlandscapes with little-to-no disturbance (0–20%) within the study area was also rare. Given the low frequency of these wetlandscapes and the small proportion of their area comprising permanent open-water wetlands, the future generation of open-water wetlands through reclamation have the capacity to alter the distribution

and size of open-water wetlands beyond natural occurrence.

Analysis of landscape metric values and disturbance stratified by inventory

Due to differences between the Central and Southern inventories (i.e., data quality, natural region, and climate), landscape metrics were analyzed in each inventory separately. First, in the Central inventory, which includes the Parkland and Boreal natural regions, results identified significant ($p < 0.001$) differences in six of the nine landscape metric values among wetlandscapes of differing disturbance levels (Online Appendix 9). Pairwise comparisons are presented in Table 2. Notably, 28/40 significant pairwise comparisons involved wetlandscapes in the highest disturbance level (80.1–99.9% cover), whereas 16/40 involved wetlandscapes in the lowest disturbance level (0–20% cover). Out of the landscape metrics with significantly differing values among disturbance levels in the pairwise comparison, only diversity of land cover types (SIDI_LAND) differed between all levels in a systematic way ($p < 0.001$).

Second, in the Southern inventory, which includes the Grassland and Parkland natural regions, results from the test of variance identified significant ($p < 0.05$) differences among disturbance levels in eight of the nine landscape metrics (Online Appendix 9). Overall, pairwise differences in landscape metric values were less common in the Southern inventory

Fig. 3 The spatial distribution of permanent open-water (LenW) wetlands and their disturbance levels. Symbols have been enlarged for increased visibility

with 19/26 significant pairwise differences involving the highest disturbance level (80.1–99.9% cover; Table 3). Again, land cover diversity (SIDI_LAND) was the only metric that had consistently significant different metric values across all disturbance levels (Table 3).

Overall, analysis of landscape patterns in the Central and Southern inventories displayed similar results, whereby wetlands in the high (80.1–99.9%) disturbance interval were significantly different from other wetlands as identified by the same six metrics. Metric values for diversity of land cover were significant in every comparison of disturbance level for both inventories.

Analysis of landscape metric values and disturbance stratified by natural regions

Similar to the analysis at the inventory level, landscape metrics were analyzed between natural regions of equivalent disturbance class within each inventory. Results identified only 3 of 45 comparisons where a landscape metric value differed significantly between Boreal and Parkland regions and between equivalent disturbance classes for the Grassland and Parkland (Table 4). These limited results may be due to the lack of data for the central Parkland and the shared characteristics between the southern Boreal and north-west Parkland and likewise, between the southern Parkland and Grassland region in the Southern inventory.

While wetlands between natural regions of the same inventory showed little structural difference

Table 2 Central inventory pairwise comparison results

Disturbance class (%)	0–20 n = 295	20–40 n = 56	40–60 n = 102	60–80 n = 149
20–40	CIRCLE_AM* SIDI_LAND***			
40–60	COHESION* SIDI_LAND*** AI*	SIDI_LAND*		
60–80	COHESION** SPLIT** AI SIDI_LAND***	SIDI_LAND***	SIDI_LAND***	
80–99 n = 382	SHAPE_AM* COHESION*** SIDI_LAND*** SIDI_WET*** CONTAG*** SPLIT*** AI***	SHAPE_AM* CIRCLE_AM* COHESION** SIDI_LAND*** SIDI_WET** CONTAG*** SPLIT*** AI**	SHAPE_AM* COHESION* SIDI_LAND*** SIDI_WET*** CONTAG** SPLIT*** AI**	COHESION** SIDI_LAND*** SIDI_WET* CONTAG_WET* SPLIT*** AI***

Statistical tests identified significant differences ($p < 0.05$) in wetlandscape patterns among disturbance levels (indicated by the table row and column) in the central wetland inventory. Eight of the nine landscape metrics evaluated were used to establish these differences. Only the average mean Euclidean nearest neighbour (ENN_AM) metric did not show any significant differences among wetlandscapes

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

within the same disturbance level, this research also sought to determine if wetlandscapes differed between disturbance levels within natural regions. Results for the Boreal region yielded six metrics that differed significantly across disturbance levels ($p < 0.01$) (Online Appendix 10). Similar to the inventory level analysis, the majority of significant pairwise comparisons (25/33) occurred in the highest disturbance level (80.1–99.9% cover), whereas 12/33 involved wetlandscapes in the lowest disturbance level (0–20% cover; Online Appendix 11). Diversity of land cover types (SIDI_LAND) was the only landscape metric of the six showing significant differences between disturbance levels that differ among all the disturbance levels in a systematic way ($p < 0.001$). For the Parkland region (Central inventory), significant differences among wetlandscapes comprising different levels of disturbance were also observed, these were captured by seven of nine metrics and with limited differences in the number of significant metrics

comparisons in the high and low disturbance levels (14/26 and 12/26 respectively; Appendix 12).

In the Southern inventory, comparisons across disturbance levels in the Parkland and Grassland regions were also investigated. Within the Parkland, only one metric value (SIDI_LAND) significantly differed among all disturbance classes ($p < 0.001$; Online Appendix 13), while in the Grassland region eight of the nine metrics identified significant differences among wetlandscapes ($p < 0.05$; Online Appendix 14). With 17/33 of the significant comparisons being in the highest disturbance level and 19/33 being in the lowest. Land cover diversity was significantly different among nearly all disturbance levels except the 20–40% level, where limited sample size may have affected the outcome.

To quantify landscape structure, nine landscape metrics (Table 1) were applied to five levels of disturbance in each of three natural regions. Only

Table 3 Southern inventory pair-wise comparison results

Disturbance class (%)	0–20 n = 132	20–40 n = 64	40–60 n = 69	60–80 n = 117
20–40	SIDI_LAND*** SPLIT*			
40–60	SIDI_LAND***	SIDI_LAND**		
60–80	SIDI_LAND***	SIDI_LAND**	SIDI_LAND***	
80–99.99 n = 318	CIRCLE* COHESION*** SIDI_LAND*** SIDI_WET** CONTAG* SPLIT***	SIDI_LAND***	CIRCLE* SIDI_LAND*** SIDI_WET** SPLIT** COHESION**	AI** CIRCLE_AM*** COHESION** SIDI_LAND*** SIDI_WET** SPLIT*** AI**

Dunn's and Kolmogorov–Smirnov tests identified significant differences ($p < 0.05$) in wetlandscape patterns among disturbance levels (indicated by the table row and column) in the southern wetland inventory. Seven of the nine landscape metrics evaluated were used to establish these differences. Only the average mean Euclidean nearest neighbour (ENN_AM) and average mean shape index (SHAPE_AM) metrics did not show any significant differences among wetlandscapes

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 4 Landscape metrics were analyzed between natural regions of equivalent disturbance class within each inventory

	Metric	Disturbance (%)				
		0–20	20–40	40–60	60–80	80–100
<i>Central inventory</i>	SHAPE_AM	0.51	0.219	0.86	0.016	0.699
	CIRCLE_AM	0.536	0.605	0.694	0.452	0.652
	AI	0.533	0.792	0.397	0.863	0.563
	COHESION	0.246	0.599	< 0.001	0.097	0.743
	CONTAG	0.246	0.262	0.697	0.126	0.363
	ENN_MN	0.76	0.752	0.911	0.978	0.565
	SPLIT	0.595	0.136	0.638	< 0.001	0.429
	SIDI_WET	0.401	0.243	0.609	0.152	0.311
	SIDI_LAND	0.967	0.051	0.5	0.253	0.124
<i>Southern inventory</i>	SHAPE_AM	0.46	0.452	0.104	0.727	0.488
	CIRCLE_AM	0.847	0.976	0.013	0.614	0.72
	AI	0.445	0.407	0.124	0.806	0.502
	COHESION	0.183	0.538	0.107	0.824	0.637
	CONTAG	0.951	0.452	0.194	0.225	0.135
	ENN	0.393	0.282	0.706	0.512	0.886
	SPLIT	0.612	0.97	< 0.001	0.598	0.515
	SIDI_WET	0.188	0.994	< 0.001	0.142	0.677
	SIDI_LAND	0.558	0.654	0.205	0.683	0.718

p-values that less than 0.05 are shown in bold and represent statistically significant differences between between natural regions in each inventory. Results identified only 3 of 45 comparisons where a landscape metric value differed significantly within each inventory

one of these metrics, Simpson's Diversity Index applied to quantify the diversity in land cover (SIDI LAND), showed significant differences across all levels of disturbance in each natural region, except one comparison where sample size may have been a factor. One metric, Euclidean Nearest Neighbour Distance was unable to distinguish any differences in sampled landscapes, which is likely due to the low frequency of permanent open-water wetlands within each sample landscape and should not be used to guide spatial patterns of reclamation. The remaining seven metrics primarily differentiated landscapes comprising a high level (80.1–99.9%) or low level (0–20%) disturbance landscapes from others within a specific natural region.

Discussion

Contrary to expectations, results did not show statistically significant differences in landscape structure for open-water wetland rich landscapes between Boreal and Parkland or Parkland and Grassland natural regions when holding disturbance levels constant. Comparisons between Boreal and Grassland regions could not be made due to differences in data quality in the two wetland inventories used in the presented research. While natural regions and similarly defined ecoregions (Downing and Pettapiece 2006) for bioclimate envelopes (e.g., Metzger et al. 2013) are useful for synthesizing surficial, ecological, and climate conditions, the discrete delineation of these boundaries are not observed in nature. Compounding the issue of boundary delineation between natural regions is (1) the Parkland has been described as an ecotone, sharing common landscape characteristics with both the Grassland and Boreal natural regions as well as being highly disturbed by agriculture (Downing and Pettapiece 2006) and (2) the central portion of the Parkland region was not captured by either inventory (Fig. 1). These limitations may have reduced the ability to detect differences across natural regions. However, the presented results provide a novel synthesis of open-water wetland rich landscapes for which others may compare and contrast results for corroboration or identification of conditions where differences may be observed.

The comparison of landscape structure in permanent open-water wetlandscapes across disturbance

levels and natural regions identified five generalized wetlandscapes: (1) Boreal 0–80% disturbed, (2) Boreal 80.1–99.9% disturbed (3) Parkland 0–99.9% disturbed, (4) Grassland 0–20% disturbed, and (5) Grassland 80.1–99.9% disturbed. The distribution of landscape metric values for each of these generalized wetlandscapes can be used to guide reclamation planning and closure permitting approvals by ensuring the reclaimed landscapes fall within the distribution of values for the generalized wetlandscape within which the location resides (Fig. 4). A more restrictive approach would provide distributions for each configuration of disturbance and natural region that differs significantly from others, as is the case with landscape diversity (represented by Simpson's Diversity Index—SIDI LAND). While the five generalized wetlandscapes could be used for SIDI LAND, the metric differed significantly for all but one disturbance level comparison and all natural regions, which could then require a look-up table comprising 15 different distributions of diversity values. Regardless of the approach, implementation of distribution-based reclamation targets for wetlandscapes through coordinated planning by regulators and industry is necessary to avoid the creation of homogeneous wetlandscapes as some configurations within the distribution of metric values observed will be less costly to implement.

While a variety of extensions of the presented research are possible, it should be noted that the final 1,684 sample landscapes used for statistical analysis were chosen due to the presence of permanent open-water wetlands (LenW), which are the most common form of reclaimed wetland constructed in Alberta's oil sands region (Rooney and Bayley 2011). Other types of wetlands (e.g., semi-permanent, temporary) and other classifications may obtain different samples and subsequently different results. For example, from the initial generation of 13,676 samples, 3682 contain semi-permanent wetlands. This larger sample size, with greater spatial representation may yield landscapes that are statistically significantly different for various disturbance levels or across natural regions compared to the results presented for permanent open-water wetlandscapes. Future research into these comparisons and the effects of classifications on quantifying landscape structure and change across disturbance levels and natural region would further the presented results and increase the applicability of the presented methodology.

Fig. 4 Example of how metric values can be used for reclamation planning and approval. In this example, distributions of contagion values are displayed along the x-axis from a minimum value of 36 to 100 (left to right) and the frequency of their occurrence in each Generalized Wetland Landscape (GWL) along the y-axis. Distributions of metric values (e.g., contagion) were compared across five disturbance levels and

three natural regions. Our results identified five GWLs: Boreal 0–80%, Boreal 80–99%, Parkland, Grassland 0–20%, Grassland 20–99%. Similar lookup tables can be generated for other metrics as shown with labels for aggregation index (AI), area-weighted mean shape index (SHAPE_AM), and land cover diversity using Simpson's diversity index (SIDI_LAND)

Using landscape structure for reclamation

The concept of managing ecosystems in a manner consistent with their undisturbed structure and process was widely applied by landscape managers and government agencies for ecological monitoring in the 1990s (Christensen et al. 1996; Bowman and Somers 2005; Pardo et al. 2012). During this time, ecosystem integrity, resiliency, and biodiversity became synonymous with the goal of ecosystem management—to create healthy and sustainable ecosystems that can preserve their structure and organization over time (Grumbine 1994; Whitford and deSoyza 1999). The quantification of abiotic and biotic elements in low disturbance conditions was used as a benchmark or reference condition to evaluate and compare the health of restored or reclaimed ecosystems (Bailey et al. 2004; Hawkins et al. 2010).

Evaluating landscapes with a reference condition approach typically involves the comparison of biotic indices. A similar method called historical range and variability (HRV) has been used to evaluate landscape pattern, primarily in forested landscapes, with historical evidence obtained from remotely sensed imagery (e.g., Abella and Denton, 2009; Keane et al. 2002). Applications of HRV in wetlandscapes are scarce, but changes in the complexity, shape, and aggregation of wetlands have been observed with increasing anthropogenic disturbance (Liu and Cameron 2001; Li et al.

2010). While the presented results corroborate this literature, a major challenge with using a reference condition or HRV approach involves selecting the appropriate historical reference date and condition (e.g., level of natural variability and disturbance) (Stoddard et al. 2006; Keane et al. 2009). This challenge is compounded by the fact that it may not be possible to return a landscape back to its original state for a variety of reasons (e.g., Johnson et al. 2016), including the placement of permanent infrastructure or shifts in natural regions and bioclimate envelopes due to climate change (Rooney et al. 2015).

To guide reclamation and closure planning and regulatory evaluation, reference conditions were generated that quantify the spatial structure of permanent open-water wetlandscapes for fifteen different contexts (i.e., five levels of disturbance and three natural regions). Using nine landscape metrics, aspects of landscape structure that are sensitive to different levels of disturbance and natural region application were identified, whereby different distributions of metric values should be applied. To achieve these outcomes with statistical rigor, several statistical comparisons were conducted due to the nature of the data (i.e., non-parametric, and unequal sample sizes and variances). For example, separate methods for assessing statistical significance due to unequal variance across compared samples (i.e., Kruskal–Wallis and Kolmogorov–Smirnov) were required, which may have lowered the

statistical power, particularly in the Southern inventory where sample sizes were smaller. As a result, consistent and distinct patterns in the structure of permanent open-water wetland landscapes, across disturbance levels, and across inventories and natural regions were limited.

Reclamation of wetlandscapes associated with megaprojects tend to substantially alter local topographic conditions (Branton and Robinson 2020). The costs of recreating initial topographic conditions are often prohibitive and costly (Lemphers et al. 2010), thus if natural landscapes can maintain a specific extent of permanent open-water wetlands, then modeling reclaimed wetlands based on natural permanent open-water should enable stakeholders to build reclaimed landscapes where the surrounding landscape can maintain wetland integrity. While landscapes in Alberta do comprise permanent open-water wetlands, of the 1684 sample landscapes in this study, the area classified as permanent open-water in the sample landscapes was predominately low with the majority (86.1% and 84.3% in the Central and Southern inventory respectively) having 8% (0.08 km²) or less of their area in permanent open-water (LenW) wetlands.

Climate and wetlandscape reclamation

Hydrology is critical to wetland development, chemistry and ecology (Winter 1989, 1992; Sánchez-Carrillo et al. 2004; Hayashi et al. 2016; Kessel et al. 2018). In semi-arid Alberta, potential evapotranspiration exceeds precipitation and the water balance of wetlands is sensitive to changes in climate and land-use practices in surrounding uplands (Conly and van der Kamp 2001; Foote and Krogman 2006; Schneider et al. 2016). Canadian climate models and studies using future climate scenarios predict increases in extreme temperatures and precipitation (Tebaldi et al. 2006; Masud et al. 2018) as well as an earlier snowmelt, decrease in snowpack depth and length of the snow season, increase in stream flow during the start of the growing season, increase in the length of growing season (Kompanizare et al. 2018; Chunn et al. 2019), and an increase in evapotranspiration (Pan et al. 2015). Modeling efforts have emphasized the key interactions between hydroclimatic forcing and landscape configuration in wetlandscapes (e.g.,

Kompanizare et al. 2018; Bertassello et al. 2019; Johnson and Poiani 2016).

Given projected increases in hydrologic connectivity and evapotranspiration, megaproject reclamation that increases the density of open-water habitat in wetlandscapes will have serious consequences for landscape function, including aquatic species dispersal and habitat suitability (e.g., Johnson and Poiani 2016; Zamberletti et al. 2018), as well as groundwater fluxes (e.g., Ameli and Creed 2019), peak water storage capacity (Leibowitz 2003; Cohen et al. 2016), and pollutant retention capacity (Marton et al. 2015). Further, increased presence of open-water in a semi-arid region may lead to increased loss of critical water resources through evaporation, which in similar locations (e.g., south western United States) has been shown to alter local weather patterns (Penman 1948; Lawrimore and Peterson 2000; Smith et al. 2002). Thus, the sustainability of wetlandscape-level reclamation must be evaluated in light of projected climate change (Rooney et al. 2015).

Conclusion

Permanent open-water wetland-rich landscapes were the focus of this research because earth movement in resource extraction is costly and therefore megaproject plans often retain large permanent open-water wetlands that did not previously exist at the location of resource extraction. This study analyzed 13,676 spatially independent landscapes across five levels of disturbance and three natural regions (Grassland, Parkland, and Boreal). A set of landscape metrics representing the spatial configuration of wetland landscapes was applied to a final subset of 1,684 permanent open-water wetland landscapes and a set of non-parametric tests were used to determine if the landscape pattern of the sample landscapes differed across levels of disturbance and between natural regions. Results indicate that the amount of permanent open-water in the sample landscapes was predominately low with ~ 85% of our samples having less than or equal to 8% (0.08 km²) of the area classified as permanent open-water wetland.

Five distinct landscape patterns were identified, which varied across analysis at the inventory and natural region levels and identified limited landscape patterns in the low (0–20%) disturbance landscapes,

with the exception being the Grassland region. These results indicate a reference condition approach may not be ideal for reclaiming permanent open-water wetland landscapes or that landscape patterns may have been affected by limited statistical power in some comparisons. Instead it is recommended that climate envelopes containing similar proportions of permanent open-water wetlands be used. Diversity of land cover was the exception, whereby it was statistically significantly different across nearly all disturbance levels and natural regions.

The goal of this research was to identify differences in landscape patterns, quantify those patterns, and provide empirical distributions of pattern to guide reclamation efforts and regulatory oversight. The outcome of which is to foster the creation of sustainable permanent open-water wetlands. However, permanent open-water wetlands alone cannot be used to evaluate the effects of disturbance in wetland-rich landscapes, which function as spatially distributed complexes made up of several different types of wetlands (Zedler 2000). Other factors such as topography (Branton and Robinson 2020) and physico-chemical characteristics (Kraft et al. 2019) should also be taken into account. Furthermore, reclamation failure will likely increase if the reclamation effort is focused on a single type of wetland (i.e., permanent open-water wetlands), particularly in the Boreal region and given predicted climate changes (Schneider 2013). To maintain diversity and sustainability of reclaimed wetland-rich landscape, regulators should enforce the creation of multiple wetland types (i.e., semi-permanent, temporary, seasonal) to maintain, diversity, functions and services.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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