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Regional wetland status and sensitivity to disturbances near Fox Creek, Alberta

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Regional wetland status and sensitivity to disturbances near Fox Creek, Alberta

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Executive Summary

Wetlands cover large areas of Alberta's boreal regions. They play critical roles in flow regulation and flood control, groundwater discharge/recharge, and pollutant filtration. Peat-forming bogs and fens sequester and store large amounts of atmospheric CO_2 and harbor a variety of wildlife. The Fox Creek study area is located between the Upper Peace River and Upper Athabasca Watersheds. Wetlands cover 34806 km^2 or 11.6% of the Upper Athabasca Watershed and 64224.5 km^2 or 12.25% of the Upper Peace River Watershed. Among the five classes of wetlands, fen is the most abundant class (55.2%), followed by swamp (33.5%), shallow open water (9.7%), marsh (1.2%), and bog (0.4%) in the Upper Athabasca Watershed. Bog is not a significant component in this region, likely due to its steeper topography close to the foothills of the Canadian Rockies. In the Upper Peace River Watershed, swamp is the most abundant class (47.9%), followed by fen (25.1%), bog (12.6%), shallow open water (10.9%), and marsh (3.4%).

Within the 6501.3 km^2 extended study zone, wetlands cover 1344.2 km^2 or 20.68% of the area. Fen is the most abundant wetland class (45.5%), followed by swamp (37.2%), shallow open water (9.1%), bog (7.1%), and marsh (1.1%). Within the 90 km^2 local study area near Fox Creek, wetland coverage is relatively low at 4.7 km^2 or 5.2%. Swamp is the most abundant wetland class (56.8%), followed by fen (36.4%), shallow open water (4.5%), and bog (2.3%).

The Little Smoky caribou range falls within the Smoky/Wapiti and Athabasca River subwatersheds and covers an area of approximately 3084 km^2. While the caribou range is located outside the Local Study Area, its eastern corner, nearly 1134 km^2 or 37%, lies within the Extended Study Zone and approximately 166 km^2 or 5.4% is overlapped by the Study Area Watershed.

The formation and functioning of boreal wetlands are dictated by regional climate, hydrology, and the vegetation that develops. Natural disturbances such as warming and changing fire regimes, and human disturbances such as forestry, agriculture, oil and gas activities, and urban development can greatly affect the water balance, hydrology, and vegetation within a watershed, leading to the loss of critical function and services provided by natural wetlands. Wetland conservation is prioritized in several regional watershed management initiatives. Reclamation and restoration of boreal wetlands have come a long way since the early 2000s, although significant knowledge gaps and technical challenges remain.

This study was conducted as part of the Fox Creek project, which is jointly funded by the Environmental Geoscience Program, the Groundwater Geoscience Program and the Cumulative Effects Initiative of the Geological Survey of Canada.

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1. INTRODUCTION

The Geological Survey of Canada (GSC) of the Lands and Minerals Sector is carrying out a multidisciplinary project in the Fox Creek area, in west-central Alberta. The study area (700 km^2) is located within the Athabasca River Basin, but very close to the limit of the Peace/Slave River Basin; these correspond to two very large watersheds of Alberta. This study area is also located in close proximity to the Little Smoky woodland caribou range, a very well-known range that is infamous for being the most critically disturbed boreal caribou habitat in the country. The objective of the Fox Creek project is to assess environmental impacts of oil and gas activities, including cumulative effects stemming from the different activities in the area.

Numerous wetlands are present in these vast and flat watersheds. Their contribution is of tremendous importance as they regulate overflow, filter pollutants, and shelter a remarkable variety of plant and animal species, including woodland caribou. Peat-accumulating wetlands also contribute to the long-term sequestration and storage of atmospheric carbon in the form of peat. They can also represent an important component of surface water/groundwater interactions. Therefore, wetlands must be considered an integral part of watershed management.

However, oil and gas activities and especially unconventional development that uses a lot of water for hydraulic fracturing operations can affect boreal wetlands by altering regional water balance and disrupting groundwater recharge/discharge. Since water balance and hydrological processes are controlling factors in peatlands, these changes will likely have significant impacts on vegetation, nutrient cycling, greenhouse gas fluxes and net carbon balance, and overall wildlife habitat value. These aspects are of utmost importance within the framework of a study on environmental cumulative effects.

The goal of this report is to provide an overview of the different types of wetlands within the Fox Creek area and to assess the potential impacts of changes in regional hydrology and water balance due to oil and gas activities on critical services and functions of boreal wetlands. Current best practices to mitigate negative impacts and to reclaim disturbed wetland ecosystems and key knowledge gaps and challenges will be discussed.

2. CURRENT STATUS OF WETLAND CLASSES AND KEY WILDLIFE (CARIBOU) HABITAT WITHIN THE FOX CREEK AREA

2.1. Alberta's Wetland Classification

Wetlands are a critical component of Alberta's natural landscape. These systems form in areas where the ground is saturated for the majority of the growing season, if not for the whole year (Vitt 2006a), resulting in the development of vegetation which is well adapted to growing in saturated soil conditions (DUC, 2015). Among their many features, wetlands are richly biodiverse; provide habitat for a number of fauna (Desrochers and van Duinen 2006); regulate water access for the surrounding landscape (Vitt 2006a); and store a globally significant amount of carbon (Vasander and Kettunen 2006, Vitt and Wieder 2006). Wetlands developed on the Alberta landscape in the early to mid-Holocene, following deglaciation of the area (Kuhry et al. 1993, Kuhry and Turunen 2006a). Wet and cool conditions allowed for the accumulation of organic matter directly on exposed mineral soil, a process called *primary peat formation* (Kuhry and Turunen 2006a). Over time, wetlands also formed through the processes of *paludification* and *terrestrialization*, wherein changes in water table level enabled the accumulation of organic material over inorganic soils in areas which were previously drier and vegetated with forest or grassland communities (*paludification*) or wherein vegetation formed floating or grounded mats in shallow bodies of water and eventually filled in the inundated areas (*terrestrialization;* Vitt, 2006).

Differences in five key factors play a large role in the functioning and characteristics of wetlands. These are hydrology, climate, chemistry, substrate, and vegetation (Vitt 2006a). While influential in regulating the development and persistence of wetlands on the landscape, a number of these factors can also be used to categorize wetlands into different classes due to the influence that they exert on the form and function of the wetlands. Climatic factors of temperature and precipitation dictate the location, size, and pattern of individual wetlands and wetland complexes (Vitt 2006a). The source of water received by a wetland governs the concentration of dissolved anions and cations based on the substrate that the water has come into contact with, in turn influencing the vegetation communities which develop (Vitt 2006a). The identity and quantity of vegetation species present in a wetland influence the amount of organic matter which accumulates under saturated, low-oxygen conditions (which is also dependent on water table depth and fluctuation) and has been used as indicators to distinguish between different wetland types (Vitt 2006a).

In Alberta, a number of wetland classification systems and inventories have historically been used to differentiate wetland types. These include the Canadian Wetland Classification System, the Steward and Kantrud System, the Cowardin Wetland Classification System, ecosite guides for Alberta, the Ducks Unlimited Boreal Plains Ecozone Classification, the Alberta Wetland Inventory, the Grassland Vegetation Inventory, and the Alberta Merged Wetland Inventory (ESRD, 2015). In 2015, the Alberta Wetland Classification System (AWCS) was created through incorporation and merging of prior classification systems in an effort to provide a more consistent and standardized characterization of wetlands in the province using Alberta-specific indicators (ESRD, 2015). A full listing of the peatland and mineral wetland types described by the AWCS in comparison to other classification systems and inventories can be referenced within Appendix A of the AWCS (ESRD, 2015). The Alberta Environment and Park's Reclamation Criteria for Wellsites and Associated Facilities for Peatlands (2017), outlining the reclamation certification criteria for oil and gas associated disturbances reclaimed to peatlands, also provides a clear overview of different wetland types found in Alberta based mainly on the Canadian Classification of Wetlands.

The AWCS divides wetlands into five broad classes: bogs, fens, marshes, shallow open waters, and swamps (ESRD, 2015). Wetlands within these five broad classes are further divided into form based on vegetation structure, and type based on biological; hydrological; or chemical characteristics. Within the Reclamation Criteria, the fen class is divided into poor and rich fens, while the shallow open water class is not discussed as the majority of Alberta wetlands are made up of bogs, poor fens, rich fens, marshes, and swamps (AEP, 2017).

The amount of organic material which has accumulated in a system is used to divide wetlands into two key classes: peatlands or mineral wetlands (ESRD, 2015). *Peatlands* are defined as systems which have a minimum of 40 cm of accumulated unconsolidated to moderately-decomposed organic material (peat) (ESRD, 2015; AEP, 2017). *Mineral wetlands* have less than 40 cm of organic soil or organic soil which is highly decomposed (von Post decomposition rating greater than 5) within the top 40 cm of the soil profile. Due to the large quantities of carbon stored within peatland soils, these systems are particularly important to consider during landscape conservation planning and reclamation design. Bogs and fens are both peatlands, while marshes and shallow open waters are mineral wetlands. While some swamps have been observed to have accumulated greater than 40 cm of peat, they are typically classified as mineral wetlands (ESRD, 2015; AEP, 2017).

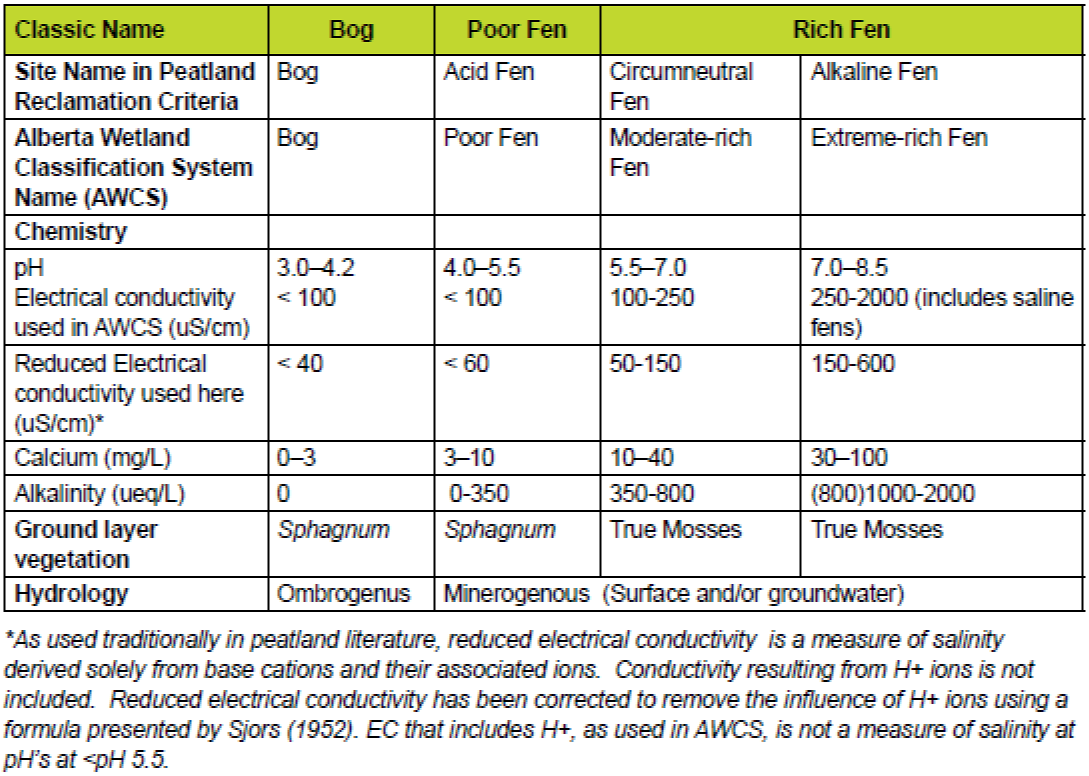
2.1.1. *Peatlands*

Bogs and fens are distinguishable from one another primarily based on the water source, which influences the system's acidity/alkalinity; nutrient levels; and water table, in turn affecting the vegetation communities which are present.

Bogs are traditionally defined as receiving their nutrients, minerals, and water available for vegetation growth predominantly from atmospheric sources due to peat accumulation which elevates the surface vegetation aboveground water inputs, though exceptions do exist (Kuhry and Turunen 2006a). Water found within a bog is generally low in nutrients (oligotrophic) and acidic, with low calcium and sodium concentrations (AEP, 2017;). Due to low nutrient conditions, bogs have a low plant diversity in comparison to fens (DUC, 2015). Vegetation indicative of bogs consist of herbaceous species *Rubus chamaemorus* and *Smilacina trifolia*; bryophytes *Sphagnum fuscum*, *Spahgnum magellanicum, Polytricum strictum,* and *Mylia anomala*; and the lichen species *Cladina mitis* (AEP, 2017). *Sphagnum fuscum* mosses typically form hummocks, which in later successional stages may transition to *Hylocomium splendens, Pleurozium schreberi*, and *Ptilium crista-castrensis* (Benscoter and Vitt 2008a). In Alberta bogs, tree cover is dominantly *Picea mariana*, while *Ledum groenlandicum*; *Vaccinium vitis-idaea*; and *Oxycoccus microcarpus* are typical shrubs found in these systems. For a full list of characteristic species, refer to Appendix E within the Reclamation Criteria (AEP, 2017).

Fens receive water predominantly from ground and surface water sources (geogenous; Vitt, 2006), which contain varying amounts of dissolved ions and nutrients based on the substrate that the waters have come into contact with. Water found in a fen is typically less acidic and more alkaline than that found in bogs (AEP, 2017). Fens are also higher in nutrients and minerals (minerotrophic) than bogs, though may still have overall low available nutrient concentrations (ESRD, 2015). Increasing alkalinity and nutrient levels in fens influence the species richness of the system, thus resulting in different classifications of fens. **Table 1** shows the fen classifications made within the AWCS based on the number of species present (richness), as well as chemistry-based classifications for the same systems made in the Reclamation Criteria (AEP, 2017). Vegetation cover in fens is highly variable depending on the acidity/alkalinity of the system, with sedge-dominated, shrub or tree-dominated, and moss-dominated systems all possible (AEP, 2017). Moss cover tends to be mesotrophic *Sphagnum* species or true mosses, while tree cover (when present) is *Picea mariana* or *Larix laricina*. A number of shrub and herbaceous species such as *Carex spp.* are indicative of different fen types (see Appendix E in AEP, 2017).

Table 1. Peatland characteristics and associated names under the Peatland Reclamation Criteria (AEP, 2017) and Alberta Wetland Classification System (ESRD, 2015). Table shown as presented in the Reclamation Criteria (AEP, 2017).



Classic Name	Bog	Poor Fen	Rich Fen	
Site Name in Peatland Reclamation Criteria	Bog	Acid Fen	Circumneutral Fen	Alkaline Fen
Alberta Wetland Classification System Name (AWCS)	Bog	Poor Fen	Moderate-rich Fen	Extreme-rich Fen
Chemistry				
pH Electrical conductivity used in AWCS (uS/cm)	3.0–4.2 < 100	4.0–5.5 < 100	5.5–7.0 100-250	7.0–8.5 250-2000 (includes saline fens)
Reduced Electrical conductivity used here (uS/cm)*	< 40	< 60	50-150	150-600
Calcium (mg/L)	0–3	3–10	10–40	30–100
Alkalinity (ueq/L)	0	0-350	350-800	(800)1000-2000
Ground layer vegetation	*Sphagnum*	*Sphagnum*	True Mosses	True Mosses
Hydrology	Ombrogenus	Minerogenous (Surface and/or groundwater)		

**As used traditionally in peatland literature, reduced electrical conductivity is a measure of salinity derived solely from base cations and their associated ions. Conductivity resulting from H+ ions is not included. Reduced electrical conductivity has been corrected to remove the influence of H+ ions using a formula presented by Sjors (1952). EC that includes H+, as used in AWCS, is not a measure of salinity at pH's at <pH 5.5.*

2.1.2. *Mineral Wetlands*

Mineral wetlands receive water from a range of sources, including precipitation, surface water, and groundwater. These systems have water tables which are present near, at, or above the ground surface for varying time periods over the course of a given year (ESRD, 2015). Water table fluctuation within mineral wetlands influences water chemistry, nutrient availability, and vegetation communities, as well as increasing organic matter decomposition rates. Vegetation community structure can, in turn, be used to distinguish wetland class, form, and type in marshes, swamps, and shallow open waters (ESRD, 2015).

Swamps are generally considered mineral wetlands with a minimum of 25% woody cover. The type of woody cover (tree or shrub) and stand type (coniferous, mixed wood, or deciduous) are used to distinguish different forms of swamps (ESRD, 2015). Swamps contain nutrient-rich water, with groundwater levels remaining close to the ground surface throughout the year and surface water flooding possible for varying amounts of time. Ground surface topography tends to be hummocky, with water-filled depressions interspersed with elevated mounds occupied by water-tolerant trees and shrubs (ESRD, 2015; DUC, 2015). These systems are often found in the transitional area between other wetlands and uplands and can be found in river floodplains, deltas, and alluvial fans.

Marshes and shallow open waters are mineral wetlands with less than 25% woody cover, which experience fluctuating water levels which are near to or above the ground surface for varying lengths of time within the growing season and have a wide range of chemical conditions (ESRD, 2015; DUC, 2015). These systems may receive water from groundwater or surface water connections or may be dependent on atmospheric sources for water. Due to a generally greater rate of decomposition than production, marshes and shallow open waters do not accumulate peat and typically have higher concentrations of available nutrients than peatlands as nutrients are released back into the system through decomposition (ESRD, 2015). Marshes and shallow open waters are distinguished based on the vegetation cover of the deepest wetland zone which covers greater than 25% of the wetland area. Marshes have a dominant cover of water-tolerant graminoids in this area, while shallow open waters have an area of open water less than 2 m deep at midsummer which may contain floating or submersed aquatic vegetation (ESRD, 2015). Further division of marshes and shallow open waters into types can be made based on the permanence of surface water in these systems. In the Boreal Region of Alberta, marshes are found in locations where high salinity limits bryophyte and salt-intolerant plant growth, as well as in areas experiencing frequent water table fluctuation such as locations adjacent to rivers, streams, lakes, and ponds (ESRD, 2015).

2.2. Hydrologic Characteristics of Boreal Wetlands

Wetlands cover more than 20% of the northern midlatitudes where the Fox Creek area (54 18’ 29.57” N 117 12’27.06” W) which encompasses three major river basins: Peace, Slave, and Athabasca Rivers. They are one of most important components of the northern Alberta landscape. The large extent of wetlands in west-central Alberta play a significant role in maintaining regional water balance, regulating flow patterns, improving the quality and quantity of surface water supplies, and providing wildlife habitat to a diverse fauna and flora. The valuable hydrological services that wetlands provide include the following:

- All wetlands absorb and/or store water from spring snowmelt and precipitation events such as summer storms. Peatlands store water using their shrinking and swelling properties. The stored water provides aquatic habitat to a diverse range of plant and animal species (e.g. waterfowl).
- Peatlands filter surface and/or groundwater before it flows to the downstream ecosystems or rivers and streams. The discharge is also regulated by attenuating runoff and increasing baseflow. Most of the impurities or pollutants within the water are removed and may be transformed during or after the filtration process.
- Fen peatlands are geogenous; they recharge shallow groundwater aquifers.
- Wetlands reduce the impacts of flooding and drought by maintaining late-season surface and subsurface low flows within the area or region.
- Having been carbon sinks for millennia, peatlands moderate the impacts of climate change (warming and water table lowering, and altered precipitation patterns);
- They provide an array of recreational services which support regional economic activity; the recreational services include (but are not limited to): tourism, nature photography, hunting, fishing, boating, and bird watching.
- Wetlands support dynamic biodiversity, provide wildlife habitat for mammals (e.g. woodland caribou), birds, plants, and fish.
- Many wetlands are connected to other wetlands and upland systems on the boreal landscape through surface and/or subsurface groundwater flows, and therefore play an integral role in maintaining regional water balance, flow patterns, and hydrological resilience on the landscape.

Wetland types in Alberta are differentiated based on their hydrological, biological, and chemical characteristics (see section 2.1.). This section focuses on hydrology which is the driving force for the formation and functioning of all wetlands (Vitt, 1994). Hydrological indicators include standing (lentic) or flowing (lotic) waters during at least part of the growing season (Alberta Environment and Parks (AEP) 2017).

2.2.1. *Peatlands – Bogs and Fens*

Bog and fen peatlands tend to have relatively stable water tables and permanently saturated soil. Bogs are ombrogenous, receiving water and nutrients exclusively from precipitation. They are freshwater wetlands with water tables well below the surface (AWCS 2015). Bogs are generally considered to be isolated from the influence of groundwater inputs by virtue of their raised topographic position within the landscape, although geogeneous water may come in contact with peat at the base of a raised bog ((Vitt 2006b, Devito et al. 2012)). They are also regarded as permanent wetlands, as moisture levels are effectively maintained by the capillary action of *Sphagnum* mosses (AWCS 2015). Hydrological processes operating within a bog basin are entirely responsible for the nature of the discharge regime (Price and Maloney, 1994) under extreme precipitation events.

Fens, in contrast to bogs, have a water table at or near the ground surface. They are minerogenous as they receive water and accumulate minerals from a variety of sources including groundwater from surface and subsurface soils and bedrock, precipitation, and surface runoff. Fens typically receive groundwater and surface water inflows; therefore, the hydrological processes operating therein may profoundly affect the ecosystem.

West-central Alberta watersheds have fen and bog peatlands which are characterized by hummock (higher elevation) and hollow (lower elevation/depressions or pools) microforms. Hydrology (or water table position) of peatland microforms is governed by hydrological parameters such as porosity, hydraulic conductivity, and density, which in turn regulate the nature and magnitude of hydrological processes such as infiltration and runoff (Whittington and Price, 2006) across the watershed. The horizontal and vertical flows in peatlands are impeded because of low hydraulic gradients and the depth dependence of hydraulic conductivity (Price and Maloney, 1994; Schlotzhauer and Price, 1999). Hummock and hollow microforms are effective in storing large amounts of water (up to 99% of their volume) and attenuating storm events and runoff or torrents by storing surface water.

2.2.2. *Mineral wetlands – Marshes and Shallow Open Waters*

Marshes and shallow open waters form mineral wetlands in Alberta which are mainly characterized based on their fluctuating water levels and varying nutrient status (National Wetlands Working Group 1997; Stewart and Kantrud 1972). Although nutrient levels vary widely in marshes and shallow open waters, many in Alberta are naturally eutrophic, with higher amounts of available nutrients than are present in peatlands (Smith et al. 2007). The water level fluctuations within mineral wetland systems promote aerobic decomposition rates, increasing available nutrient concentrations and thus influencing the system's overall water chemistry. These systems may be permanently flooded, flooded repeatedly, or infrequently inundated for short periods of time (AWCS 2015). Marshes may have shallow water levels (below, at/or aboveground) which vary during the growing season. Shallow open waters typically have an open water zone which supports emerging (floating) and/or submerged aquatic vegetation. For more information, see section 2.1.2 of this report.

Precipitation, surface water, and groundwater are the dominant water inputs for mineral wetlands. The National Wetlands Working Group (1997) also divide mineral wetlands into the following categories:

- Closed or isolated marshes and open waters that are only fed by precipitation and surface runoff. They may be isolated from surface water connections (e.g. some prairie potholes);
- Marshes and shallow open waters may have a variety of water sources that present complex surface-ground hydrologic interactions and/or are connected to fen peatlands, streams, ponds, or lakes. Specific examples include recharge, discharge, and flow-through wetlands, and wetlands bordering lotic (e.g. streams) and lentic (e.g. lakes) water bodies (AWCS 2015).

2.3. Distribution of Wetlands of Upper Athabasca Watershed near Fox Creek

The Athabasca River is one of the largest rivers in Alberta, second only to the Peace River, and is the only major river which has not been dammed to regulate water flow (Council 2018). Approximately 1400 kilometers in length, the Athabasca River has its headwaters at the Columbia Icefields in Jasper National Park before flowing northeast into the Foothills and Boreal Forest Natural Regions of the province. This river eventually drains into Lake Athabasca, after which point the waters join the Peace/Slave River system. An area of approximately 150000 square kilometers is drained by the Athabasca River and its tributaries; this area composing the overall Athabasca Watershed has been subdivided into 10 subwatersheds including the Upper Athabasca subwatershed which extends from the river's headwaters in Jasper National Park to just past the town of Whitecourt (Athabasca Watershed Council, 2018). Discussions of key pressures faced by the Athabasca Watershed can be found within the Status of the Athabasca Watershed: Summary Report published by the Athabasca Watershed Council in 2018, wherein the Upper Athabasca subwatershed is combined with the McLeod subwatershed to form the Upper Athabasca area (Council 2018).

Very little information has been published regarding the distribution and status of wetlands within the Upper Athabasca area. In order to ascertain knowledge regarding the location of wetlands within this area, the Alberta Environment and Parks' open geospatial datasets containing information on the Watersheds of Alberta (GOA) and the Alberta Merged Wetland Inventory were consulted (AEP, 2014, 2020). The Upper Athabasca subwatershed and area for this process were defined based on the State of the Athabasca Watershed: Summary Report (Council 2018); within the report, the Upper Athabasca subwatershed consists of the Water Survey of Canada tertiary watersheds 07AA, 07AB, 07AC, 07AD, 07AE, and 07AH. This was used in GIS mapping to delineate the Upper Athabasca watershed, as this designation did not exist on any of the available Government of Alberta watershed layers. **Figure 1a** and **b** display the subwatersheds and Water Survey of Canada tertiary watersheds which were utilized to delineate the Upper Athabasca area of interest as well as the Upper Peace River watershed (see Section 2.4). Areal coverage and percentages of the five wetland types listed in the Alberta Merged Wetland Inventory which fall within the Upper Athabasca area are provided in **Table 2**. It is worth noting that only a portion of the overall Athabasca subwatershed was utilized to define the Upper Athabasca area, thus the areal percentages of wetland cover within this subwatershed apply to the partial subwatershed rather than the entire subwatershed. In addition, Jasper National Park is excluded from the Alberta Merged Wetland Inventory, thus wetlands within this area are not represented in the estimates of wetland coverage. Based on geospatial analysis, wetlands cover approximately 11.6% of the Upper

Athabasca area. Overall, fens are the most common type of wetland within this area, covering around 6.4% of the total area and representing 55.2% of the total wetlands. The second most common type of wetland in the Upper Athabasca area are swamps, which cover approximately 3.9% of the area and compose 33.5% of the total wetlands. Both of these wetland types are more prevalent (in terms of areal coverage) within the McLeod subwatershed than within the portion of the Athabasca subwatershed which falls into the Upper Athabasca area. Bogs make up a very low proportion of the total wetlands in the Upper Athabasca area (0.4%) and cover only 0.04% of the total area.

Table 2: Wetland Coverage within the Upper Athabasca Area. The coverage of the subwatersheds of interest and the overall Upper Athabasca area occupied by wetlands are given as areas (A), percent of watershed areas (B), and percent of total wetland coverage (C). Wetland areal coverage data across Alberta was obtained from the Alberta Merged Wetland Inventory geospatial dataset (AEP, 2020), while watershed boundaries and areas were obtained from the Watersheds of Alberta (GOA) geospatial dataset (AEP, 2014). Note: Only a portion of the overall Athabasca subwatershed lies within the Upper Athabasca area, thus the areas and percentages presented here do not represent wetland coverage within the entire Athabasca subwatershed. In addition, Jasper National Park is excluded from the Alberta Merged Wetland Inventory, thus wetlands within this area are not represented in the estimates of wetland coverage within the Athabasca subwatershed and the Upper Athabasca area.

(A)

		Area (km^2)		
Location		Athabasca Subwatershed (partial)	McLeod Subwatershed	Upper Athabasca Area
Wetland Class	Bog	10.4	3.9	14.2
	Fen	1167.5	1061.4	2228.9
	Marsh	36.2	11.6	47.9
	Open Water	278.3	112.6	390.9
	Swamp	484.1	869.8	1353.9
	Total Wetland	1976.5	2059.3	4035.8
Total Area		25149.1	9656.9	34806.0

(B)

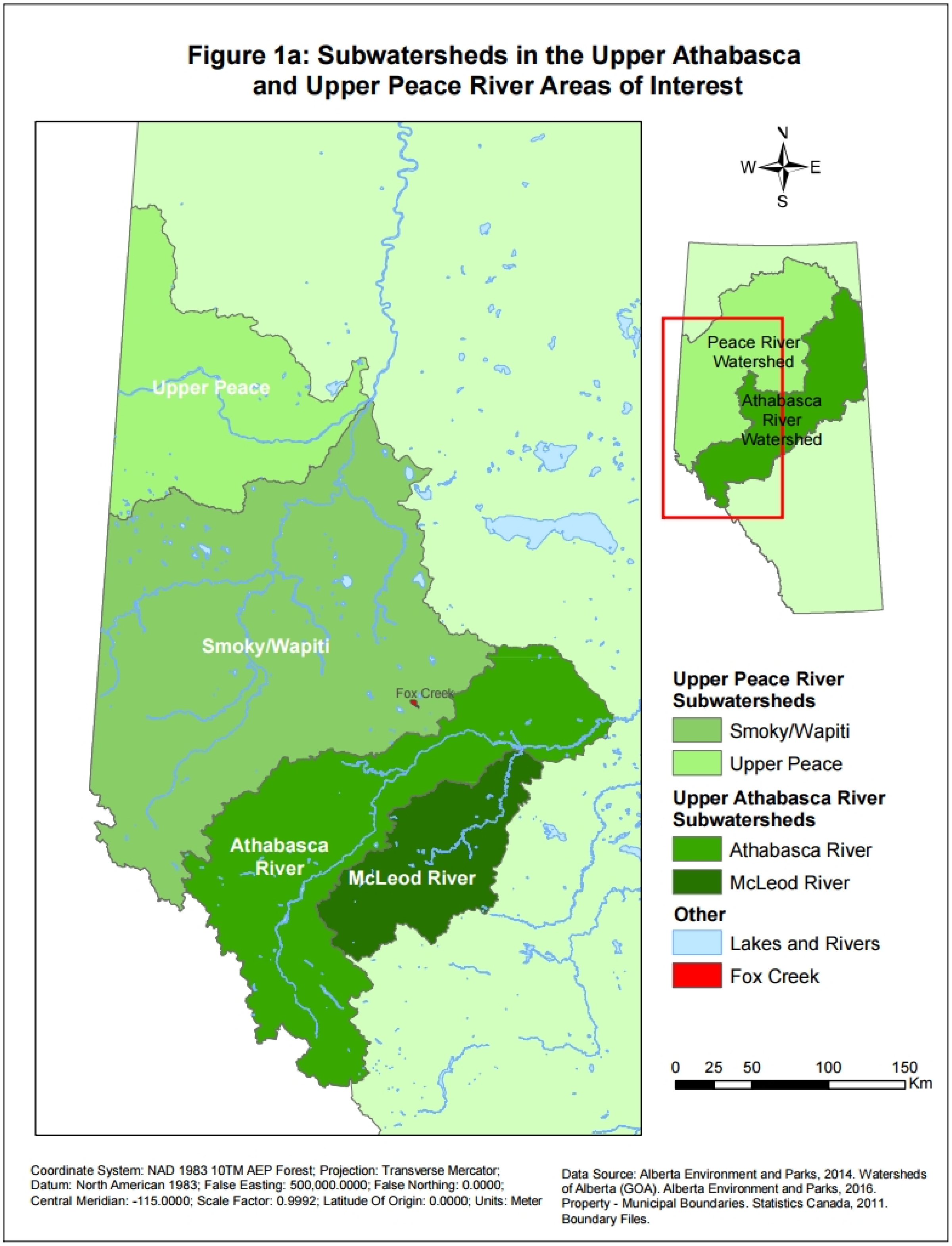
		Percentage of Watershed Area		
Location		Athabasca Sub-watershed (partial)	McLeod Subwatershed	Upper Athabasca Area
Wetland Class	Bog	0.04	0.04	0.04
	Fen	4.64	10.99	6.40
	Marsh	0.14	0.12	0.14
	Open Water	1.11	1.17	1.12
	Swamp	1.92	9.01	3.89
	Total Wetland	7.86	21.32	11.60

(C)

		Percentage of Total Wetlands		
Location		Athabasca Sub-watershed (partial)	McLeod Subwatershed	Upper Athabasca Area
Wetland Class	Bog	0.5	0.2	0.4
	Fen	59.1	51.5	55.2
	Marsh	1.8	0.6	1.2
	Open Water	14.1	5.5	9.7
	Swamp	24.5	42.2	33.5

While not focused directly on wetlands within the watershed, the State of the Watershed: Summary Report consolidates information regarding the overall health of the Athabasca Watershed in terms of water quantity, water quality, fisheries, aquatic wildlife and associated habitat, point-source pollution inputs, and cumulative watershed pressures (Council 2018). Within the Upper Athabasca area, cumulative watershed pressure ratings move from low to moderate and high as the river leaves Jasper National Park and enters the Foothills Region where land uses such as forestry, oil and gas extraction, coal and aggregate mining, recreation and tourism intensify (Council 2018).

Landscape pressures within this area are dominated by linear disturbances such as pipelines, roads and seismic lines, while clearcut forestry operations also occur within the Upper Athabasca area. Human activity in the area has resulted in stressors including loss of stream connectivity, loss of native vegetation, habitat loss, and habitat fragmentation. Nutrient enrichment and selenium loading in surface waters, as well as moderate pressure to groundwater quantity and quality from high well density and large volumes of groundwater withdrawals also occur within this area (Council 2018). As all of the aforementioned landscape pressures and stressors have the ability to influence wetland health and coverage, it is not unreasonable to assume that the cumulative pressures faced by the overall Upper Athabasca area provide an accurate estimate of the pressures faced by wetlands in this area as well. The Upper Athabasca area is listed within the State of the Watershed: Summary Report as a region which should be targeted as a priority for Integrated Watershed Management Planning; logically, the same can be said in regards to the importance of strategic planning when it comes to wetlands within this area.



Coordinate System: NAD 1983 10TM AEP Forest; Projection: Transverse Mercator; Datum: North American 1983; False Easting: 500,000.0000; False Northing: 0.0000; Central Meridian: -115.0000; Scale Factor: 0.9992; Latitude Of Origin: 0.0000; Units: Meter

Data Source: Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA). Alberta Environment and Parks, 2016. Property - Municipal Boundaries. Statistics Canada, 2011. Boundary Files.

Figure 1a. Subwatersheds in the Upper Athabasca and Upper Peace River Areas of Interest

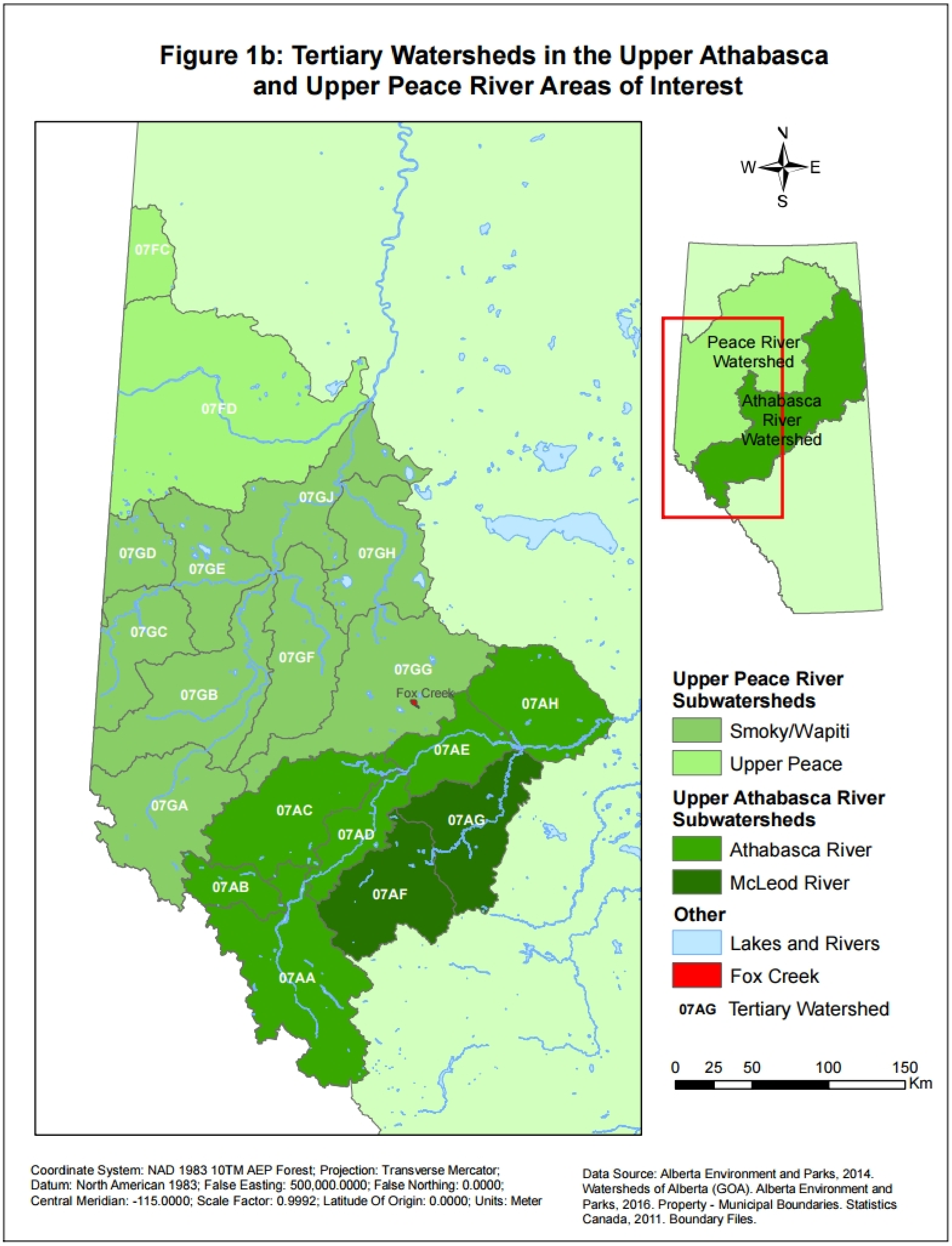


Figure 1b: Tertiary Watersheds in the Upper Athabasca and Upper Peace River Areas of Interest

Coordinate System: NAD 1983 10TM AEP Forest; Projection: Transverse Mercator; Datum: North American 1983; False Easting: 500,000.0000; False Northing: 0.0000; Central Meridian: -115.0000; Scale Factor: 0.9992; Latitude Of Origin: 0.0000; Units: Meter

Data Source: Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA). Alberta Environment and Parks, 2016. Property - Municipal Boundaries. Statistics Canada, 2011. Boundary Files.

Figure 1b. Tertiary Watersheds in the Upper Athabasca and Upper Peace River Areas of Interest.

2.4. Distribution of Wetlands in the Upper Peace River Watershed near Fox Creek

The Peace River is the largest river in Alberta, with a length approaching 2000 km and maximum width of nearly 2 km in some locations (Mighty Peace Watershed Alliance 2015). The Peace River originates in British Columbia's Rocky Mountains, where the Finlay and Parsnip River watersheds contribute flow into Williston Lake which then acts as the headwaters for the Peace River (Mighty Peace Watershed Alliance 2015). The Peace River is a regulated river, with multiple dams present or planned for future construction along its length to control flow and generate hydroelectricity. The largest of these is the W.A.C. Bennet Dam located at the outlet of Williston Lake in British Columbia (Mighty Peace Watershed Alliance 2015). Annually, approximately 48.6 billion m^3 of water is carried by the Peace River into Alberta. At its mouth, the Peace River joins the Slave River near the Northwest Territories and contributes greater than 68 billion m^3 of water annually, comprising approximately 65% of the Slave River's average discharge (Mighty Peace Watershed Alliance 2015).

The overall Peace River Watershed has been divided into several subwatersheds for the purpose of watershed planning (Mighty Peace Watershed Alliance 2015). At the western extent of the Peace River Watershed within Alberta, the Upper Peace subwatershed lies along the main trunk of the Peace River. Adjacent to this area, the Smoky River acts as a major tributary to the Peace River, conveying flow from the Wapiti River, Little Smoky River, and a number of smaller rivers and streams to the Peace. Designated as the Smoky/Wapiti subwatershed, the land drained by the Smoky River covers the area south of the Upper Peace subwatershed and north of the Upper Athabasca area defined in Section 2.3 (Mighty Peace Watershed Alliance 2015). The Upper Peace and Smoky/Wapiti subwatersheds discussed herein were defined based on the State of the Watershed report published by the Might Peace Watershed Alliance in 2015; **Figure 1a** and **b** display the subwatersheds and Water Survey of Canada tertiary watersheds which were utilized to delineate this area of interest within the overall Peace River Watershed.

A limited amount of information regarding the coverage and status of wetlands in the Peace River Watershed is available; that which has been published can be found within the Summary of the Watershed report for this area (Mighty Peace Watershed Alliance 2015). With the exception of the Wood Buffalo National Park area and shallow open-water wetlands, which were not included due to data limitations, 29% of the overall Peace River Watershed area within Alberta is composed of wetlands (Mighty Peace Watershed Alliance 2015). These wetlands are concentrated within the Boreal Forest Natural Region, where human activity is limited and land surface drainage is slowed by a more subdued topography than in the Foothills Region where surface water drains relatively quickly due to steep slopes (Mighty Peace Watershed Alliance 2015). Areal coverage and percentages of wetlands within the Upper Peace and Smoky/Wapiti subwatersheds specifically were calculated using the Alberta Merged Wetland Inventory (AEP, 2020) and are provided in **Table 3**. Within the Upper Peace and Smoky/Wapiti subwatersheds, the areal coverage of wetlands is less than in the overall Peace River watershed, with a total coverage of 11.7% and 12.5% respectively. This translates to a coverage of approximately 12.3% of the Upper Peace River area by wetlands. Swamps are the most common wetland type within the Upper Peace River area, occupying approximately 5.9% of the total area, and composing 47.9% of the wetlands in the area. Fens are the second most prevalent wetland type, covering 3.1% of the Upper Peace River area and making up 25.1% of the area's wetlands. Both of these wetland types are similar in their coverage of the Upper Peace and Smoky/Wapiti subwatersheds. Bogs compose approximately 12.6% of the total wetlands and cover 1.6% of the landscape within the Upper Peace River area. While bog coverage within the Smoky/Wapiti subwatershed is similar to that within the overall Upper Peace River area, within the Upper Peace Watershed bogs cover approximately 2.5% of the area and makeup 21.1% of the total wetlands.

Table 3: Wetland Coverage within the Upper Peace River Watershed Area. The coverage of the subwatersheds of interest and the overall Upper Peace River watershed area in Alberta occupied by wetlands are given as areas (A), percent of watershed areas (B), and percent of total wetland coverage (C). Wetland areal coverage data across Alberta was obtained from the Alberta Merged Wetland Inventory geospatial dataset *(AEP, 2020)*, while watershed boundaries and areas were obtained from the Watersheds of Alberta (GOA) geospatial dataset *(AEP, 2014)*.

(A)

		Area (km^2)		
Location		Upper Peace Subwatershed	Smoky/Wapiti Subwatershed	Upper Peace River Area
Wetland Class	Bog	434.0	561.2	995.2
	Fen	541.1	1436.0	1977.1
	Marsh	58.0	212.0	270.0
	Open Water	179.6	679.5	859.1
	Swamp	843.5	2924.3	3767.8
	Total Wetland	2056.3	5813.0	7869.3
Total Area		17567.5	46657.0	64224.5

(B)

Location		Percentage of Watershed Area		
		Upper Peace Subwatershed	Smoky/Wapiti Subwatershed	Upper Peace River Area
Wetland Class	Bog	2.47	1.20	1.55
	Fen	3.08	3.08	3.08
	Marsh	0.33	0.45	0.42
	Open Water	1.02	1.46	1.34
	Swamp	4.80	6.27	5.87
	Total Wetland	11.71	12.46	12.25

(C)

Location		Percentage of Total Wetlands		
		Upper Peace Subwatershed	Smoky/Wapiti Subwatershed	Upper Peace River Area
Wetland Class	Bog	21.1	9.7	12.6
	Fen	26.3	24.7	25.1
	Marsh	2.8	3.6	3.4
	Open Water	8.7	11.7	10.9
	Swamp	41.0	50.3	47.9

While the extent of wetland coverage within the watershed has been reported previously (Mighty Peace Watershed Alliance 2015) and calculated on a subwatershed basis within this literature review using the Alberta Merged Wetland Inventory (AEP, 2020), knowledge gaps currently exist in regards to wetland health and function, as well as locations of wetland loss within the Peace River Watershed and subwatersheds (Mighty Peace Watershed Alliance 2015). In the face of these knowledge gaps, inferences regarding impacts to wetlands must be made based on overall human impacts to surface water and groundwater quality and quantity within the watershed. Based on the Alberta Biodiversity Monitoring Institute's Human Footprint index data from 2010, the Peace

River Watershed is, on a whole, largely undisturbed (Mighty Peace Watershed Alliance 2015). However, while only 15.1% of the total Peace River Watershed area is directly impacted by human footprint, this disturbance is proportionally much higher within the Upper Peace and Smoky/Wapiti subwatersheds. Human footprint from land uses such as agriculture, forestry, mining, oil and gas extraction, and recreation covers 45.32% of the Upper Peace subwatershed and 29.91% of the Smoky/Wapiti subwatershed (Mighty Peace Watershed Alliance 2015) and is likely indicative of wetland habitat loss in these subwatersheds in the past. Human land-use appears to have had a limited negative impact on the water quantity and quality within major rivers of the Upper Peace and Smoky/Wapiti watershed. Water quantity with the Peace River has remained consistent following the implementation of the W.A.C. Bennet Dam, and a very minimal amount of the water has been allocated for use (less than 1%). Surface water quality, measured in terms of metals; nutrients; bacteria; and pesticides, within the major rivers of the Upper Peace and Smoky/Wapiti subwatersheds has remained excellent to good on average from 1996 to 2010 (Mighty Peace Watershed Alliance 2015). A decrease in water quality was observed in the Wapiti River downstream of Grande Prairie due to nutrient and bacteria inputs from industrial and municipal sources which continue to affect water quality downstream into the Smoky River, however, the threat to overall river water quality in this area is still minimal (Mighty Peace Watershed Alliance 2015). While surface water quality within the major rivers remains good, water quality within smaller tributaries and lakes serves as a more representative metric for human impacts on a natural area (Mighty Peace Watershed Alliance 2015). The intensity of the human footprint in the Upper Peace and Smoky/Wapiti subwatersheds is reflected in the measured phosphorous concentrations in lakes in this area, with the majority of the lakes sampled returning phosphorous concentrations which fell within the highest two concentration categories for lakes in Alberta (ranking 7-10 on the concentration index scale which ranges from 0-10; Mighty Peace Watershed Alliance 2015). While not measuring wetlands directly, this impact of human activities on lakes in the area is indicative of overarching human disturbance to natural ecosystems; as some wetland types can receive water inputs from the same sources as lakes, it is reasonable to assume that wetlands in the Upper Peace and Smoky/Wapiti subwatersheds also experience water quality disturbance from human activities. As the vegetation communities within wetlands are highly influenced by water chemistry, changing metal and nutrient levels from human activities in the area may have lasting impacts on overall species composition, richness, and diversity.

Groundwater quantity and quality is also important for wetland health; groundwater is particularly significant for fen systems, and may also influence the state of swamps, marshes, and shallow open water wetlands. Within the Upper Peace and Smoky/Wapiti subwatersheds, a shortage of high-yield freshwater aquifers exist, however additional supplies of saline groundwater may exist in deeper aquifers (Mighty Peace Watershed Alliance 2015). Only 10% of the groundwater within the Upper Peace subwatershed has been allocated, while 50% has been allocated within the Smoky/Wapiti subwatershed (Mighty Peace Watershed Alliance 2015). The proportionally greatest groundwater allocation within the Upper Peace subwatershed has been for municipal uses, with industrial uses being the second most common. This is reversed for the Smoky/Wapiti subwatershed (Mighty Peace Watershed Alliance 2015). A more intensive groundwater quality monitoring program is needed within the Peace River watershed; however, it is known that two areas within the Smoky/Wapiti subwatershed face significant stress on groundwater quality. The southern Smoky/Wapiti basin near Grand Cache is in an area where historic coal mining has led to increased selenium levels in surface water, and underlying groundwater formations yield low volumes of water with poor quality (Mighty Peace Watershed Alliance 2015). The area located north of the Wapiti River between Grande Prairie and Beaverlodge faces groundwater stress due to a large amount of conventional hydrocarbon extraction and hydraulic fracturing (Mighty Peace Watershed Alliance 2015). Due to limited groundwater resources within the Upper Peace and Smoky/Wapiti subwatersheds, and within the highlighted areas of the Smoky/Wapiti subwatershed, in particular, increased groundwater use and stresses in these areas could lead to a decreased amount of groundwater available for wetland systems and resulting decline in wetland coverage or shift in wetland type with changes in vegetation species assemblages and carbon storage capacity.

2.5. The Little Smoky Woodland Caribou Range

Northern Alberta is home to a number of herds of woodland caribou (*Rangifer tarandus caribou*), of both the mountain and boreal ecotypes (Alberta Caribou Recovery Team, 2005). This species utilizes a mosaic of boreal forest ecosystems, with habitat preference believed to be based predominantly on predator avoidance (Rettie and Messier 2000). Boreal woodland caribou in northeastern Alberta have been observed to select forested fen peatland complexes at the individual and population levels, with feeding occurring in raised bogs where conditions are optimal for *Cladina spp.* growth (Bradshaw et al. 1995). In addition to the observed selection of forested to open fen complexes and forested bogs, these caribou were noted to randomly use patterned and nonpatterned fens, as well as forested to open fens with 15 – 50% coverage as winter habitat and to avoid upland areas and nonpatterned fens with 15 – 50% coverage (Bradshaw et al. 1995). Observations of woodland caribou within central Saskatchewan showed similar habitat preference, with female woodland caribou selecting open and treed peatlands, as well as black spruce or jack pine upland forests over other habitat types (Rettie and Messier 2000). Terrestrial and arboreal lichens are believed to be the primary food source for North American woodland caribou in the fall and winter (Bergerud 1972, Johnson et al. 2001, McMullin et al. 2011). This is true for woodland caribou within west-central Alberta as well, as shown by a study including the herd in the Little Smoky River region, which concluded that *Rangifer tarandus caribou* is a lichen specialist which feeds predominantly on terrestrial lichens during the winter, while also feeding on graminoids, *Salix spp.* leaves, and forbs in the summer (Thomas Edmonds & Brown). As terrestrial and arboreal lichens are slow-growing, mature forest habitats such as pine, fur, or spruce-dominated upland and peatland complexes are needed for woodland caribou survival (Alberta Caribou Recovery Team, 2005; Thomas et al. 1994). Within their chosen habitat, boreal caribou use spatial separation from other ungulates as a predator avoidance strategy and therefore need large areas of undisturbed habitat (James et al. 2004, Russell et al. 2016). Thus, mature, large, undisturbed peatland complexes and black spruce or pine-dominated uplands are key habitat requirements for woodland caribou.

Woodland caribou have been listed as *Threatened* in Alberta under the provincial Wildlife Act (Alberta Woodland Caribou Recovery Team, 2005; Wildlife Regulation, 2019) as well as within Canada under the federal *Species at Risk Act* Schedule 1 (Russell et al. 2016, Justice 2020). The majority of the caribou herds within Alberta are declining in population; of the eighteen caribou herds listed within the Alberta Woodland Caribou Recovery Plan in 2005 (Alberta Woodland Caribou Recovery Team), nine populations were in decline with three of these at immediate risk of extirpation, while only three herd populations were stable (Alberta Woodland Caribou Recovery Team, 2005; McLoughlin et al. 2003). Population data for the remainder of the eighteen herds in Alberta was unknown at the time. As of 2017, seven of twelve caribou populations within Alberta were noted to be declining in the Report on the Progress of Recovery Strategy Implementation for the Woodland Caribou (*Rangifer tarandus caribou*), Boreal population, in Canada for the period 2012-2017, with three populations stable (Environment and Climate Change Canada 2017). While caribou survival rates were observed to coincide with those of stable caribou populations elsewhere, the recruitment rate of new caribou into the herds in northeastern Alberta was not high enough to prevent declines in the overall population (McLoughlin et al. 2003).

The declines in woodland boreal caribou populations in Alberta are most likely due to increased predation leading to higher calf mortality (Latham et al. 2011b, 2011a, Russell et al. 2016). Natural and human-disturbance which reduces or fragments caribou habitat, changes forest composition, and creates linear corridors through habitat has led to altered predator-prey interactions (Dickie et al. 2017; Latham, Latham, Mccutchen, et al. 2011; Alberta Woodland Caribou Recovery Team, 2005). The amount of incidental predation of caribou has increased in some areas due to increased populations of moose and white-tailed deer which utilize young forest stands as habitat following wildfire or logging disturbance and support greater quantities of predators (Latham, Latham, Mccutchen, et al. 2011; Rettie & Messier, 2000; Russell et al. 2016; Alberta Woodland Caribou Recovery Team, 2005). The creation of linear features such as seismic lines, access roads, and pipelines also enable greater predation of caribou as they are preferential travel corridors for predators and decrease the amount of undisturbed area in which caribou are able to distance themselves from predators and other prey species (Dickie et al. 2017; A. James & Stuart-Smith, 2000; Latham, Latham, Boyce, et al. 2011; Alberta Woodland Caribou Recovery Team, 2005). Wolves in northeastern Alberta and northwestern Saskatchewan have been shown to be able to travel at faster rates and for further distances when utilizing human-created linear corridors, increasing their search rate for prey (Dickie et al. 2017). A study of caribou and wolf habitat usage in relation to linear corridors found that caribou on average avoid linear corridors, while wolves were on average closer to linear corridors than random (James and Stuart-Smith 2000). Predation-caused caribou mortalities recorded in the study were closer to linear corridors than live caribou locations, indicating a higher risk of predation for caribou that live close to linear corridors (James and Stuart-Smith 2000). Thus, when the area around linear features which is avoided by caribou is considered, anthropogenic disturbance in the boreal forest is greater than strictly the habitat which is directly disturbed and increases caribou vulnerability to predation (Alberta Woodland Caribou Recovery Team 2005).

In response to the declining woodland caribou populations within Alberta, the province has been tasked with developing and implementing caribou recovery plans which outline how land within each caribou range will be protected, restored, or undergo strategic development with a minimized footprint from industry (Government of Alberta 2017). The goal of these recovery plans will be to "achieve self-sustaining woodland caribou herds and maintain the distribution of caribou in Alberta", as well as "ensure the long-term habitat requirements for woodland caribou are met within Alberta's caribou ranges" (Alberta Woodland Caribou Recovery Team 2005). Within each range, 65% of the area is required to be achieved and maintained as undisturbed habitat with the biophysical habitat properties necessary for caribou herds (Environment and Climate Change Canada 2017, Government of Alberta 2017). This is the minimum habitat predicted to be necessary to allow caribou herds a 60% chance of reaching self-sustaining levels (Environment and Climate Change Canada 2017, Government of Alberta 2017). Specific actions which are necessary to achieve this minimum undisturbed habitat will include addressing industrial and other human activities with the range, possible predator and other prey species management, and regular monitoring of population trends (Alberta Woodland Caribou Recovery Team 2005).

The southernmost remaining caribou habitat within Alberta is located west of the town of Fox Creek in west-central Alberta (Alberta Woodland Caribou Recovery Team 2005, Russell et al. 2016, Alberta Environment and Parks 2017b, Government of Alberta 2017). This area, known as the Little Smoky Caribou Range, serves as year-round habitat for the Little Smoky boreal woodland caribou herd and borders the A La Peche mountain woodland caribou range (Russell et al. 2016, Government of Alberta 2017). The Little Smoky caribou range lies within the Foothills, Subalpine, and Alpine Natural Regions, and within the Lower Foothills and Upper Foothills Subregions of the province, constituting the last boreal caribou range on the eastern slopes of Alberta (Government of Alberta 2017). Based on population monitoring from 1998-2003, the Little Smoky herd traditionally experienced population decline with an average rate of population change (λ) of 0.883; this rate of population decline placed the Little Smoky herd in immediate risk of extirpation (Alberta Woodland Caribou Recovery Team 2005). In the winter of 2005/06, an annual wolf management program was implemented in the Little Smoky range, allowing the caribou population to reach a stable growth rate and a population of approximately 110 individuals; though stable, the caribou population in this area is still not self-sustaining due to limited undisturbed habitat within the Little Smoky range (Government of Alberta 2017). As of 2017, 99% of the Little Smoky range was disturbed by anthropogenic sources; 97% of the range area was leased to oil and gas companies, while 100% of the range was allocated to forestry companies, and 1% was leased to metallic and industrial mineral companies (Russell et al. 2016, Government of Alberta 2017). As the amount of undisturbed habitat within this range is currently far less than the 65% required by the federal caribou recovery strategy, all habitat which currently exists in the area and will contribute to the achievement of 65% undisturbed habitat in time is considered critical habitat (Russell et al. 2016). In order for caribou to persist within the Little Smoky range, conservation of the existing habitat and restoration of anthropogenic disturbances will need to be prioritized within this area.

2.6. Maps of Wetlands and the Little Smoky Caribou Range in the Study Area

Based on provided mapping layers, the study areas in the vicinity of Fox Creek exist at multiple scales of interest. **Figure 2** shows the location of the study areas in relation to the town of Fox Creek and nearby waterbodies. The Extended Study Zone is approximately 6501 square kilometers in size and encompasses the Study Area Watershed and the Local Study Area. The Study Area Watershed and Local Study Area are around 706 and 90 square kilometers in area respectively.

A series of maps showing the distribution and coverage of wetlands within the Upper Athabasca and Upper Peace River watershed areas of interest near Fox Creek, as well as within the more detailed study areas have been created, and are included herein as **Figure 3a-f**. **Figure 3a** provides an overview of all subwatersheds within the areas of interest, while **Figure 3b-e** gives additional details on wetland coverage within each subwatershed individually. **Figure 3f** shows wetland coverage within the Local Study Area, Study Area Watershed, and Extended Study Zone near Fox creek. These maps were created using the Alberta Environment and Parks Watersheds of Alberta (GOA), Alberta Merged Wetland Inventory, and Property – Municipal Boundaries open geospatial datasets (AEP, 2014, 2016, and 2020), as well as boundary layer data for the province from Statistics Canada (2011). Areal coverage and percentages of the five wetland types listed in the Alberta Merged Wetland Inventory which are present within the study areas of interest near Fox

Creek are provided in **Table 4**; these data are discussed in Section 1.2 and 1.3 for the Upper Athabasca and Upper Peace River areas respectively.

Table 4: Wetland Coverage within the Study Areas of Interest near Fox Creek. The coverage of the study areas of interest by wetlands are given as areas (A), percent of total areas (B), and percent of total wetland coverage (C). Wetland areal coverage data across Alberta was obtained from the Alberta Merged Wetland Inventory geospatial dataset (AEP, 2020).

(A)

		Area (km^2)		
Location		Extended Study Zone	Local Study Area	Study Area Watershed
Wetland Class	Bog	95.7	0.1	0.8
	Fen	611.6	1.7	63.4
	Marsh	14.8	0.0	1.3
	Open Water	122.2	0.2	13.7
	Swamp	500.0	2.7	41.4
	Total Wetland	1344.2	4.7	120.5
Total Area		6501.3	90.0	706.3

(B)

		Percentage of Total Area		
Location		Extended Study Zone	Local Study Area	Study Area Watershed
Wetland Class	Bog	1.47	0.12	0.11
	Fen	9.41	1.89	8.98
	Marsh	0.23	0.00	0.18
	Open Water	1.88	0.24	1.94
	Swamp	7.69	2.95	5.86
	Total Wetland	20.68	5.20	17.06

(C)

		Percentage of Total Wetlands		
Location		Extended Study Zone	Local Study Area	Study Area Watershed
Wetland Class	Bog	7.1	2.3	0.7
	Fen	45.5	36.4	52.6
	Marsh	1.1	0.0	1.1
	Open Water	9.1	4.5	11.3
	Swamp	37.2	56.8	34.3

Based on geospatial analysis, wetlands cover approximately 20.68% of the Extended Study Zone, 5.20% of the Local Study Area, and 17.06% of the Study Area Watershed. Fens and swamps are the two most common types of wetland found within the study areas of interest at all scales, with the percent coverage varying slightly based on the study scale investigated. Fens cover 1.89 to 9.41% of the study areas and compose 36.4 to 52.6% of the total wetlands in the study areas of interest. Similarly, swamps cover 2.95 to 7.69% of the study areas and compose 34.3 to 56.8% of the total wetlands in these areas. Bogs, open water, and marshes are also present within the study areas at smaller areal coverages, with the exception of marshes in the Local Study Area.

Figures 4a and **4b** show the location of the Little Smoky caribou range in relation to the Upper Athabasca and Upper Peace River subwatersheds of interest near Fox Creek (**4a**), as well as the more detailed study areas near Fox Creek (**4b**). The Little Smoky range is located within the Smoky/Wapiti and Athabasca River subwatersheds, and covers an area of approximately 3084 square kilometers (AEP, 2012). While the Little Smoky caribou range is not located within the Local Study Area, the caribou range is within the Extended Study Zone and is overlapped by the Study Area Watershed (see **Figure 4b**). The overlapping area between the Little Smoky caribou range and the Study Area Watershed is approximately 166 square kilometers or 5.4% of the total caribou range. The Extended Study Zone covers nearly 1134 square kilometers or 37% of the Little Smoky range.

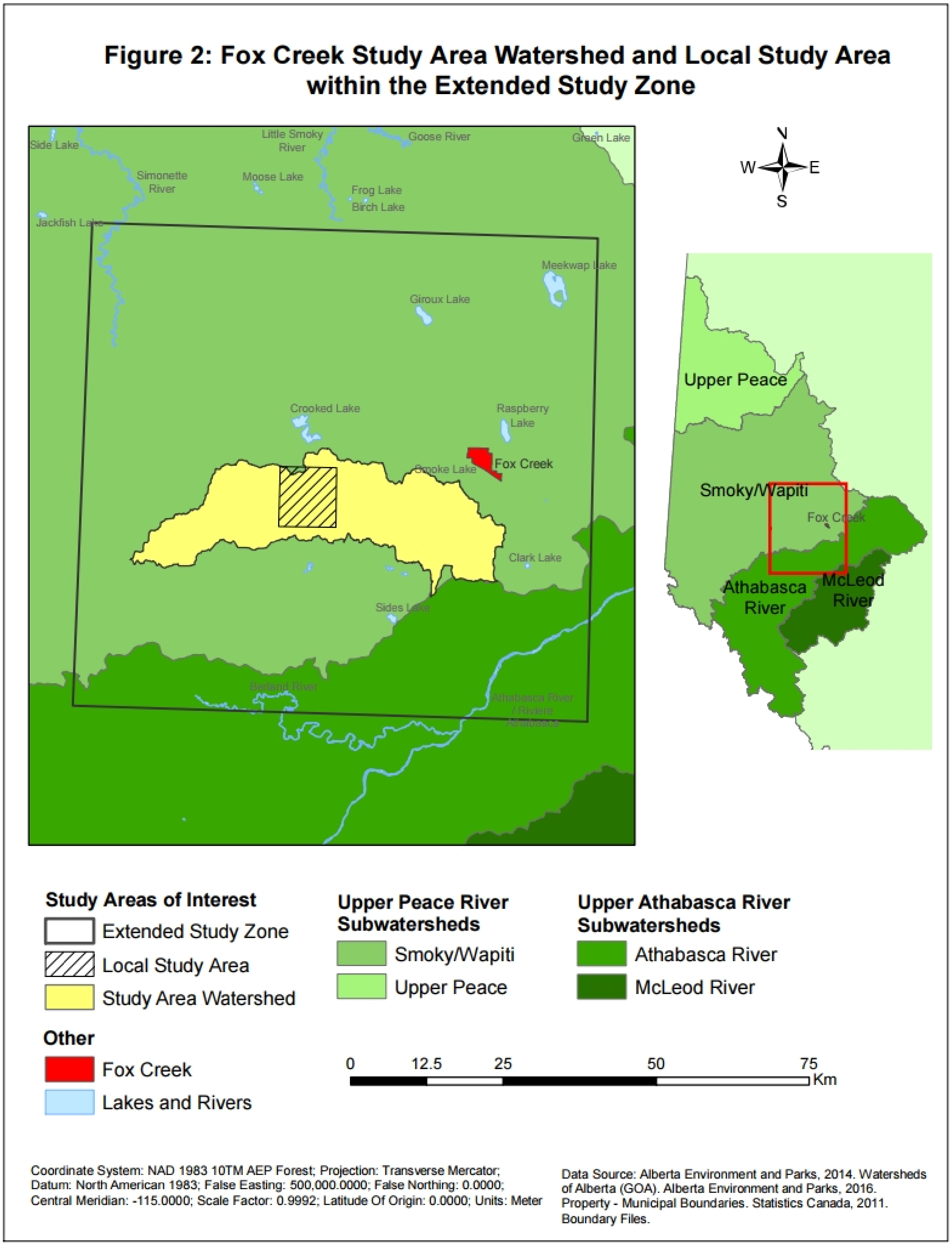
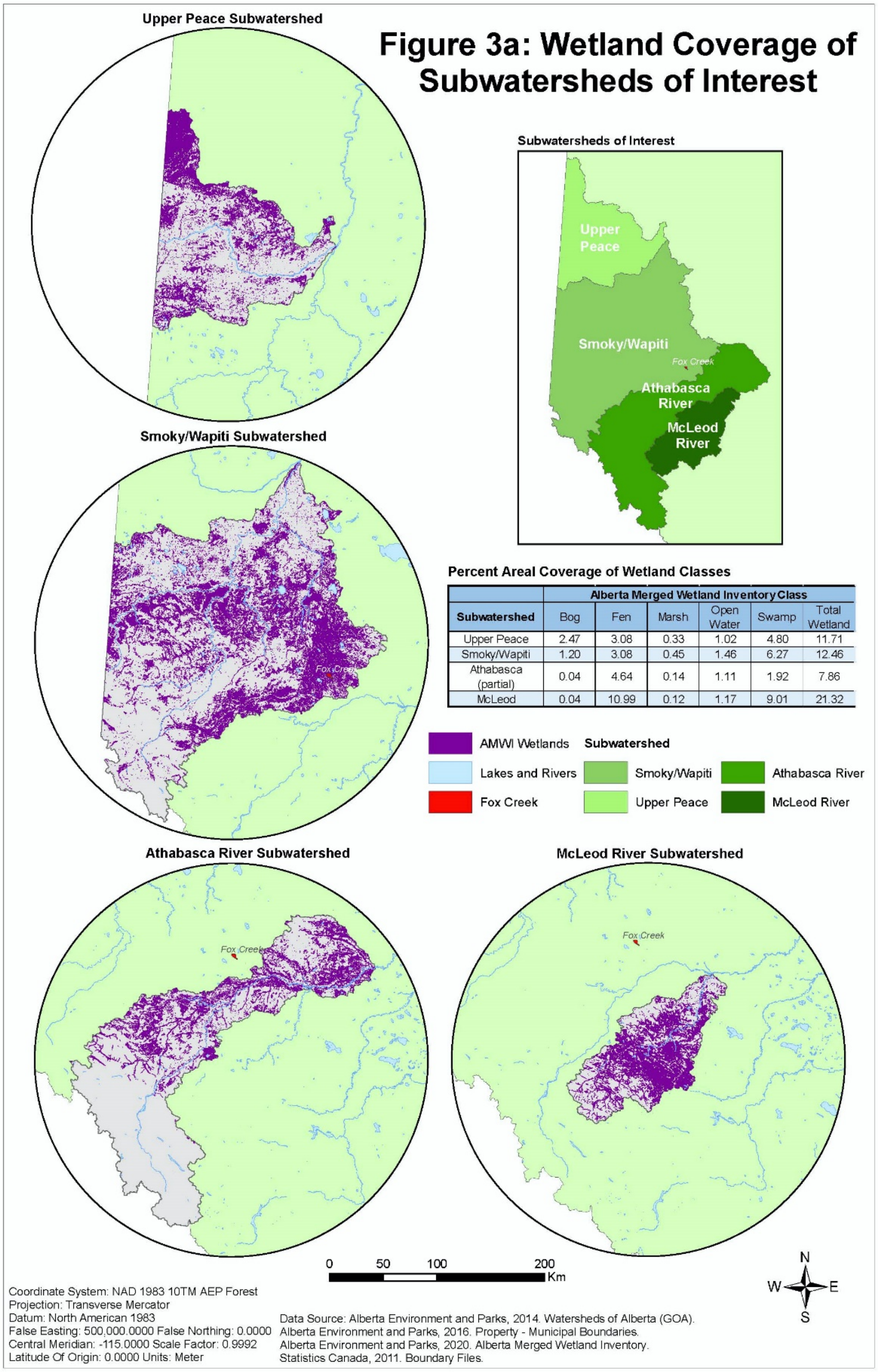


Figure 2: Fox Creek Study Area Watershed and Local Study Area within the Extended Study Zone

Coordinate System: NAD 1983 10TM AEP Forest; Projection: Transverse Mercator; Datum: North American 1983; False Easting: 500,000.0000; False Northing: 0.0000; Central Meridian: -115.0000; Scale Factor: 0.9992; Latitude Of Origin: 0.0000; Units: Meter

Data Source: Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA). Alberta Environment and Parks, 2016. Property - Municipal Boundaries. Statistics Canada, 2011. Boundary Files.

Figure 2. Fox Creek Study Area Watershed and Local Study Area within the Extended Study Zone.



Percent Areal Coverage of Wetland Classes

	Alberta Merged Wetland Inventory Class					
Subwatershed	Bog	Fen	Marsh	Open Water	Swamp	Total Wetland
Upper Peace	2.47	3.08	0.33	1.02	4.80	11.71
Smoky/Wapiti	1.20	3.08	0.45	1.46	6.27	12.46
Athabasca (partial)	0.04	4.64	0.14	1.11	1.92	7.86
McLeod	0.04	10.99	0.12	1.17	9.01	21.32

Coordinate System: NAD 1983 10TM AEP Forest
Projection: Transverse Mercator
Datum: North American 1983
False Easting: 500,000.0000 False Northing: 0.0000
Central Meridian: -115.0000 Scale Factor: 0.9992
Latitude Of Origin: 0.0000 Units: Meter

Data Source: Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA).
Alberta Environment and Parks, 2016. Property - Municipal Boundaries.
Alberta Environment and Parks, 2020. Alberta Merged Wetland Inventory.
Statistics Canada, 2011. Boundary Files.

Figure 3a. Wetland Coverage of Subwatersheds of Interest.

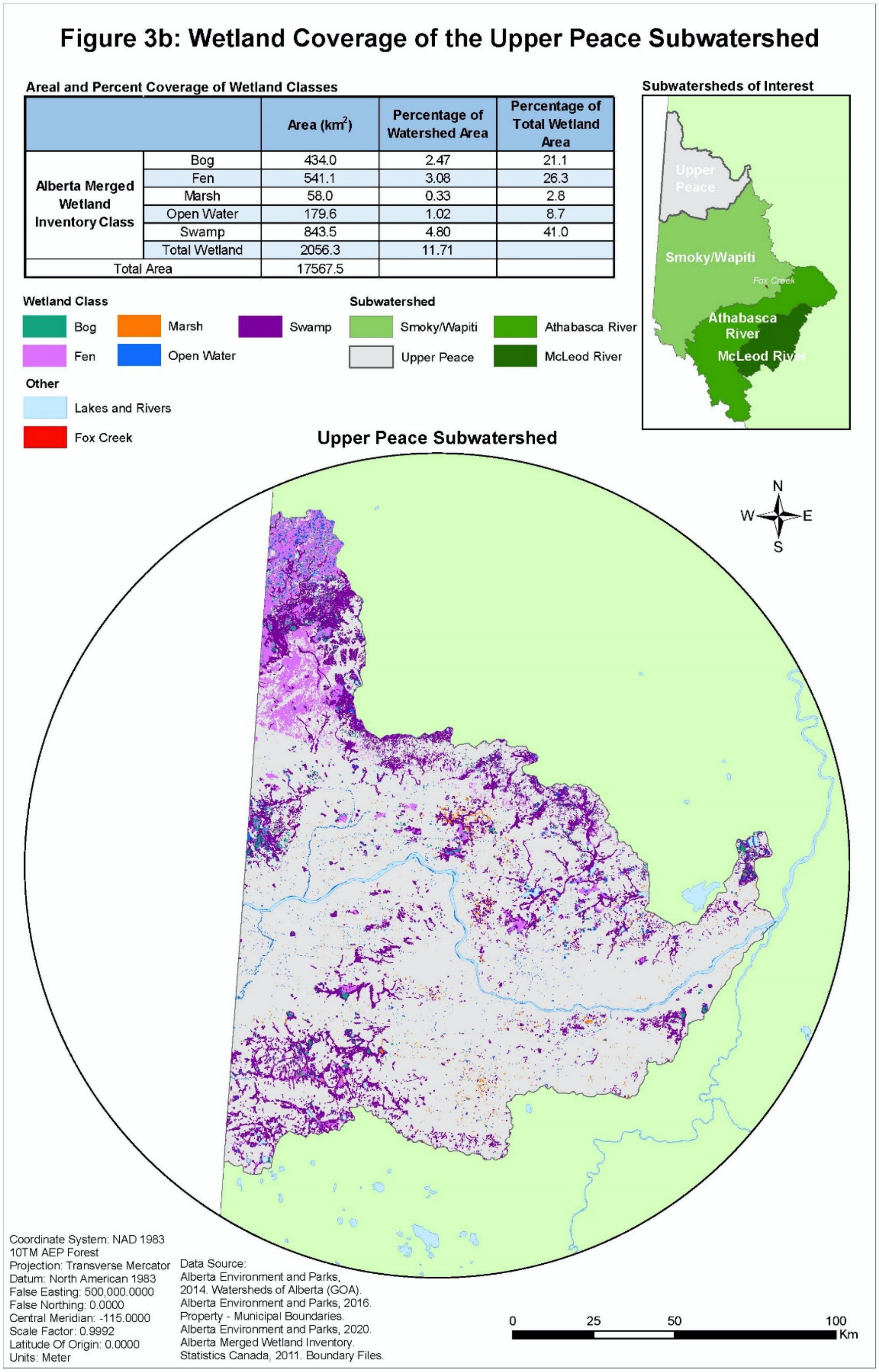


Figure 3b: Wetland Coverage of the Upper Peace Subwatershed

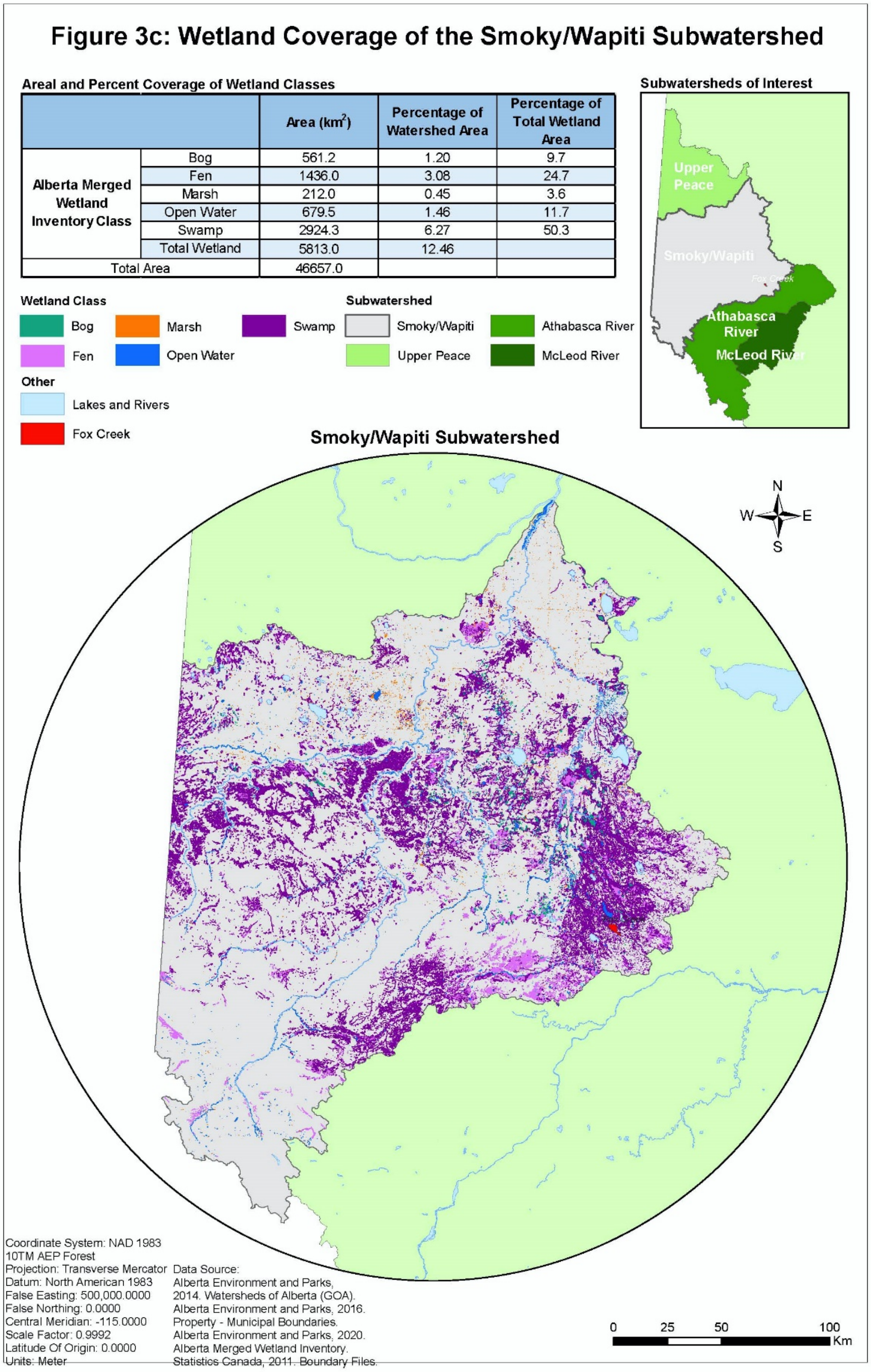
Areal and Percent Coverage of Wetland Classes

		Area (km^2)	Percentage of Watershed Area	Percentage of Total Wetland Area
Alberta Merged Wetland Inventory Class	Bog	434.0	2.47	21.1
	Fen	541.1	3.08	26.3
	Marsh	58.0	0.33	2.8
	Open Water	179.6	1.02	8.7
	Swamp	843.5	4.80	41.0
	Total Wetland	2056.3	11.71	
Total Area		17567.5		

Coordinate System: NAD 1983 10TM AEP Forest
Projection: Transverse Mercator
Datum: North American 1983
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: -115.0000
Scale Factor: 0.9992
Latitude Of Origin: 0.0000
Units: Meter

Data Source:
Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA).
Alberta Environment and Parks, 2016. Property - Municipal Boundaries.
Alberta Environment and Parks, 2020. Alberta Merged Wetland Inventory.
Statistics Canada, 2011. Boundary Files.

Figure 3b. Wetland Coverage of the Upper Peace Subwatershed.



		Area (km^2)	Percentage of Watershed Area	Percentage of Total Wetland Area
Alberta Merged Wetland Inventory Class	Bog	561.2	1.20	9.7
	Fen	1436.0	3.08	24.7
	Marsh	212.0	0.45	3.6
	Open Water	679.5	1.46	11.7
	Swamp	2924.3	6.27	50.3
	Total Wetland	5813.0	12.46	
Total Area		46657.0		

Figure 3c. Wetland Coverage of the Smoky/Wapiti Subwaterhsed.

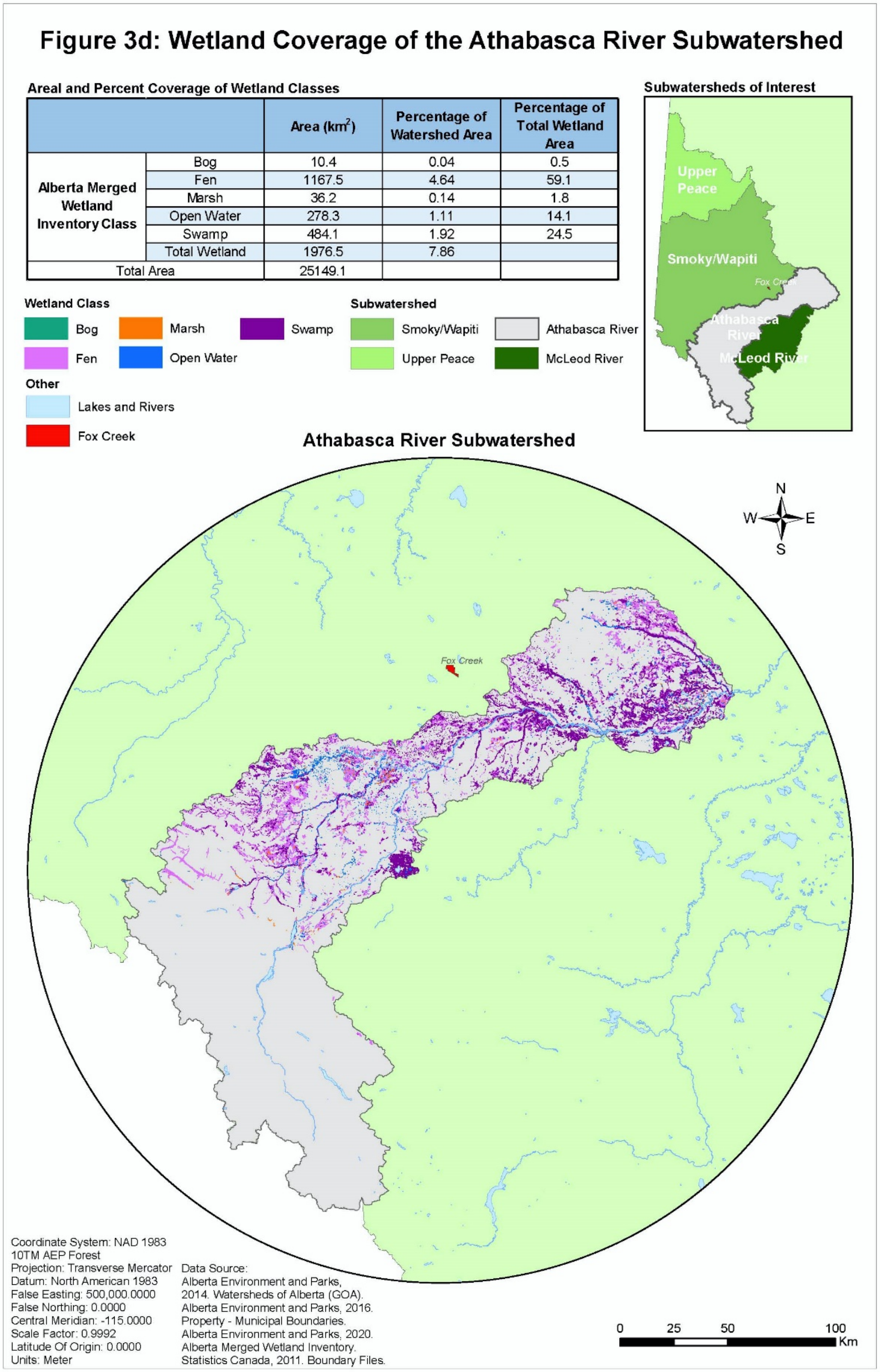


Figure 3d: Wetland Coverage of the Athabasca River Subwatershed

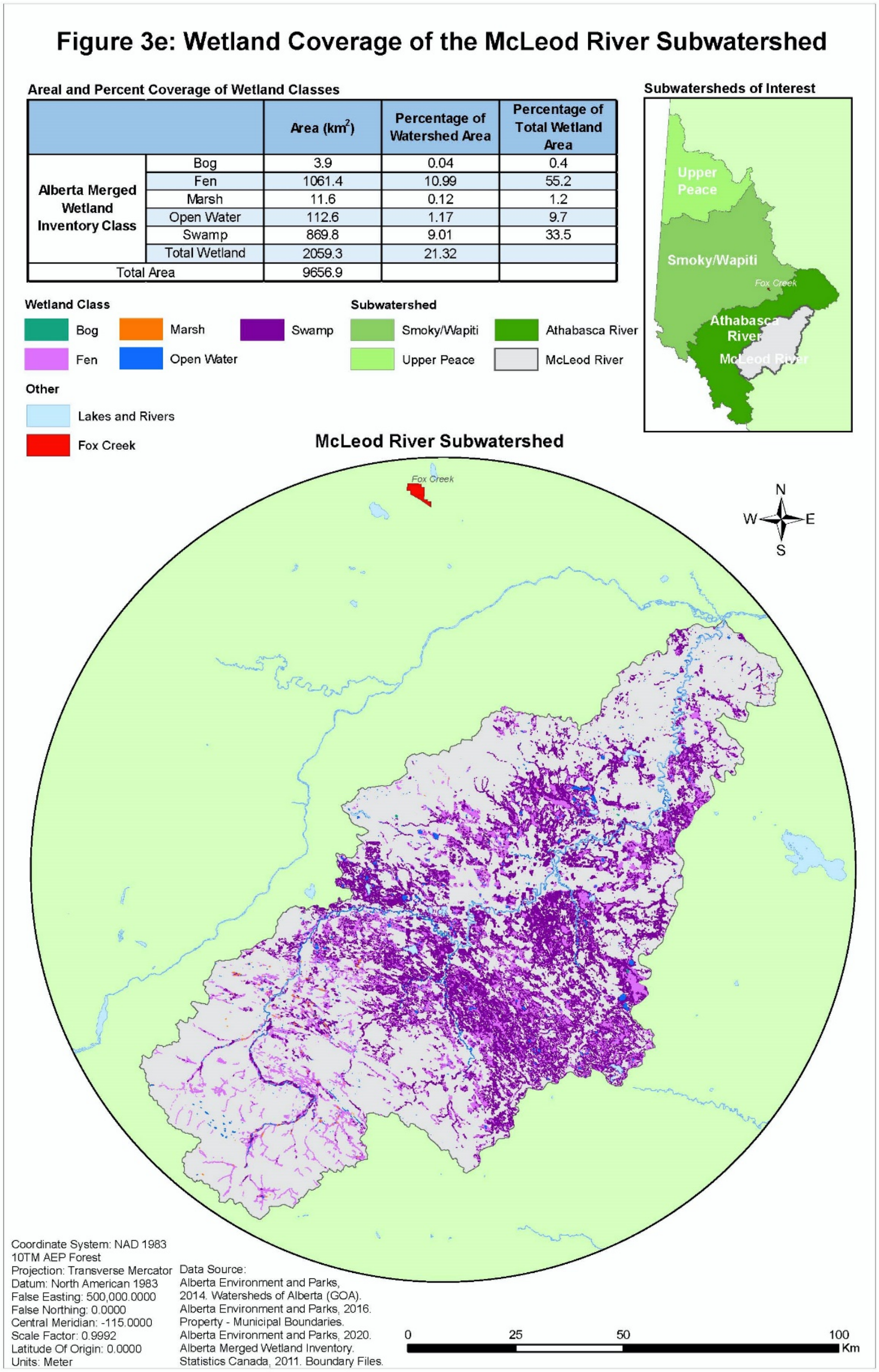
Areal and Percent Coverage of Wetland Classes

		Area (km^2)	Percentage of Watershed Area	Percentage of Total Wetland Area
Alberta Merged Wetland Inventory Class	Bog	10.4	0.04	0.5
	Fen	1167.5	4.64	59.1
	Marsh	36.2	0.14	1.8
	Open Water	278.3	1.11	14.1
	Swamp	484.1	1.92	24.5
	Total Wetland	1976.5	7.86	
Total Area		25149.1		

Coordinate System: NAD 1983
10TM AEP Forest
Projection: Transverse Mercator
Datum: North American 1983
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: -115.0000
Scale Factor: 0.9992
Latitude Of Origin: 0.0000
Units: Meter

Data Source:
Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA).
Alberta Environment and Parks, 2016. Property - Municipal Boundaries.
Alberta Environment and Parks, 2020. Alberta Merged Wetland Inventory.
Statistics Canada, 2011. Boundary Files.

Figure 3d. Wetland Coverage of the Athabasca River Subwatershed.



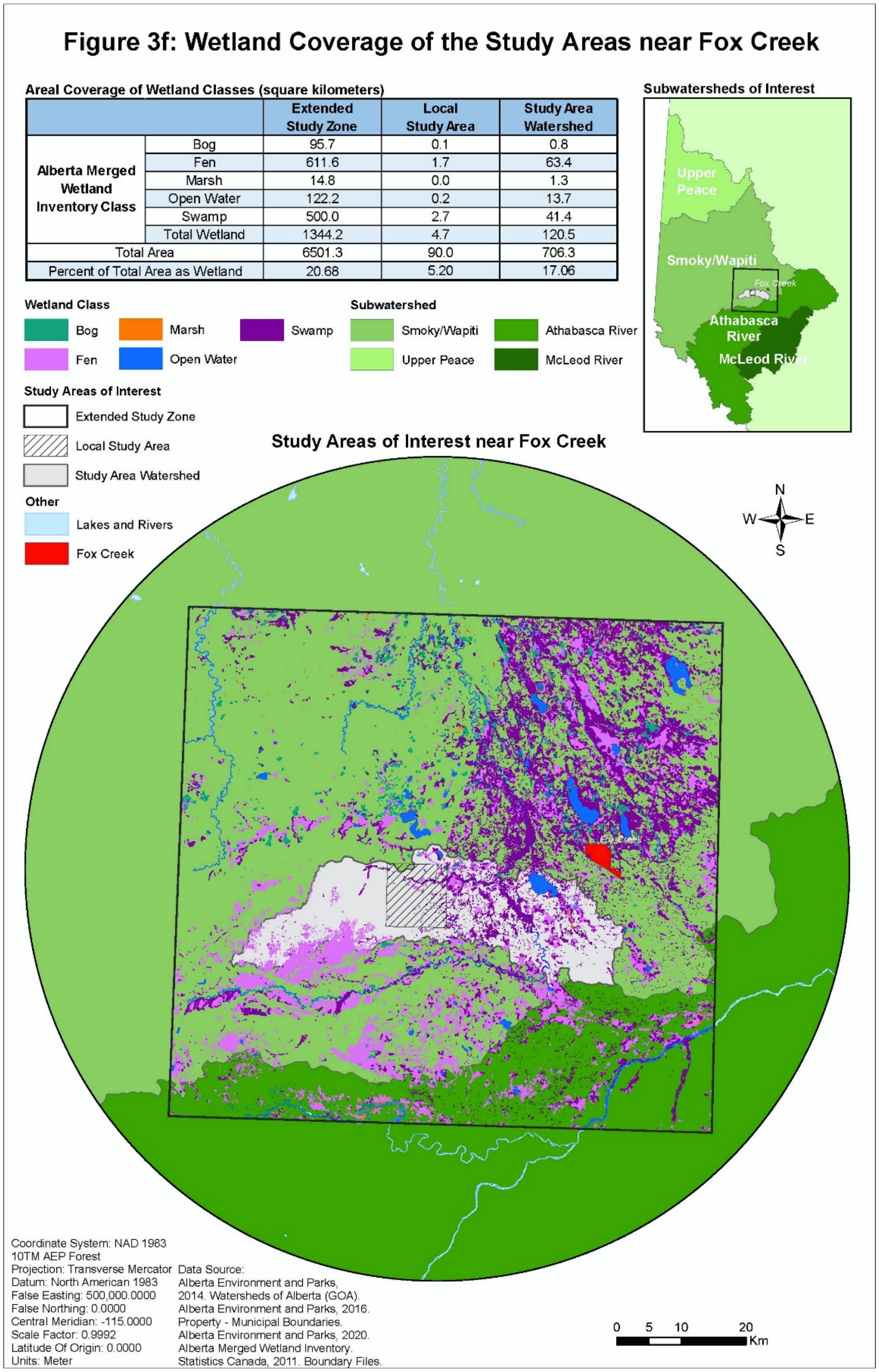
Areal and Percent Coverage of Wetland Classes

		Area (km^2)	Percentage of Watershed Area	Percentage of Total Wetland Area
Alberta Merged Wetland Inventory Class	Bog	3.9	0.04	0.4
	Fen	1061.4	10.99	55.2
	Marsh	11.6	0.12	1.2
	Open Water	112.6	1.17	9.7
	Swamp	869.8	9.01	33.5
	Total Wetland	2059.3	21.32	
Total Area		9656.9		

Coordinate System: NAD 1983
10TM AEP Forest
Projection: Transverse Mercator
Datum: North American 1983
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: -115.0000
Scale Factor: 0.9992
Latitude Of Origin: 0.0000
Units: Meter

Data Source:
Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA).
Alberta Environment and Parks, 2016. Property - Municipal Boundaries.
Alberta Environment and Parks, 2020. Alberta Merged Wetland Inventory.
Statistics Canada, 2011. Boundary Files.

Figure 3e. Wetland Coverage of the McLeod River Subwatershed.

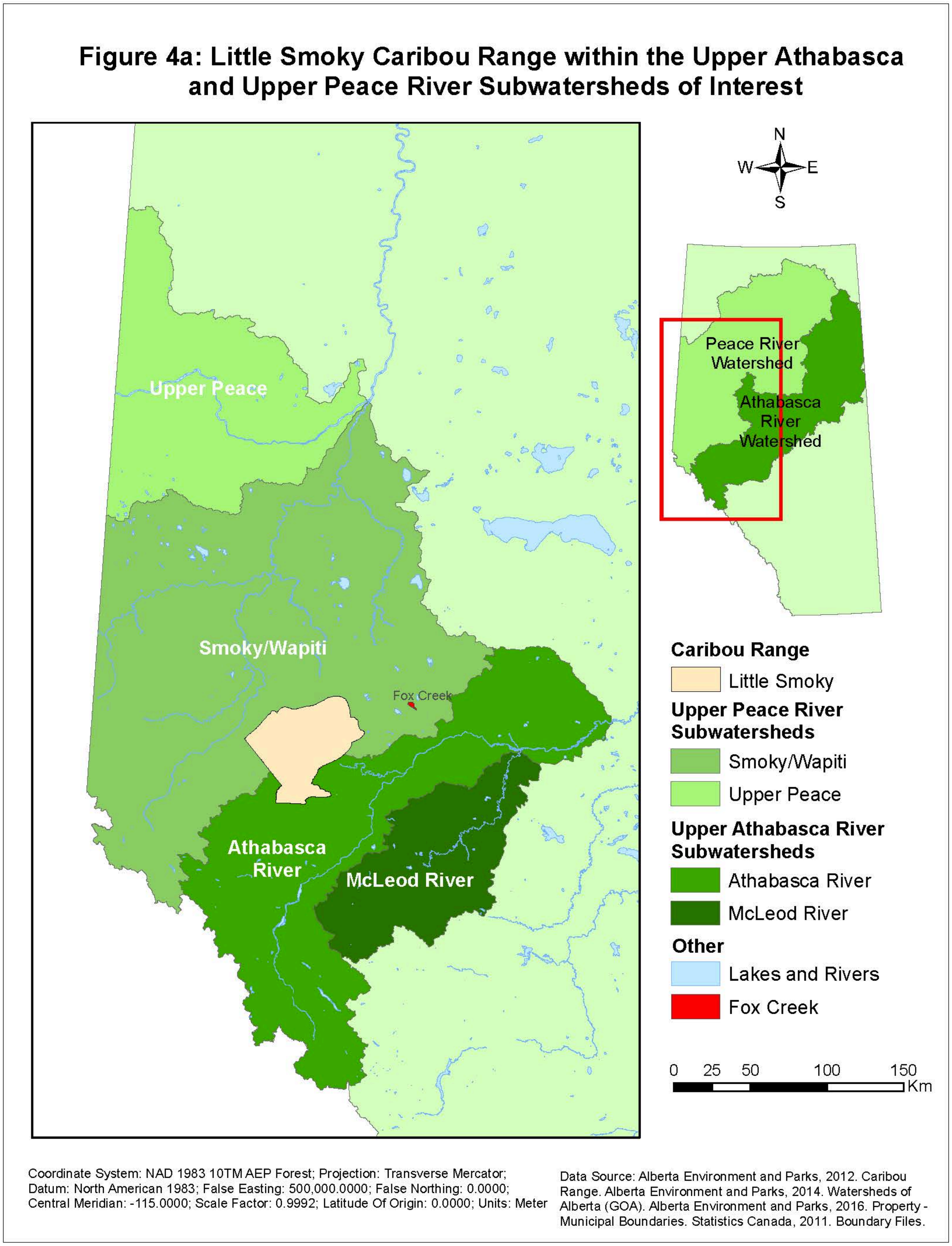


		Extended Study Zone	Local Study Area	Study Area Watershed
Alberta Merged Wetland Inventory Class	Bog	95.7	0.1	0.8
	Fen	611.6	1.7	63.4
	Marsh	14.8	0.0	1.3
	Open Water	122.2	0.2	13.7
	Swamp	500.0	2.7	41.4
	Total Wetland	1344.2	4.7	120.5
Total Area		6501.3	90.0	706.3
Percent of Total Area as Wetland		20.68	5.20	17.06

Coordinate System: NAD 1983
10TM AEP Forest
Projection: Transverse Mercator
Datum: North American 1983
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: -115.0000
Scale Factor: 0.9992
Latitude Of Origin: 0.0000
Units: Meter

Data Source:
Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA).
Alberta Environment and Parks, 2016. Property - Municipal Boundaries.
Alberta Environment and Parks, 2020. Alberta Merged Wetland Inventory.
Statistics Canada, 2011. Boundary Files.

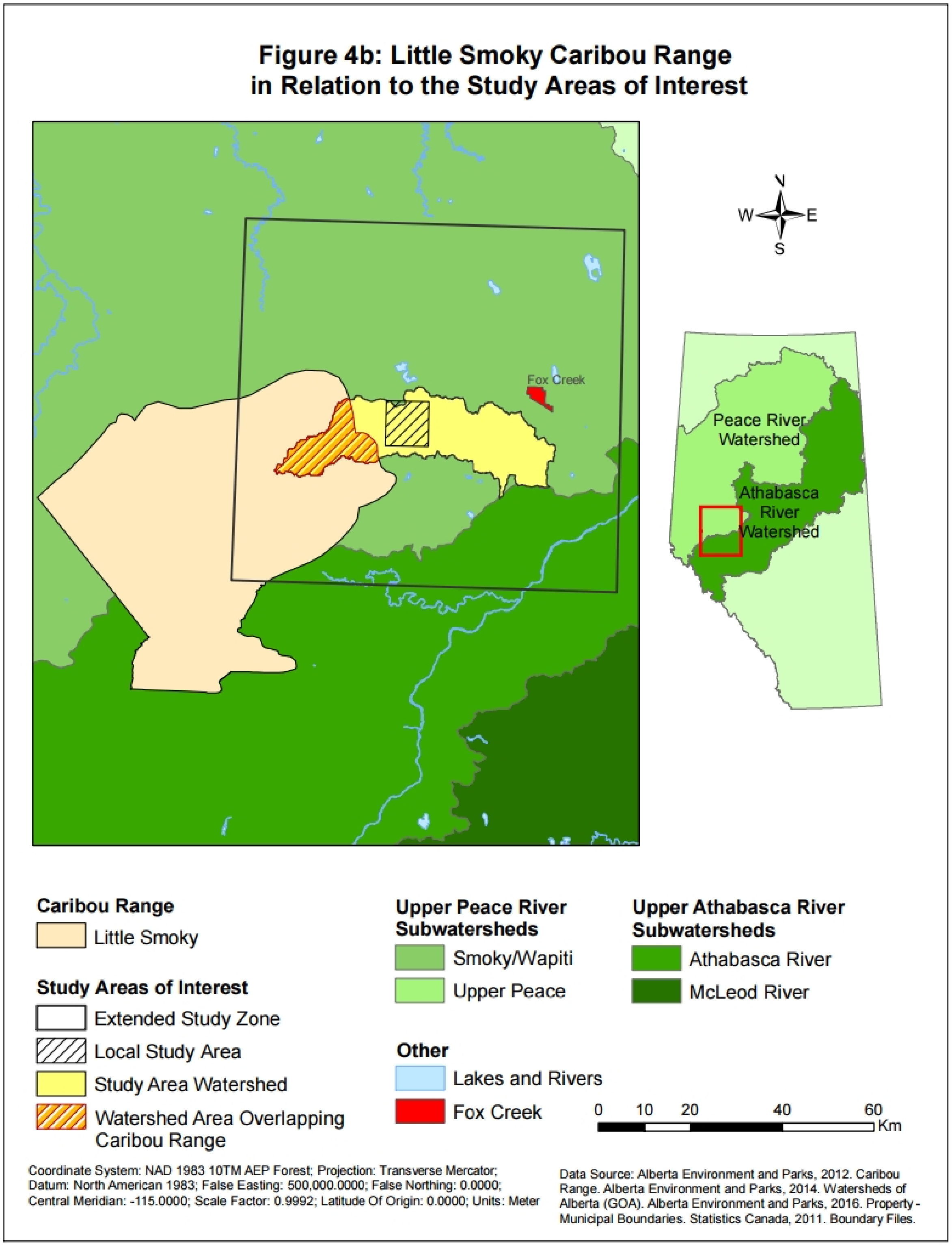
Figure 3f. Wetland Coverage of the Study Areas near Fox Creek.



Coordinate System: NAD 1983 10TM AEP Forest; Projection: Transverse Mercator; Datum: North American 1983; False Easting: 500,000.0000; False Northing: 0.0000; Central Meridian: -115.0000; Scale Factor: 0.9992; Latitude Of Origin: 0.0000; Units: Meter

Data Source: Alberta Environment and Parks, 2012. Caribou Range. Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA). Alberta Environment and Parks, 2016. Property - Municipal Boundaries. Statistics Canada, 2011. Boundary Files.

Figure 4a. Little Smoky Caribou Range within the Upper Athabasca and Upper Peace River Subwatersheds of Interest.



Coordinate System: NAD 1983 10TM AEP Forest; Projection: Transverse Mercator; Datum: North American 1983; False Easting: 500,000.0000; False Northing: 0.0000; Central Meridian: -115.0000; Scale Factor: 0.9992; Latitude Of Origin: 0.0000; Units: Meter

Data Source: Alberta Environment and Parks, 2012. Caribou Range. Alberta Environment and Parks, 2014. Watersheds of Alberta (GOA). Alberta Environment and Parks, 2016. Property - Municipal Boundaries. Statistics Canada, 2011. Boundary Files.

Figure 4b. Little Smoky Caribou Range in Relation to the Study Areas of Interest.

3. Disturbance Impacts on Boreal Wetlands – Hydrology, Vegetation, Carbon and Wildlife

Canada is estimated to have 20% of the world's freshwater, 2% of which flows in Alberta (Water (nrcan.gc.ca). Northern Alberta river basins supply's greater than 80% of the freshwater consumed in the Southern part of the province. Most Canadian hydrological models predict noticeable degradation of watershed streams or decreases in stream flows under future natural and/or anthropogenic disturbances and rising requirements of freshwater supplies. The degradation of watersheds/streams will further impact various hydrological processes at the watershed scale and in the nested wetlands which form integral parts of Alberta watersheds. The impacted hydrological processes may include overland flow, infiltration, percolation, pipe flow, and the generation or attenuation of storm runoff.

Wetlands play an important role in maintaining hydrologic resilience of watersheds, defined as the quick return of natural hydrologic functions during and after hydrologic perturbations (Acreman and Holden, 2013). Non-riparian wetlands exercise hydrologic resilience by reducing the risk of floods or drought through attenuation of peak flow and supply of baseflow (Ameli and Creed, 2019), while riparian wetlands maintain the hydrologic resilience of a watershed by reducing flood pulses (overflow) (Bullock and Acreman, 2003; Westbrook, 2019). Wetlands also filter pollutants and shelter a remarkable variety of plant and animal species including woodland caribou, beaver, and waterfowl (Bullock and Acreman 2003; Westbrook 2019).

Many of the wetlands in the southern boreal forest where the Fox Creek area is located are peat-forming (fens and bogs), which modulate precipitation and regulate surface and subsurface hydrological flows, while the non-peat forming wetlands in this area represent an important component of surface water-groundwater interactions. Since the movement of water is a controlling ecological factor in wetlands, any disturbance has the potential to alter regional water balance and disrupt groundwater/discharge. Hydrological changes will have significant impacts on greenhouse gas (GHG) fluxes, net carbon balance, vegetation productivity, nutrient cycling, and overall wildlife habitat value on the landscape.

Disturbed watersheds and wetlands may be reclaimed or put on a restoration trajectory to original ecosystems; however, it may take reclaimed peatlands decades before they start to accumulate peat. Moreover, the reclaimed or restored wetland may not return the spatial heterogeneity of surface and subsurface flow in peatland environments or the spatial structuring of hydraulic peat properties which were present prior to disturbance; instead, a homogenous environment could be created which will not favor the return of the original water balance and hydrological flows within the watersheds and associated catchment.

Regional water balance of a watershed is estimated by using the water-balance equation:

$$\textbf{I (input)} - \textbf{Q (discharge)} = \Delta \textbf{S (change in storage)} \qquad \textbf{1)}$$

$$\textbf{Or: } (P + G_{in}) - (ET + \underset{\underset{\textbf{(Runoff)}}{\Downarrow}}{(Q + G_{out})}) = \Delta S \qquad \textbf{2)}$$

Where: P is precipitation; Rainfall intensity is the dominant control on the rate of rise of WT

G_{in} is groundwater inflow

Q is stream outflow

ET is evapotranspiration

G_{out} is groundwater outflow

ΔS is change in the amount of stored water

Different components of the water balance equation including hydrological flow patterns may be impacted by natural and anthropogenic disturbances. In the following sections, potential disturbances and their impacts on water balance and flow patterns in Alberta watersheds and/or wetlands are briefly discussed.

3.1. Warming, Drying and Changing Precipitation

Atmospheric or land surface warming and precipitation are the most important components of climate change. Global climatic changes of surface air temperature and precipitation are expected to be severe at northern midlatitudes including west-central Alberta, where there is a dense coverage (> 20%) of wetlands or peatlands (Bernstein et al. 2008; Kettles and Tarnocai 1999; Vitt et al. 2009). If global mean temperature increases by 2.8°C, most of the boreal forest belt will experience 4-5°C warming and some northern parts of Canada will experience an even greater change in temperature (Bhatti et al. 2012). Changes in precipitation are more difficult to predict; however, precipitation is expected to decrease by 20% in northern Alberta (Amiro et al. 2001; Flannigan et al. 2001). The atmospheric or land surface warming and reduced precipitation could play a very important role in controlling regional water balance (input-output) in Alberta, thereby impacting associated watershed hydrology.

Global warming can severely impact short- and long-term regional water balance by enhancing evapotranspiration to a greater magnitude than precipitation, lowering water table levels, and/or reducing water storage. Altered precipitation patterns may result in dramatic shifts in surface- and subsurface flows and drainage patterns across the watersheds.

Climate warming is likely to severely impact wetland hydrology by land surface drying, water table lowering, and an increase in evapotranspiration, which may influence the hydrological processes of infiltration, surface- and groundwater flow, runoff, and drainage across watersheds. The warming-induced hydrological shifts may or may not be offset by altered precipitation patterns. Within a wetland, the lowered water table will stop any horizontal water flows and enlarge the aerobic zone (acrotelm), which may result in accelerated decomposition or carbon dioxide (CO_2) emissions. Peatlands can subside or shrink as a result of water table lowering and accordingly the water storage capacity may be significantly reduced. Therefore, the impacted surface water quantity and quality of the Peace River and Athabasca River basins may not sufficiently fulfill the freshwater requirements of northern Alberta under future climatic conditions.

Regional climate and precipitation patterns are also strong determinants of wetland vegetation composition and diversity. Elevated winter temperatures and/or an early summer season may change the phenology of various plants which are food for wildlife, potentially negatively impacting wildlife. Bogs and fens are the most vulnerable to climate-induced warming and water table lowering because they may experience a shift in vegetation community; for example, a steep and persistent decline of the water table may transition a sedge-dominated fen to a shrub-dominated bog in the long term. Further and permanent lowering (drainage) of the water table could convert the *Sphagnum*-dominated bog to a shrub and tree-dominated ecosystem of higher productivity.

The shifts in vegetation coverage and plant community composition may be different between peatland microforms, whereas mosses in a bog are replaced by vascular plants (e.g. shrubs) at hummocks and by lichens at hollows in the long term.

Climate warming and drying are also robust controls on GHG fluxes and carbon balance of the wetland ecosystems across the river basins. The two most relevant GHG fluxes are CO_2 and methane (CH_4). The amount of CO_2 stored (as peat) in a wetland results from the difference between CO_2 uptake through gross primary productivity (GPP) and CO_2 loss through ecosystem respiration (ER). Net ecosystem exchange (NEE) is represented by the equation:

$$\mathbf{NEE = -GPP + ER} \qquad \mathbf{3)}$$

The above and belowground C balance and cycling in wetlands is driven by hydrology; this balance is expected to be affected by climate change, as climate change may lead to a lowering of the water table within wetland systems in the boreal forest (Munir et al. 2015; Strack et al. 2008; Waddington and Price 2000). Climate change-induced warming and lowered water table could cause an increase in soil temperature, degrade permafrost to thermokarst leading to flooding (Hinzman et al. 2005), alter snowpack thickness (Dye and Tucker 2003), lengthen growing seasons (Euskirchen et al. 2006), and potentially switch peatlands in boreal forest from a net C sink to a net source of C to atmosphere.

The net C sink of the boreal forest is reported to have increased significantly over the period of 1990-2007 by between 0.54 and 1.0 Pg C yr^{-1} (Pan et al. 2011). However, IPCC (2007) has predicted an average global warming between 1-3 ℃ by the year 2029 and up to 5-6 ℃ by the end of this century. The largest increase of up to 10 ℃ in northern regions, including central Alberta, is projected by the end of this century. This may potentially lower regional water table levels due to higher evapotranspiration than precipitation (IPCC, 2007). Since vegetation species adapt to their environments through the process of natural selection, the current tree and shrub vegetation in the midlatitude forest, as well as mosses and lichens in peatlands, may be affected by the changes in climate (warming) and hydrology (lowering in water table). This could affect the productivity, respiration function, and ultimate C stocks of the boreal forest.

For estimating the regional C balance, forest biomass and annual GPP are important (Kurz and Apps 1993; Shvidenko et al. 2007). Moss species may have equal or higher annual productivity than that of overstory woody species (Wieder 2006) but they decompose much slower than vascular species due to the presence of several phenolic compounds (Moore and Basiliko 2006). Other factors contributing to slower decomposition rates in boreal peatlands include high acidity, limited volume of the oxic zone in the peat profile, low soil temperatures during the majority of the year, and poor decomposability of substrate (Moore and Basiliko 2006). These factors should be accounted for when estimating the regional C balance.

All waterfowl use wetlands as feeding and breeding habitat; therefore, wetlands and supporting uplands play an essential role in the lifecycle of boreal waterfowl (Forestry and Waterfowl – Practitioner Guide 2018). Expected climate warming is likely to create a shortage of surface water within wetlands due to impacts on wetland hydrology or through increased periods of drought. The warming may also have direct impacts on wetland waterfowl by extending the summer seasons and changing the phenology of the plants and their wetland habitats. In either scenario, warming and subsequent drying are expected to impact waterfowl habitat negatively.

Muskegs (bogs) and their adjacent areas provide habitat to woodland caribou (*Rangifer tarandus* caribou) which is designated as a threatened wildlife species in Alberta (Alberta Wildlife Act 1985; see section 2.5). The Fox Creek area is occupied by woodland caribou within the Little Smoky caribou range. Woodland caribou in Alberta use remote bogs (characterized by black spruce/Tamarack trees with lichen epiphytes) for their food and shelter during extreme winters and for calving in late winter (Nietfel et al. 1985; Proul 2015). Stands of 400 m diameter provide protection cover and are optimal as wintering areas for the woodland caribou. Warming is likely to impact the habitat value of these wetlands by surface drying, subsequent water table lowering, and vegetation changes. This has the potential to convert current habitat to ecosystems that may not foster the threatened woodland caribou or other critical wildlife species.

3.2. Permafrost Thawing

Permafrost is an important feature of northern peatlands. Permafrost occurs in the arctic, subarctic, and northern boreal forest peatlands where both low air temperature and peat insulation result in ground temperatures that remain below freezing (Belland and Vitt1995). Midlatitude Alberta, Saskatchewan, and Manitoba peatlands have been found to have discontinuous or sporadic and isolated or patchy permafrost occurrences (Turetsky et al. 2007; Turetsky et al. 2002; Turetsky et al. 2000). In these regions, permafrost is found in locally cold settings such as north-facing slopes, low-lying, and/or poorly drained areas. Permafrost peatlands can be an exception, as the development of perennial ice can result in a surface that is often raised above the water table by up to one meter (Vitt, 1994; AWCS 2015). More carbon is contained in permafrost than is currently in circulation in the atmosphere (Bowden, 2010); therefore, any natural or anthropogenic disturbance resulting in permafrost melt may have significant consequences for global warming, watershed and wetland hydrology, water balance, and stream flows.

Permafrost in boreal peatlands is continuously degrading or melting at its southernmost limit, with no evidence of regeneration (Beilman and Robinson, 2003; Vitt 1994). Melting of frozen peat and ice in peat plateaus leads to ground subsidence and the formation of thermokarst ponds or lakes (Sannel and Kuhry 2011). Permafrost thaw results in increased saturation of surface peat, as the peat surface collapses to levels at or below the water table during thaw (Turetsky et al. 2007). Therefore, permafrost thawing under natural and/or anthropogenic stressors (e.g. atmospheric warming) may significantly impact wetland hydrology by degradation of localized or isolated permafrost leading to an extreme flooding event and runoff to downstream ecosystems.

Degradation and thawing of permafrost at its southern limit (midlatitudes) in Canada is expected to lead to increased net CO_2 uptake due to the greater increase in GPP than the increase in ER. However, increases in CH_4 emissions in response to peatland thaw may be 10-fold or higher than that of frozen peatlands (Wickland et al. 2006). Therefore, the net climate cooling or warming as a result of permafrost thaw in northern peatland is uncertain (Rydin and Jeglum 2013). As permafrost melts, the peatlands may transition from hummocky, dwarf shrub-dominated bogs to wetter minerotrophic fens with an increase in CH_4 emission by 22% (Johansson et al. 2013). Bohn et al. (2007) determined that a 3 °C-warming scenario with 10% higher precipitation may double the current CH_4 emissions. Turetsky et al. (2007) suggested that the loss of surface permafrost in peatlands increases net carbon storage as peat, though in terms of radiative forcing, increased CH_4 emissions to the atmosphere will partially or even completely offset this enhanced carbon sink for at least 70 years following permafrost thaw.

Permafrost melt may indirectly influence the wildlife habitat in several ways. West-central Alberta mostly has sporadic isolated or patchy permafrost from winter to late spring. These permafrosts are very sensitive to temperature change. A small increase in temperature (approximately 1 ℃) through atmospheric/soil warming and/or wildfire may degrade these subsurface landforms and result in flooding in early spring which overlaps with the calving season of the Little Smoky woodland caribou.

3.3. Wildfire

Wildfire is a natural, but critically major disturbance process that has well-defined impacts on watershed hydrology, vegetation, C exchange, and wildlife habitat value. Fire may affect the resilience of forest wetland ecosystems to other natural and anthropogenic disturbances and can increase soil temperature and thus humification through increased biological activity (Cole et al. 2015). It can also increase the impact of frost events on peat in cold climates. Wildfire has an average return period of about 120 years in the boreal forest (Wieder et al. 2009).

Fire burns aboveground biomass including vegetative layers and litter from peatlands. Fires in ombrotrophic Alberta bogs burn the needles and lichen-covered branches of black spruce trees, leaving behind standing dead boles (Wieder et al. 2009); however, the moss layer burns differently in hummocks (partially) than hollows (completely) (Benscoter and Wieder 2003). A complete cover of vegetation is established within 20 years after fire (Benscoter and Vitt 2008b; Zoltai et al. 1998). As successional development proceeds and the black spruce trees become denser and larger, shading of the shrub and ground layers increases, such that conditions gradually become moister and cooler (Wieder et al. 2009).

Natural fires play a critical role in impacting watershed hydrology. The Athabasca and Peace River basins have extensive webs of waterlogged peaty soils (peatlands) in the midlatitude boreal forest (Glaser 1987). Waterlogged conditions restrict or lessen the spread and frequency of wildfires (Wieder et al. 2009). Depending on the level of moisture within the wetland system at the time of the fire, wildfires will likely burn the upper peat surface including the forest floor vegetation and litter. Intense fires may burn the whole acrotelm and even further down to bedrock, which results in a steep reduction in water storage capacity or yield of the peatland and associated hydrological flows and patterns. Severely burnt peatlands are left with damaged physical and/or hydrological properties of soil porosity and pore space which can become hydrophobic at the surface (Mallik et al. 1984). Milder burns can leave behind live roots and rhizomes for quick regeneration, leading to greater peat formation due to an increase in water-logging and subsequent decrease in decay rates (Charman 1992; Wieder et al. 2009). Burnt peatlands can have a low capacity for storing water and reducing flood pulses; therefore, much of the precipitation received may not infiltrate and may instead runoff and cause flooding events in nearby low-lying areas.

Wildfires, along with atmospheric warming and extreme drought, represent the greatest risks to the C sequestration or sink function in the boreal forest (Bhatti et al. 2002). Fires burnt an average of two million hectares (ha) of boreal forest annually in Canada from 1959 to 1999, releasing an average of 27 Tg C year^{-1} (Amiro et al. 2001). The carbon sink in Canadian managed forests was reduced by half during the last two decades, mainly due to vegetation loss from intensive wildfires and insect outbreaks (Kurz et al. 2008). The area burnt annually is expected to increase upon interactions of fire events with expected climate warming of 2.8 ℃ and decrease in precipitation of 20% (during this century) in Alberta (Flannigan et al. 1998; Volney and Fleming, 2000). Fire events may remove surface peat, create a truncated and cracked profile with enhanced mineralization activity, and can convert a bog or fen peatland into a blanket bog (Macphail et al. 1999) of low carbon exchange capacity. Zoltai et al. (1998) calculated that 0.5% of North America's peatlands burn annually and the total direct C emission from the combustion is 9.6 Mt yr^{-1}. About 2/3rd of the C emissions from peatland burning comes from the combustion of peat in permafrost bogs which are the driest peatlands, and 1/3rd from swamp forests where most of the C comes from the combustion of wood (Rydin and Jeglum 2013). Methane emissions only make up a small part of the total C emissions from burned peatlands.

Therefore, peatlands may switch from being net stores to net sources of carbon (CO_2) with changes in soil temperature and water table position (Bubier et al. 1999). Thus, fire intensity and frequency may need to be normalized (Garnett et al. 2000) by avoiding or minimizing anthropogenic impacts or restoring wetland ecosystems across the watershed or catchment areas.

As discussed in section 2.5, the Fox Creek area includes the Little Smoky Woodland Caribou range which is occupied by a herd of boreal woodland caribou, a designated species at risk (Alberta Wildlife Act 1985; Proulx 2015). The woodland caribou is a climax forest species; wildfire removes climax forest habitat essential to caribou for cover and the production of lichen for food (Bloomfield, 1979; Wright and Heinselman, 2014). While wildfires are kept mostly suppressed in Alberta, any intensive fire in the area could be a significant threat to the existing Little Smoky Woodland Caribou habitat value. Caribou avoid recently burned areas, which impacts their movements by fragmenting their habitat ranges (Sorensen et al. 2008). Since early succession following a wildfire is an evenly aged forest stand, it may take centuries for a mature forest system suitable to sustain a caribou population to develop post-fire. Fire also removes snow-trapping canopy and windbreak vegetation, which results in thicker snow depths before and during the calving season of late winter (Bradley and Neufeld 2012).

Several mammals such as moose and some deer species also use wetlands (or bogs) during summer for shelter and food. Burning of these systems may affect these species differently depending on the fire severity and the wetland type. Light fires create patches that can quickly regenerate, which may be favored by herbivores.

3.4. Forestry

Draining of wetlands for forestry has traditionally been one of the most common practices that resulted in a significant reduction in the coverage of midlatitude peatland ecosystems. The practice was applied to peatland sites that were forested or sparsely wooded (Rydin and Jeglum 2013). Trees are known to show significantly increased productivity following drainage (e.g. Munir et al. 2015), thus removal of the excess water from a peatland allows for increased growth of vascular vegetation prior to harvesting.

During forestry practices, peatlands are overly drained by creating shallow open ditches with 10-25 m spacing in the peatlands which results in dramatic changes in the ecohydrology of the ecosystem. These changes include significant peat subsidence (of up to 22 cm in the first five years), vegetation succession or loss of biodiversity, and lowering of water table levels to depths that can sometimes be close to the underlying mineral substrates. The drained peatlands significantly lose their critically important ecosystem functions including water storage and runoff regulation (increased baseflow and reduced stream peak flow). The deregulated runoff events result in the degradation and erosion of tributaries draining into the catchment area. The runoff events, combined with excessive evapotranspiration and reduced low flows, may significantly impact the resilience of watershed hydrology and regional flow patterns and, thus, the regional water balance. Within west-central Alberta, disturbance of the regional water balance may affect the resilience of the Peace, Slave, and Athabasca River baseflows, as well as surface water supplies to south and south-eastern Alberta.

The use of heavy machinery for ditching the peatland sites for drainage leads to blockage of the peat's micro-drainage lines and porosity which results in peat surface subsidence and compaction. This, in turn, results in reduced evapotranspiration, increased desiccation of the peat surface/vegetation, and delayed regeneration of impacted vegetation. Additionally, drainage results in vegetation succession and loss of biodiversity with significant ingression of non-native or invasive species.

Draining peatlands for forestry is a dramatic change in land use which causes large emissions of greenhouse gases and very likely turns carbon sink peatlands into sources in the short term. The change in land use also impacts wildlife species, such as the woodland caribou which uses the peatlands within the Little Smoky Caribou Range during late winter for calving but cannot do so in areas that have been drained and harvested. This may result in a reduction in the population of this species at risk.

3.5. Agriculture

Growing food demand is commonly the motive that drives the use of existing natural peatland or upland forest areas for agricultural purposes, such as for a hay crop or grazing of livestock. Prior to practicing agriculture on these ecosystems, peatlands are harvested by peat extraction and upland forests are cleared by clear-cutting. This is followed by the cultivation of crops such as rye, wheat, oats, rice, onions, potatoes, and large cranberry for human use or as growing forage for livestock.

Peatlands for agriculture are traditionally drained by shallow open ditches (with 10-25 m spacing) or by subsurface mole and slit drainage (Rydin and Jeglum 2013). During this process, critical peatland hydrological functions such as water storage and filtration, flood or runoff water regulation (with attenuation of stream peak flows and increases in baseflow or low flows), and interplay with regional surface and/or subsurface hydrological flows are fully or partially lost. As the wetlands are forested or wooded at the mid-latitudes near the Fox Creek area, agricultural disturbance of these ecosystems may affect the overall water balance and flow patterns of the associated watersheds.

Transforming peatland and upland to agricultural fields results in the total or partial loss of these ecosystems depending on their agricultural uses; for example, the haying of sedge fens with smaller understory plants such as *Eriophorum angustifolium* (Moen 1995; Moen et al. 1995) leads to a partial loss of the ecosystem, compared to the complete drainage; harvesting; fertilization; and use of a peatland for growing crops, which is a total loss of the ecosystem. Similarly, clear-cutting of an upland forest followed by fertilization and cultivation with cereal crops also causes the extinction of the upland forest ecosystem (Elveland 1993; Winkler et al. 2010).

If wooded peatlands in the boreal forest near the Fox Creek area are converted to agricultural fields, this may result in huge losses of carbon to the atmosphere in the form of CO_2 which may further lead to atmospheric warming. A part of the carbon deposits may be transferred with the mass flow of the drained water in the form of dissolved organic carbon and impact the downstream ecosystems of the catchment or river basin of which the peatland is a part. Removal of wooded peatlands is also expected to impact wildlife habitat such as the Little Smoky woodland caribou herd.

3.6. In-Situ Oil and Gas

3.6.1. *Temporary Features (OSEs, seismic lines, winter roads)*

Exploration of natural resources (i.e. oil and gas, forestry) creates numerous temporary access features including seismic lines, winter roads, and oil sands exploration (OSE) wells in boreal peatlands (CAPP 2004). These features are not required by law to be reclaimed since they are only used briefly during exploration and the impact on vegetation and soil is assumed to be minimal. Although the size of seismic lines and winter roads and the associated soil disturbance have been greatly reduced with new construction technology such as low-impact seismic (LIS) lines, their density has increased significantly. It is estimated that over 1900 km^2 of peatland area has been disturbed by seismic lines and trails in Alberta (Strack et al. 2019).

Although construction is usually completed in winter under frozen ground conditions, the clearing of vegetation and the repeated access of these features (i.e. recreational use of winter roads by trappers) often leads to flattened surface topography, altered moisture regime, rise of the water table to the surface, and shift in species composition compared to undisturbed peatlands (Williams et al. 2013; Dabros et al. 2017; Lovitt et al. 2018). These changes can compromise critical functions and services such as wildlife habitat and long-term carbon sinks provided by natural peatlands (Pigeon et al. 2016; Strack et al. 2019). Linear temporary features are favored by predators for ease of access, leading to changes in predator-prey dynamics (Dyer et al. 2002, Latham et al. 2011a). Removal of woody vegetation exposes the ground surface, leading to higher decomposition rates and emission of potent greenhouse gases (Strack et al. 2018). The hydrological impact of temporary features on surrounding areas is not well studied. Field observations found that the cleared and compressed seismic lines become flow channels during spring melt. There is little evidence that OSEs and seismic lines block vertical or horizontal water flow. Without active reclamation, recovery of OSEs and seismic lines in peatlands can remain stagnated for decades (Caners et al. 2014, Kansas et al. 2015, Van Rensen et al. 2015).

3.6.2. *Well Pads and Access Roads*

Well pads and associated features built with mineral fill affect a wide range of microclimatic, biogeochemical, and hydrological parameters, which can alter ecosystem functions and services (Miller et al. 2015, Saraswati et al. 2019, 2020). The impacts of mineral in-situ footprint on peatlands can be direct through the loss of vegetation and leaching of nutrients, or indirect through the changes in hydrology and vegetation in the surrounding areas. These effects vary across spatial and temporal scales. Potential impacts of mineral features in boreal wetland ecosystems include:

- Clearing of vegetation and elimination of primary productivity and long-term C accumulation potential of the footprint,
- Changes in local hydrology including water flow and loss of water regulation function,
- Mineral soil influence on peat chemistry and soil processes of the surrounding areas and underneath the footprint (e.g. well pad),
- Altered growth and shift in the community around the footprint (e.g. roads),
- Reduced habitat value and biodiversity (e.g. roads, culverts), and

- Changes in greenhouse gas balance and long-term carbon sequestration potential over the affected areas.

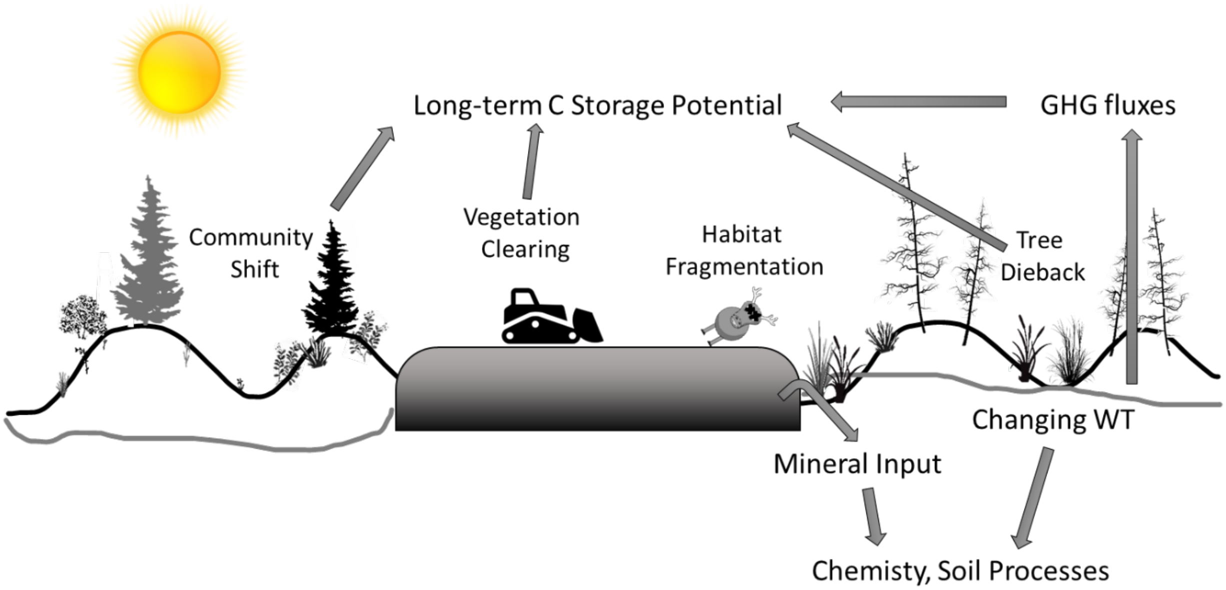


Figure 5. Illustration of a padded resource road and its impact on the surrounding peatland areas.

Placement of mineral fill on peat surfaces eliminates living surface vegetation, consequently terminating CO_2 uptake via photosynthesis and the potential for long-term C storage through peat formation. This is probably the easiest impact to quantify given our understanding of peatland ecology. Removal of trees from the footprint will remove most of the aboveground biomass and net primary productivity (NPP), potentially reducing the net carbon uptake unless the understory productivity increases to compensate for the loss. This direct biomass loss can be estimated using aboveground biomass of typical boreal peatlands at 750 and 775 g m^{-2} for fens and bogs and average NPP of 131 ± 208 g C m^{-2} yr^{-1} in black spruce bogs of Alberta (Vitt et al. 2000, Wieder et al. 2009). Across North America, peatland biomass ranges in treed sites of 351-7300 g m^{-2} for biomass and 27-310 g m^{-2} yr^{-1} for NPP (Campbell et al. 2000). Therefore, removal of the woody layer alone will reduce C uptake of the peatland by these amounts.

Leaching of nutrients from mineral fill can also alter the soil and water chemistry of the surrounding peatlands and lead to changes in plant growth, community composition, and the eventual loss of C sequestration and storage in the adjacent areas (Miller et al. 2015, Johansen et al. 2017, Bocking et al. 2017). The weight of mineral fill causes peat compaction and reduces local hydraulic conductivity (Gillies 2011, Partington et al. 2016). This can change the water table position and temperature regimes around the mineral feature. Deposition of road dust on nearby peatland areas is common and can affect chemistry and vegetation along the roads. Dry deposition of nutrient-bearing aerosols can enhance *Sphagnum* growth (Dennis Gignac et al. 1994) through a fertilization effect. Wooded peatlands with varying tree heights received a higher amount of Cl^- and total influx of nutrients than open peatlands with no trees (Schauffler et al. 1996). Within 10 m of a road, dust loading increased by 355% compared to areas without roads, leading to an annual deposition of 647 g/m^2 of gravel road dust (Creuzer et al. 2016). This increase declined to 46% at 40 m from a road. However, the effect of dust loading on water and soil chemistry was minimal compared to natural areas. This indicates that the impact of dust deposition will depend on the peatland type (bog vs. fen, treed vs. open), prevailing wind direction, and water chemistry (alkaline fen vs. acidic bog) and that the effect is confounded by other factors such as changing hydrology and water table. Dust loading of well pads is less studied and it is unclear if the impact is similar to that of linear roads.

Construction of in-situ features greatly affects the local water table and surface/subsurface water flow around the disturbance. Water can be rerouted around a well pad whereas long linear features like access roads can have a cascading effect on a large area by restricting and changing ground-water flow patterns. The weight of mineral fill causes peat compaction and reduces local hydraulic conductivity (Gillies 2011, Partington et al. 2016), greatly affecting local water table and surface/subsurface water flow around the disturbance (Plach et al 2017, Strack et al. 2017), with flooded conditions on the upstream areas and dry conditions in the downstream areas (**Figure 5**). Saraswati et al. (2020) studied two access roads built in a treed bog and a rich fen near Peace River, Alberta. They found that the construction of a resource access road disturbed the surface and subsurface water flow at the bog, but the effect was minimal at the fen site. Alignment of the road parallel to the local water flow direction reduced the hydrological impact of the road at the fen site. At the bog site, water flow was reduced, and the water table was raised along the road. Culverts provide a point source of water transportation to the downstream side of the road, but their effects were only evident close to the road and the water was not evenly distributed in the downstream areas. In the flooded areas, phenol oxidase and hydrolase activities were significantly higher than those in the undisturbed areas, suggesting that access roads may cause enhanced decomposition and ultimate carbon loss from the upstream side with a raised water table (Saraswati et al. 2019, 2020). This loss can be further exacerbated by land cover changes if the peat-forming ground layer bryophytes are replaced by vascular species (graminoids and *Typha*) which decompose more easily. On the downstream side, the lowered water table may lead to a shift in vegetation community and changes in net carbon balance. Munir et al. (2014) found a significant increase in the coverage of shrubs on the hummocks and lichens in the hollows in a treed bog after ten years of water table drawdown for peat harvesting. Drainage-induced changes in vegetation led to a shift from a net sink of 70-92 $g\ C\ m^{-2}$ to a net source of 23-27 $g\ C\ m^{-2}$ (Munir et al. 2014). However, the long-term effect of changing water table and changing water flow on vegetation and ecosystem function is unclear and requires additional research.

Canada's boreal forests are home to thousands of different species of birds, mammals, reptiles, amphibians, insects, and fish. In Alberta, mature treed bogs are an important shelter and foraging ground for woodland caribou (see section 2.5). Human activities including in-situ exploration and extraction, forestry, and urban development are known to cause degradation and fragmentation of wildlife habitat in the boreal. Linear disturbances (e.g. all-season roads, seismic lines) in particular have been considered to be the leading cause of caribou population decline (Boutin et al. 2012, Finnegan et al. 2018). Clearing and poor regeneration of the woody layer provide corridors that connect upland and lowland habitats, thus reducing the spatial separation between wolves and caribou (Latham et al. 2011a). Facilitated by the easily travelable linear corridors, the likelihood that wolves will encounter and kill a caribou in an already limited habitat (Latham et al. 2013) increases significantly. Roads with moderate traffic act as semipermeable barriers to caribou movement (Dyer et al. 2002), which may exacerbate habitat loss through avoidance by caribou in already limited space (Dyer et al. 2002, Schindler et al. 2006). Wolf packs prefer areas close to the roads (<25 m), trails, and railway lines compared to high-use roads and trails (Whittington et al. 2005, Houle et al. 2010). To conserve and restore fragmented habitat for the caribou population, the restoration of linear features has been a high priority initiative among the government, industry, and the general public (Ray 2014, Pigeon et al. 2016). Studies that have evaluated linear restoration effectiveness in terms of caribou habitat conservation are limited (Vinge and Lieffers 2013) and evidence of positive impact on caribou population is scarce (Pyper et al. 2014). In addition to their impacts on caribou habitat, linear disturbances also impact other wildlife species. Industrial stream crossings can change abiotic habitat characteristics in freshwater ecosystems, restrict biotic connectivity, and impact fish community structure at the whole-stream and within-stream scales (Maitland et al. 2016). Hanging culverts (e.g. outfall elevated above the stream surface) associated with roads crossing wetlands are known to cause stream fragmentation and create upstream movement barriers for fish communities (Park et al. 2008). Roads are also found to be associated with the invasion of exotic earthworms, facilitated by vehicle traffic and bait abandonment (Cameron et al. 2008).

Impacts of multiple well pads and roads on local and regional peatland hydrology, chemistry, vegetation, and GHG fluxes is a key knowledge gap highlighted by both regulators and industry respondents. This has implications for both reclamation planning and variance approval by regulators. There is a need for establishing a cumulative effect threshold based on scientific and geographical approaches to allow a proportion of wetland in a given area to be “lost” without significant degradation of function in the region.

3.6.3. *Pipelines and Utility Corridors*

Numerous pipelines associated with oil and gas production and transport cross the northern boreal landscape of Alberta. In peatland areas, pipelines are installed through the clearing of vegetation within a construction right of way (ROW) or utility corridor, digging and dewatering of a trench, fabricating and placing of the pipeline in the trench, followed by backfilling of the trench with removed soil, and seeding of the ROW with appropriate vegetation (Ryder et al. 2004, Sakhalin Energy 2005). Pipeline installation may occur in winter when the upper peat is frozen and ice roads can be created to facilitate the travel of heavy equipment across the peatland (Sakhalin Energy 2005). The construction of pipelines through peatlands has been recognized internationally as a key issue facing peatland conservation (Minayeva et al. 2009), however, limited studies have investigated the environmental effects of this construction. Based on the limited research which has been done in this area as well as through comparison with other linear features such as access roads and powerline ROWs, it is evident that pipelines have the potential to disrupt the hydrology, thermal regime, vegetation community, carbon storage capacity, and wildlife habitat value of peatland systems.

During pipeline installation, the upper layer of peat within the ROW may be removed during vegetation clearing (Ryder et al. 2004), and the peat layers within the trenched area are mixed during backfilling (Ryder et al. 2004, Sakhalin Energy 2005). The use of heavy equipment for pipeline installation can also compact and mix peat within the ROW (Groot 1987, Nugent et al. 2003, Sakhalin Energy 2005, Locky and Bayley 2007), with the severity of compaction and mixing dependent on the season in which construction occurs (i.e. summer versus winter) as this influences the compressibility of the peatland soils which are frozen in winter (Sakhalin Energy 2005). Compaction or removal of the low-density upper peat surface within the ROW can alter the rate of infiltration while mixing of the peat layers within the trench can disrupt water flow across the pipeline corridor (Sakhalin Energy 2005). As is seen with access road construction in peatland systems, when linear features are placed perpendicular to local or regional groundwater flow directions, disruption of the water flow can lead to changes in water table depth, pH, phenolic concentration, and enzyme activity upstream and downstream of the linear feature (Saraswati, Parsons, & Strack, 2019; see section 3.6.2 for additional details). Removal of the aboveground vegetation (trees, shrubs, and herbs) within the pipeline ROW can also alter transpiration and interception in the area leading to higher water table levels, as is seen when peatland areas are clear-cut during forestry operations (Locky and Bayley 2007). As hydrology is a key control on vegetation and soil redox conditions, hydrological changes resulting from pipeline installation in peatlands can have lasting impacts on the vegetation community structure and carbon storage capacity of the peatland system (Sakhalin Energy 2005, Saraswati et al. 2019).

The thermal regime of the peatland soils can also be modified due to pipeline installation. Removal of aboveground vegetation and the exposure of bare peat reduces shading and changes the albedo of the pipeline ROW, influencing soil and surface water temperature (Naeth et al. 1993, Sakhalin Energy 2005, Locky and Bayley 2007). This may affect local permafrost conditions, freeze/thaw characteristics, nutrient conditions, and vegetation establishment following pipeline installation (Turchenek 1990, Sakhalin Energy 2005, Locky and Bayley 2007, Corson and Campbell 2013).

Perhaps the most visibly noticeable effect of pipeline installation in peatlands is a shift in vegetation community within the pipeline ROW. As has been observed following powerline ROW creation, after removal of the native aboveground vegetation in ROWs through peatlands, invasive and non-peatland species are able to colonize the ROW and, in some cases, can extend into the surrounding natural peatland (Rubino et al. 2002, Sakhalin Energy 2005, Dubé et al. 2011). Removal of the tree and shrub layers during the construction of ROWs opens up the forest canopy, leading to increased light intensity and ground surface temperature within the ROW. These changes, combined with physical disturbance of the upper layers of peat; changes in surface water availability and chemistry; and lessened competition from native vegetation species, allow invasive and non-peatland species which are carried in on the wind to establish (Dubé et al. 2011). This effect is greater in fens than in bogs (Dubé et al. 2011). Changes in peatland community composition and species richness were also observed in peatlands which were clear-cut during forestry operations (Hannerz and Hånell 1997, Locky and Bayley 2007). A reduction in the number of species adapted to shaded and moist conditions and an increase in species that prefer high nitrogen conditions were observed in clear-cut spruce peatlands in Norway (Hannerz and Ha°nell 1997). Southern boreal peatlands in Manitoba were observed to experience an increase in the species diversity of vascular plants, trees, and shrubs, but have lower bryophyte and lichen species richness, and lower overall plant cover following clear-cutting (Locky and Bayley 2007). As reforestation rates of peatland areas cleared with heavy equipment can be quite slow, as observed for seismic lines constructed within peatlands (Coupal & Bentham, 2014; also see section 4.6.1), shifts in vegetation communities following the clearing of pipeline ROWs may be long lasting and could have long-term implications for the carbon storage capacity of the ROW areas. Likewise, pipeline releases of fluids such as crude oil and process water have the potential to impact the succession of vegetation communities within pipeline ROWs (White 1990, Bright, D. Harris, C. & Meier 2010).

The installation of pipelines through peatland areas results in the direct and indirect loss of wildlife habitat. Clearing of the vegetation within pipeline ROWs and subsequent change in vegetation community composition represents a direct loss in wildlife habitat, which is compounded by the indirect loss of habitat through fragmentation and avoidance (James and Stuart-Smith 2000, Schneider and Dyer 2006, Coupal and Bentham 2014). Both mammals (including the endangered woodland boreal caribou) and bird species have been shown to avoid linear disturbances as well as otherwise suitable habitat within the vicinity of these disturbances (James and Stuart-Smith 2000, Schneider and Dyer 2006, Coupal and Bentham 2014). Linear disturbances such as pipeline ROWs have also been shown to modify natural predator-prey interactions, as they provide preferential travel corridors for predators such as wolves (Alberta Woodland Caribou Recovery Team, 2005; Dickie, Serrouya, McNay, & Boutin, 2017; James & Stuart-Smith, 2000; Latham, Latham, Boyce, & Boutin, 2011; see section 2.5). When considering the impact of pipelines and utility corridors through peatlands in the boreal forest, it is important to consider both the direct and indirect impacts on hydrology, thermal regime, vegetation, carbon storage, and wildlife, and to also consider the cumulative impact of multiple linear disturbances on the landscape as a whole (Schneider and Dyer 2006).

3.6.4. *Fracking*

Fracking is the common name of hydraulic fracturing which is a method by which fluid water under high pressure is injected into a well to fracture the surrounding rock and open up fissures to extract oil or natural gas within (Ayers, 2014). This is an unconventional oil and gas extraction technique that is known to exert severe impacts on the surface- and groundwater quantity and quality through the land-use-change, which in turn is a leading cause of wetland loss (Dahl, 1990). The Duvernay Shale Formation (Play) in the Fox Creek area was recently explored and extracted for oil and/or gas using a combination of multi-stage hydraulic fracturing and horizontal drilling (Rai, 2015). This type of unconventional gas development involves large footprints and intense developments, the impacts of which are longer lasting compared to conventional oil and gas developments (Measham and Fleming, 2013; Measham and Fleming, 2014). Moreover, unconventional oil and gas development risks groundwater contamination with aryl phosphates (Funk, 2019), disturbs regional water balance (by excessive use of freshwater), and has cumulative impacts on regional ecological landscapes (Notte et al. 2017).

Headwater forested wetlands are among the most common and important ecosystems to be impacted by this land-use-change as they are one of the most vulnerable water resources in the watershed (Drohan et al. 2012). Massive water withdrawals from surface and groundwater resources for fracking could diminish drinking and irrigation water resources. Fracking operation creates impervious soil layers (indurated pans) and disturbs sedimentation (Allred et al. 2015) and other benthic processes (Funk et al. 2019) within wetland ecosystems. As a result, surface and groundwater horizontal and vertical flows are fragmented or disrupted, placing the regional water balance and flow patterns in jeopardy.

Land clearing for hydraulic fracturing operations removes all surface vegetation that would otherwise sequester atmospheric carbon and accumulate it in the form of peat in peatlands. Therefore, a sink of carbon is converted to a source of emissions and could result in net atmospheric warming. In addition, the construction of well-pads and access roads for fracking disrupt subsurface and surface hydrological flows which severely impact the vegetation in the surrounding wetlands (see section 3.6.2).

Roads built for heavy machinery that service the fracking operations end up cutting across numerous streams and wetlands (habitat fragmentation), disturbing local fish and wildlife populations (Sutter et al. 2019). The habitat fragmentation leaves many adverse impacts on wildlife including boreal mountain and woodland caribou. Also, it disrupts pollination, dispersal, herbivory, and predation and may lead to greater invasion of non-native plants, reduction in biodiversity, the introduction of songbird nest predators, severed migratory pathways, and altered wildlife behaviors and mortality (Allred et al. 2015; Kiviat, 2013). Certain species such as woodland caribou may also have aversion to light and sound affiliated with unconventional drilling installations during active periods (Sutter et al. 2019).

4. WATERSHED MANAGEMENT PRIORITIES AND STRATEGIES

The two large basins of the Peace/Slave and Athabasca Rivers, which meet greater than 80% of the surface water requirements for Southern Alberta, have one of the densest wetland ecosystems. Watersheds within these basins are connected to wetlands through surface or subsurface hydrology. While these wetlands are critical to the active hydrology of the two basins, they also provide other significantly important ecosystem services for the Fox Creek area, such as wildlife habitat for the Little Smoky woodland caribou. The Little Smoky is a unique woodland caribou habitat that is situated across the southern boreal forest margin and the rocky mountain foothills within the Fox Creek area in west-central Alberta (see section 2.5). The watersheds and the associated wetlands are being impacted or degraded under the discussed natural and anthropogenic disturbances. Due to their critical importance, the watersheds/wetlands in the area should be managed using set priorities and strategies to promote hydrologic resilience and sustain ecosystem services. Some of the most important management priorities and strategies relative to the wetlands in the reviewed watersheds are suggested below:

Priorities

- Place-based wetland outcomes are a priority for the Government of Alberta. The Fox Creek area of dense wetlands and numerous tributaries and large river watersheds/basins should be recognized as priority landscapes at the watershed scale. 86.8% of the Little Smoky area of woodland caribou habitat is in close proximity to anthropogenic disturbances (Cichowski 2010), such as the play-based regulation (PBR) pilot that was run in the Duvernay Shale Formation of the Fox Creek area (Rai 2015). This prioritization may help in sustaining watershed hydrology resilience, protecting and restoring impacted wetlands, and retaining associated uplands.
- Follow the mitigation hierarchy of Alberta Wetland Policy: 1) avoid impacts on wetlands, 2) if avoidance is not possible, minimize the impacts, and 3) if both the avoidance and minimization are not possible, replace the impacted wetlands with equal value or equivalent land capability using well-defined reclamation and restoration practices and wetland construction directive and guide (Government of Alberta 2018).
- Encourage and promote active engagement of municipal partners and stakeholders in the area.

- Avoid losses to wetlands as they regulate streamflow (by increasing baseflow and decreasing stream peak flow during the precipitation events), filter surface and subsurface water, and mitigate floods.
- Prioritize area wetlands for monitoring and restoration for sustainable, watershed-level water quality improvement.
- Create drill-free and frack-free zones, including protected areas where healthy, functioning ecosystems are maintained across the watersheds (Parfitt 2017).

Strategies

- Natural and anthropogenic impacts are cumulating in west-central Alberta, including on the Fox Creek landscape (which is relatively more vulnerable), mainly because of proximity to the southern margin of the boreal forest and the encroaching industrial and White area developments.
- Given the critical importance of the Fox Creek area, watershed and wetland planning and management specific to the area is suggested to be prepared in alignment with the overall goals of the Government of Alberta's "Water For Life" action plan (2009), Mighty Peace Watershed Alliance, and Lesser Slave and Athabasca Watershed Councils.
- Long-term community awareness programs on wetland protection, restoration, and associated upland retention.
- Since the Fox Creek area is unique due to the presence of the Little Smoky boreal woodland caribou, a strategic conservation and research plan should be launched to conserve this species at risk and inform and update science-based policy development.
- A cumulative impact management plan for the forested and foothill wetland watersheds overlying the Duvernay Shale Formation in the Fox Creek area may aid in saving the critically important ecosystems, enhancing communities and lifestyles, strengthening local economies, and improving resilience in watershed hydrology.

5. RECLAMATION AND RESTORATION OF BOREAL WETLANDS

Wetlands within the boreal forest overlying the Duvernay Shale Formation (Play) in the Fox Creek area and its extended study zones across sections of the three major river basins in Alberta are critically important ecosystems that are vulnerable to anthropogenic disturbances such as play-based regulation (PBR) pilots. With the use of excessive freshwater, these pilot projects may impact regional water balance and result in groundwater contamination which may persist for long periods of time (Rai 2015). The area resources of surface and groundwater are non-renewable in nature, and therefore, should be conserved by informed policy development which includes strategic reclamation and restoration priorities to return ecosystems to their original trajectories to mitigate cumulative impacts.

5.1. Forestry

Saturated soil conditions in peatlands limit tree growth. Although peatlands are drained for forestry globally (Laine et al. 2006, Hooijer et al. 2010), this practice is less prevalent in Canada (Malcolm 1997, Groot 2014). Drainage drastically changes the hydrology and ecology of the ecosystem. Hydrology is restored by blocking and backfilling the ditches and removing hardwood invasive trees such as birch which developed as a consequence of drainage for forestry (Anderson et al. 2016).

In Alberta, the main disturbance caused by forestry activities is resource roads bisecting wetlands. It is almost impossible to avoid wetlands in Alberta's Boreal Plains. Although forestry companies have been sharing roads with the oil and gas industry to reduce the overall footprint, each industry has specific requirements for how the roads are constructed through wetland areas. Forestry haul roads require heavy bearing capacity for the road sub-base and the installation of adequate drainage and water-crossing structures. Innovative construction techniques have been developed to mitigate the negative impact of resource roads on boreal wetlands (Partington and Clayton 2012). For example, corduroy crossings made of parallel logs are often used in wetland areas with poor bearing capacity (Partington et al. 2016). Culverts are routinely installed in areas with high water flow, but their effectiveness is highly dependent on the size and placement of culverts and the general flow direction and soil properties of the surrounding wetlands. Understanding and reducing the impact of resource roads on wetland functions is an ongoing challenge for land managers and practitioners.

5.2. Agriculture

The major issue associated with agricultural activities is the draining of water and nutrients through wetlands and riparian areas to downstream water bodies. Successively increasing applications of nitrogen and phosphorus fertilizers is the major cause of eutrophication in the downstream water bodies which may lead to episodic and/or persistent hypoxia. A great deal of coordinated strategies may be required for the ecological and hydrological restoration of impacted river basins to avoid or minimize the possible contamination to downstream surface and groundwater. Mitsch et al. (2001) suggested three general approaches for mitigating agriculturally derived nitrogen (or phosphorus) that could create eutrophic conditions in downstream water bodies: 1) reducing fertilizer doses and using a suite of management practices, 2) intercepting laterally moving ground and surface water with nitrogen-sink ecosystems such as constructed or restored wetlands, and 3) providing a system of river diversion backwaters to intercept large fluxes of nutrients associated with flood events. Restoration of agriculturally disturbed wetland ecosystems in the watersheds will improve water quality, reduce public health risks and mitigate habitat degradation. Formal and rigorous large-scale research in the river basins is required before the commencement of reclamation and restoration projects (Mitsch and Day Jr. 2006).

5.3. In-Situ Oil and gas

5.3.1. *Temporary Access Features*

Although low impact methods are recommended for creating OSEs and seismic lines, the actual practice in wetlands/peatlands can vary greatly depending on site characteristics and logistical constraints, resulting in varying degrees of disturbance and different reclamation practices used post-creation. OSEs and seismic lines can naturally regenerate if the ground disturbance during construction is mild and the features are not repeatedly disturbed by activities such as the recreational use of lines by trappers. However, natural regeneration is often not enough for the recovery of most OSEs and seismic lines.

Deactivation by mounding and planting of tree seedlings has been applied to promote canopy development on many seismic lines in Alberta and to ultimately eliminate the habitat impact on wildlife such as woodland caribou (Pyper et al. 2014). Living trees are bent along the mounded lines to further reduce the line of sight and speed of travel by predators. Mounding is also used to create hummock-hollow topography on OSE sites in highly disturbed rich fens in Alberta (Lieffers et al. 2017). Although the tree growth on mounded sites is promising, the recovery of the ground and field layers is lackluster (Kansas et al. 2015). The mounds are usually created by inverting deep peat using the bucket of an excavator (**Figure 6**). These peat mounds have no viable propagules (moss spores, fragments, or seeds) for natural regeneration. Once exposed to air, they decompose and become prone to desiccation. Mounding also creates depressions filled with water, resulting in increased methane emission, which may or may not be is compensated by tree growth on the mounds (Murray et al. in prep.).

The "Hummock Transfer Technique" is a promising alternative to the mounding and planting technique. Intact hummocks (small trees, shrubs, herbs, and mosses) from nearby natural areas are collected and placed directly on the surface of temporary access features without flipping the hummocks (**Figure 6**). This will introduce microsites and topographic features on flattened temporary access features. It also increases the structural and floral diversity, particularly of woody vegetation and peat-forming mosses, which in turn will promote the return of functions and services offered by natural peatlands (Xu 2019).

Figure 6. Seismic Line Reclamation Techniques. Left: Mounds created by inverting peat; Right: An upright, transferred hummock on a flat winter road through a treed fen. Courtesy of B. Xu

5.3.2.

Well Pads and Access Roads

The reclamation of in-situ features built with mineral fill in boreal peatlands is relatively new to most reclamation specialists and land managers. The earliest field trial dates to 2007 when portions of two well pads near Peace River, AB were reclaimed by removing some of the mineral fill to lower the ground surface to match that of the surrounding peatland. Since then, researchers have developed three approaches to restore wetland and peatland communities on padded well sites and roads, each with pros and cons (CPP Environmental 2017).

The first approach is the partial removal of mineral fill and lowering of the mineral surface to allow for water saturation. Plants can be introduced as tree seedlings, willow cuttings, and transplanted sedges (Wieder et al. 2010, Vitt et al. 2011). Bryophytes, particularly true mosses, can develop naturally through ingress from nearby sources, although this process can be very slow. The resultant communities contain a mix of marsh and fen vegetation if the water table is close to the ground surface (CEMA 2014, CPP Environmental 2017). When the site is too dry, upland species and weeds can dominate. When the water table is too high, flooding can lead to dominance by *Typha*, *Scirpus*, and aquatic species (unpublished data). This approach is called Partial Mineral Removal + Planting (**Figure 7**).

The second approach is to completely remove the mineral fill and the geotextile to expose the underlying peat surface. In some cases, the residual mineral can also be buried underneath the excavated peat layer (by at least ~40cm; burial under the peat layer or BUPL). The peat surface is adjusted to match the elevation of the surrounding areas. Donor moss material is collected and spread across the peat surface to kickstart the development of a *Sphagnum* moss-dominated community (Sobze et al. 2012, Xu et al. 2021 submitted). The use of donor moss from nearby cutlines is adapted from the Moss Layer Transfer Technique developed for the horticultural peat industry (Rochefort et al. 2003). Depending on the characteristics of the surrounding peatland, the reclaimed peat surface can support the development of a *Sphagnum* moss-dominated peatland community (Xu et al. 2021 submitted) or a mix of true moss, peatland sedges, and herbs (unpublished data). This approach is called Complete Mineral Removal + MLTT (**Figure 7**).

In the third approach, the mineral fill is partially removed to lower the ground surface elevation, similar to the first approach. Instead of planting or natural regeneration, true moss donors are introduced onto the residual mineral surface, similar to the second approach. Early trials have shown excellent growth of true mosses and peatland shrubs and sedges on the residual mineral substrate (Gauthier et al. 2017). This approach is referred to as Partial Mineral Removal + MLTT (**Figure 7**).

Current approaches to reclaim mineral features in peatlands can also be grouped based on how the final reclaimed surface is prepared and what the revegetation strategies are (**Figure 7**). Currently, the complete removal of mineral fill and/or the BUPL to create a saturated peat substrate plus MLTT is the only viable option to restore a *Sphagnum* moss dominated community due to its strict requirements for moisture, nutrients, and pH (Clymo 1984, Rydin et al. 2006, Pouliot et al. 2015). It is not recommended to leave bare peat to naturally regenerate (González and Rochefort 2014). Bog restoration of well pads and roads still represents a significant challenge to ecologists and reclamation specialists and requires more field trials (Graf 2009, CPP Environmental 2017).

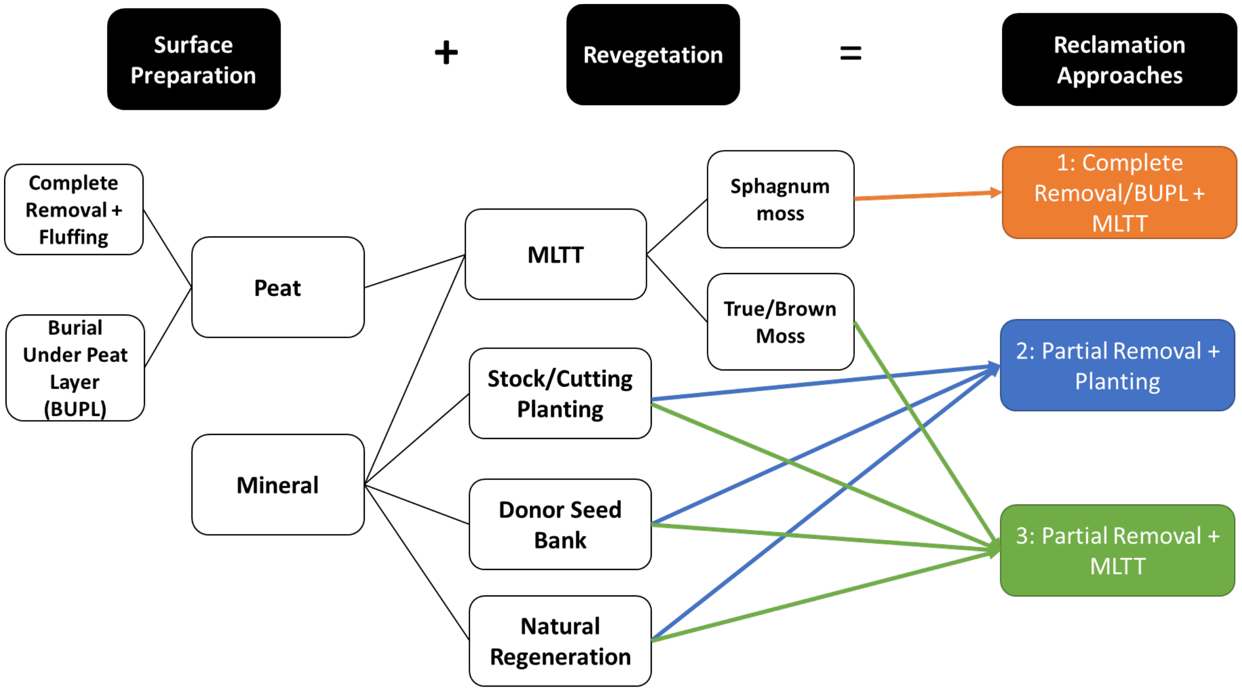


Figure 7. Summary of the three main reclamation approaches for mineral in-situ features in peatland.

On the other hand, initiation of a wetland or fen community on a residual mineral substrate after partial removal can occur through natural regeneration, planting, seeding, and moss donor transfer. This initiation process is analogous to the development of early wetland communities since the last glacial retreat (Kuhry and Turunen 2006b, Gorham et al. 2007). Vegetated or bare mineral soil became wet enough to support the encroachment of wetland plants. The buildup of organic matter under saturated conditions and the growth of mosses with a wide tolerance range of nutrients and pH (i.e. true mosses in rich fens) can turn a non-peat forming mineral wetland into a peat-forming system over time (Vitt et al. 2000). Given the prevalence of fens in Alberta (see sections 2.3 and 2.4), the wetland/fen initiation on the residual mineral substrate should be considered in future reclamation trials of well pads and roads. Donor moss transfer should be used to accelerate bryophyte development on wet mineral soil. Although bare mineral soil can naturally regenerate, it can be dominated by undesirable species or a monoculture of low species diversity when the moisture conditions are either too wet or too dry.

A land-use change request can be made to leave mineral well pads and roads in wetlands, although active reclamation is still required to turn the site into a forest stand. Some well pads built-in wet fens continue to lose material and subside as the underlying peat continues to decompose over time. Eventually, these features may disappear as the wetland and fen plants encroach from the edges. However, this process can take decades and its occurrence on the landscape is not well studied. Generally speaking, it is not recommended to leave mineral features in place since many will not return to a functional state, be it a wetland or forest stand; the process of natural encroachment of fen species is too slow and the impact on the surrounding area will last a long time.

5.3.3. *Pipelines and Utility Corridors*

Aboveground and buried pipelines and utility corridors present serious challenges to peatland ecologists and reclamation specialists. They have a long-life span and are maintained differently from well pads and roads. Wet, low-lying areas (i.e. marshes) are usually avoided when building pipelines, but construction in peatland has become feasible with improvement in construction techniques (see section 3.6.3 of this report).

Vegetation is cleared during construction and tall woody species are cut back regularly to reduce risk and to maintain the integrity of the soil medium supporting the features. Peat can have negative buoyancy, putting upward pressure on the pipes and acidic peat can also corrode the pipes (Ryder et al. 2004).

So far, most of the pipeline reclamation trials are the last step in a series of remediation procedures associated with the cleanup of a spill (Graf 2009). A hydrocarbon spill in peat is difficult to clean up because the contaminants can be trapped in pores and between organic layers. The bodies of *Sphagnum* mosses have lots of pores with a high surface area that can trap hydrocarbon particles. When a hydrocarbon spill occurs, the spill area and leachates in the surrounding water bodies are first assessed and contained. Affected soil is excavated until the contaminant level in the medium is acceptable. The excavated area is then backfilled with either treated, clean soil or peat and revegetated by planting or seeding. However, there are very few peer-reviewed publications on the recovery of these spill-affected sites in the wetland environment. It is unclear how successful it is to backfill with treated mineral soil or dead peat. Spills in bogs and poor fens may be better off left in place; bogs are isolated from groundwater so the risk of leaching is low. The low permeability of dense, highly decomposed peat can limit the spread of hydrocarbon with the peat soil (Gharedaghloo and Price 2019). This is a major knowledge gap that requires more research effort.

6. CHALLENGES AND KNOWLEDGE GAPS

Understanding the impact of in-situ oil sands footprint and the development of better management, mitigation, and reclamation methods for boreal wetlands still has a long way to go. The open-pit mining near Fort McMurray has attracted the most attention from researchers, regulators, and the general public. A similar effort to reduce and reclaim the in-situ footprint in wetlands has lagged behind the effort to reclaim upland forests and reconstruct watersheds on the post-mining landscape. With the advancement in technologies such as Steam Assisted Gravity Drainage (SAGD), in-situ production has increased significantly, along with the exponential growth of numerous interconnected well pads, OSEs, seismic lines, and roads. More recently, with the release of the Alberta Wetland Policy and several reclamation guidelines and directives, reclaiming functional boreal wetlands in areas affected by in-situ oil and gas activities has received much needed attention from the public, scientists, and practitioners. However, there are still significant challenges and knowledge gaps. These knowledge gaps are summarized below:

- Understanding the cumulative impact of different types of disturbances on different boreal wetlands

  An access road bisecting a wetland will have a long-lasting impact on the area along the footprint of the road, while an OSE site constructed over one winter may have very limited impact. Although practitioners have long observed the differences in the impact of different in-situ features on wetlands, there are very few science-based studies that have systematically looked at the impact. Only recently have we started to quantify the impact of padded access roads on peatland hydrology, vegetation, and carbon exchange. More importantly, most practitioners come from upland and agriculture backgrounds without the proper knowledge of wetland ecology. Therefore, it is imperative to continue to invest in research on the response of wetlands to disturbance created by industrial activities including forestry, agriculture, urban development, and oil and gas exploration and extraction.

- Development of science-based, practical wetland reclamation solutions for end-users.

Boreal wetland reclamation is still a young field of practice in Alberta. Although a few promising approaches have been developed, their effectiveness and efficiency remain uncertain due to the small number of field trials. So far, most of the field trials were carried out with elaborate experimental designs, which carries a higher cost than a typical reclamation project. The outcomes are highly dependent on the contractor's skill level, wetland knowledge, seasonality, budget and equipment constraints, as well as the wetland setting. We still need more field trials to improve efficiency and to develop a wide range of options to meet the needs of reclaiming different types of in-situ features in different wetland settings.

- Landscape based planning and decision-making tools

Individually, the land-use intensity and disturbance caused by in-situ oil sands features are modest compared to open-pit mining, where surface overburden is completely removed, and large areas are cleared for production. However, in-situ bitumen exploration and production creates tens of thousands of interconnected features and facilities, including well pads and associated winter roads/access roads, pipelines, utility lines, and central processing and steam-electricity cogeneration facilities, resulting in a high density of relatively small scale (relative to mining) disturbances within the boreal forest (Schneider 2006, Vitt and Bhatti 2012, Mackenzie and Renkema 2013). The interaction between the types of facilities/disturbances and the types of ecosystems they occur in is not well studied and the cumulative ecological impacts of in-situ exploration and production are difficult to quantify, thus presenting unique challenges for land managers and reclamation specialists (Vitt and Bhatti 2012, Mackenzie and Renkema 2013). With limited resources available to manage large areas of wetlands that may be disturbed by in-situ activities, it is important to prioritize the effort and focus on areas with high social, ecological, and economic values first. Decisions should be made at the watershed and landscape scale in order to maximize the reclamation outcome with the best possible results.

- A network of study sites to evaluate the long-term reclamation outcomes

Reclamation practices of peatlands are highly variable and often rely on the skill level and experience of practitioners with limited peatland/wetland knowledge. Limited efforts to restore peatlands have been trial and error approached without much scientific rigor and proven success. It is unclear if the early wetland, particularly peatland, reclamation trials will indeed evolve into functional peatland ecosystems in 10-20 years. For example, although fen vegetation can coexist with marsh species, the resilience of the mixed community relies on the regional climate and local hydrology. The system may never develop a decent ground layer cover of bryophytes, a critical component if peat-forming wetlands are the goal of restoration. We need to continue monitoring the early wetland reclamation trials of in-situ features to fully understand the long-term successional trajectory. More importantly, we need to assess the outcomes based on a holistic view of all ecosystem functions and services that are not easily measured, such as net carbon exchange and peat accumulation.

- Pipelines and Fracking

As discussed earlier, there have been very few studies on the impact of pipeline construction on boreal wetlands in Canada. Most of the limited reclamation effort is linked to the remediation of pipeline spills in the wetland environment. The impact of fracking on surface wetland ecosystems is limited. This is an area that deserves more research effort in the immediate future.

- Training of HQPs and Accessibility of Knowledge to End Users

Lack of skilled workers with proper wetland knowledge is a key obstacle in better wetland management and reclamation. The body of reclamation science and wetland knowledge should be developed into various formats for easier access by reclamation specialists. This is something often overlooked by the scientific community when publishing research findings. Short technical notes and videos are great means of communication and are a lot more digestible for machine operators than journal articles. Field tours and on-site demonstrations are very effective ways of communication with operators. Efforts should be made to equip a capable workforce with practical knowledge in order to make a real-world difference.

- Embrace UAV and geospatial technologies in wetland management and reclamation monitoring

Emerging technologies such as unmanned aerial vehicles (UAVs) present opportunities for better management and monitoring of boreal ecosystems. However, current progress in drone and remote sensing technologies is not adequate when applied to boreal peatlands. Unlike open water bodies or upland forests, peatlands usually have a shallow water table below the ground surface and are dominated by bryophytes such as mosses and lichen. This lack of distinction between vegetation, soil, and water boundaries makes it difficult to apply current UAV and remote sensing technologies in peatland settings. With the recent advancement of hyper-spectral imaging tools and UAVs, more efforts should be made to develop geospatial tools that can be used to map large wetland areas and make management decisions without the need to visit every single site. Although these tools won’t replace the boots on the ground completely, they will greatly reduce the management cost and allow for early detection of issues, thus increasing overall efficiency and reclamation success.

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