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LAND-COVER CHANGE WITHIN THE PEATLANDS ALONG THE
ROCKY MOUNTAIN FRONT, MONTANA: 1937-2009

by

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Thesis

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Land-cover change within the peatlands along the Rocky Mountain Front, Montana:
1937-2009

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Aerial photographs of nine peatlands along the Rocky Mountain Front, Montana, were analyzed in a GIS. The boundary of wetland extent was hand-digitized and the area within was classified into land-cover types including: total area, open fen, open water, woody vegetation, and non-wetland/agriculture. Changes in wetland extent and land-cover categories were evaluated from the earliest available imagery in 1937 to the last available imagery in 2009. Images prior to 1995 were orthorectified to correct inherent distortions. Results indicate little change in overall peatland area between 1937 and 2009 despite increasing air temperatures in the region. Open water area and the number of ponds increased over the study period, reflecting a rebounding beaver population. Agriculture in Pine Butte Fen, McDonald Swamp, and the Blackleaf Wetland Complex declined over the study period. Land purchases by the Nature Conservancy of Pine Butte Fen and McDonald Swamp have preserved the natural state of those peatlands, and they hold conservation easements for three of the other fens. One peatland is owned by the state and another is located within the Lewis and Clark National Forest. Conversely the sprawling Theboe Lake wetland has been heavily disturbed by ongoing agriculture since prior to 1937, and Bynum wetland has been heavily impacted since the middle of the study period.

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1 INTRODUCTION

The Rocky Mountain Front is home to a drastic change in relief where the northern Great Plains abruptly intersect the east front of the Rocky Mountains. Along this gradient, rich peatland “fens” act as corridors for flora and fauna to travel from the mountains to the prairies and preserves, which harbor species that are locally rare. Peatlands are abundant globally throughout the northern latitudes, especially in boreal areas. The fens of the Rocky Mountain Front (RMF), however, are the eastern-most, rich, peatlands in Montana, and are unique wetland habitats in this area of semi-arid continental climate (Chadde et al., 1998). The RMF fens are relatively understudied, with the exception being Pine Butte Fen, an area owned by The Nature Conservancy and known to support the richest peatland flora in the state of Montana.

Though few studies were done, the fens of the RMF have been subjected to a number of threats and disturbances throughout the past century. First, significant warming trends in western Montana ($+1.3^{\circ}\text{C}$) over the past century may have had an effect on the lateral expansion of peat in each system. Secondly, beavers play a significant geomorphological role in the hydrology of wetlands, and, while nearly extinct in the early 20th century, beaver populations have since rebounded and returned to much of their past distributional range. Finally, farmers and ranchers have relied on water from the RMF fens to grow and irrigate their crops.

This research combined remote sensing and GIS analysis to map land-cover change within nine peatland areas between 1937 and 2009. Analysis of historical aerial photographs allowed quantification of spatial change from the 1930s to 2009. Remote sensing is ideal for monitoring peatlands because it allows measurements and analysis

without disrupting the sensitive ecosystems (Kelly & Tuxen, 2009). Key characteristics were used to delineate and classify polygons within each peatland including tone or color, texture, shape, size, pattern, and context (Avery and Berlin, 1992). Nine peatland systems were analyzed and classified into total wetland area, and three broad vegetation communities within each area including: open fen, woody vegetation, and open water. Where present, non-wetland area and agricultural area were measured. By inventorying the change each system has experienced since the 1930s the following questions were addressed: 1) did increasing temperatures correlate with slower lateral expansion rates of the Rocky Mountain Front fens, 2) did change in beaver presence or abundance correlate with changes in the distribution of vegetation community type within the fens, and 3) did decline in agricultural use of the Rocky Mountain Front fens correlate with increases in woody vegetation cover within the fens? These questions addressed the spatial change occurring at and within the RMF's peatlands. At a regional scale, little overall change was observed relating to the expansion or contraction of the peatlands. The stability of these peatlands throughout the study period, reflects the critical importance of the groundwater to maintaining each system.

Conversely, dynamic spatial change can be seen within many of the peatlands. The role of beavers and agriculture within these peatland systems demonstrate changing ecosystems and landscape mosaics. These dynamics are based upon complex floral, faunal, and anthropogenic interactions. This study describes the changes seen within and across the landscape of the Rocky Mountain Front.

2 BACKGROUND

2.1 Peatlands

2.1.1 Defining Peatlands

Wetlands are ecological features that can be found worldwide. Charman (2002) describes three unique characteristics that differentiate wetlands from other landforms: (i) the presence of water at or near surface levels, (ii) often associated with low oxygen soil conditions, and (iii) specialized flora and fauna that are adapted to growing in these environments. Peatlands comprise a large subset of wetlands and have been described as “organic wetlands” (Charman, 2002). Like many terms describing wetlands, the term “peatlands” has various definitions depending on the discipline of study. Table 1 refers to the various definitions associated with wetland environments as described by Charman (2002).

Peatlands are generally defined as wetlands with waterlogged substrates and approximately 30 cm or more of peat accumulation (Kivinen and Pakarinen, 1981). Fen and bog are two distinctions that are made when referring to peatlands and depend solely on the source of incoming water and nutrients. Fens are minerotrophic, meaning they receive water and nutrients from both precipitation and water that has percolated through soil and bedrock (Chadde et al., 1998). Bogs typically are nutrient poor ombrotrophic, with precipitation being the sole source of water to the habitats..

The environmental gradient associated within peatland systems determines the vegetation composition ranging from open *Sphagnum* or *salix* covered bogs or fens to areas dominated by vascular plants, shrubs and trees. Wheeler and Proctor (2000) summarized the main directions of variability within peatland systems: (i) the

Table 1. Wetland definitions as described by Crum (1992) and Charman (2002).

Wetland	Land with a water table close to or above the surface or which is saturated for a significant period of time. Includes most peatlands and also ecosystems on mineral substrates, flowing and shallow waters
Peatland	Wetlands with waterlogged substrates in excess of 30 cm of peat has accumulated. May also include organic soils where aquatic processes may not be operating (e.g. drained or afforested peatlands)
Mire	Ecosystems described in English as swamp, bog, fen moor, muskeg and peatland. Often used synonymously with peatland, but some mires may have a mineral substrate
Fen	A mire is influenced by water from outside its own limits
Bog	A mire which receives water solely from rain and or snow falling onto its surface
Marsh	Loose term usually referring to an open, grassy or sedgy wetland developed on mineral soil which is inundated at least part of the year
Swamp	Loose term with very wide range of usage. Usually refers to a wooded wetland, rich in minerals and near-neutral to somewhat basic in reaction

minerotrophic-ombrotrophic gradient; (ii) the acid and/or base (ie pH) richness gradient; (iii) the fertility gradient, associated with the availability of nitrogen and phosphorus; (iv) the water table gradient; (v) the lithotrophic-thalassotrophic gradient, related to the influence of the ocean rather than the influence of rocks; (vi) mire expanse- mire margin gradient, or the distance from the center of the peatland; (vii) deep-peat- mineral soil gradient, (ie the depth of peat); and (viii) the spring-flush-fen gradient, or the proximity to the emerging groundwater and the flow rates associated with the water. Each factor can influence the vegetation community present within the system. Regardless of the initial situation or water source, the critical component of peatland formation is the retention of water, usually enhanced by some degree of topographical constraint. In areas

where evapotranspiration exceeds precipitation, such as the RMF, a constant source of groundwater is essential for peat accumulation.

Three main processes are responsible for the development of peatlands in the northern Rocky Mountains. Lake-filling, or terrestrialization, is the process in which a peatland spreads across a lake. This process typically occurs in areas with deep depressions, basins and kettleholes that formed after glacial retreat. Flow-through, or slope peatlands are best developed in association with streams and springs on moderate slopes. They require a continuous flow of ground and surface water. Eventually, if enough peat has developed to impede flow, water will be diverted into new areas. Lateral expansion of peat may then follow the flow of water into these new areas. In addition, there are subalpine-montane fens that develop on slope depressions. These wetlands are temporarily or seasonally flooded, while alpine-montane wet meadows develop under permanently saturated conditions, allowing peat to accumulate (Cowardin et al., 1979). Fens along the RMF are all designated as such due to their groundwater source which flow to the surface as springs near each site. In areas where water is especially abundant (i.e. Pine Butte Fen) parallel ridges (strings) occur between alternating shallow, water-filled depressions (flarks) which lie perpendicular to the direction of water movement (Lesica, 1986).

2.1.2 Distribution of Peatlands

No comprehensive inventory of wetlands, peatlands, or fens currently exists for the entire United States. However, efforts are currently in place with the Montana Natural Heritage Program to map and inventory the status of wetlands throughout

Montana. Global estimates of peatlands vary by study from a high of 421 million ha to the lowest estimate of 320 million ha (Kivinen and Pakarinen, 1981, and Pfadenhauer et al., 1993, respectively). Charman (2002) explains the difficulty estimating a global peatland inventory lies not in the data, but the inconsistent definitions and terminology result in some compromise and ultimately guesswork. While these estimates carry a large amount of variation, general consensus within the data suggests that North America, Europe, and northern Asia (particularly former USSR), contain the vast majority of the world's peatlands.

Peatlands occur extensively in boreal regions, where glaciers once dominated the landscape, including portions of Siberia, Eastern Europe, Finland, Canada and Alaska (Bedford & Godwin, 2003). Development and distribution of peatlands are largely controlled by regional factors such as climate, geology, and physiography (Foster & Glaser, 1986). Peatlands are most extensive in the northern latitudes with cool, humid climates where precipitation exceeds evapotranspiration. Halsey et al. (2000) present the extent of current *sphagnum*-dominated peatlands extending throughout the boreal and subarctic regions of North America, as far north as the Low Arctic of the Canadian Shield, and south along the west coast of Oregon, the Rocky Mountains in Wyoming, and the Appalachians of West Virginia. Amon et al. (2002) studied 70 fens located throughout the temperate zone in the midwestern United States. In the northern Rocky Mountains, peatlands are uncommon, in large part due to a climate unfavorable to their extensive development (Chadde et al. 1998). However, an assortment of mixed mires and fens occur throughout the Rocky Mountains where terrain is suitable.

In Montana, fens are concentrated in the western one-third of the State (Chadde et al. 1998), and reach the eastern limit of geographic distribution along the RMF. They are present in every ecotone, including foothills, intermontane valleys, montane and subalpine forests, and alpine tundra.

2.1.3 Ecological Significance of Peatlands

Although peatlands are relatively small and infrequent in the northern Rockies, they play critical ecological roles supporting a diverse array of flora and fauna. Peatlands along the RMF occur at stratigraphic, and/or topographic breaks that create hydrologic gradients causing ground water to reach the land surface (Bedford & Godwin, 2003). This is important along the RMF where peatland ecosystems are able to support a rich diversity of flora and fauna in what is otherwise a semi-arid environment. For example, 40 species of mammals, 59 species of birds, as well as eight species of reptiles and amphibians have been linked to Montana's Rocky Mountain Subalpine-Montane Fen ecosystem (Montana Field Guide, MTNHP, 2010).

Peatlands are also archives of the past, containing plant spores, pollen, and macrofossils which allow paleoecologists to infer biotic and abiotic dynamics of the postglacial landscape (Bursik & Moseley, 1995). This biological record can lead to better understanding of the capabilities and limitations of current and future land-management practices (Bursik & Moseley, 1995).

2.1.4 *Anthropogenic Disturbance of Peatlands*

Over the past several hundred years, approximately 50% of wetlands have been degraded worldwide (Turetsky & St. Louis, 2006), largely due to agricultural intensification, pollution, forestry practices, and urban development. Since groundwater-fed minerotrophic peatlands are connected throughout a watershed, agricultural practices can cause indirect effects. Eutrophication from neighboring fields can draw down water-table levels, reduce biodiversity and influence the nutrient status of peatlands (Bedford & Goodwin, 2003; Turetsky & St. Louis, 2006). Water diversions and ditches can have a significant impact on the hydrology and ecological integrity of fens (Cooper et al. 1998; Rocchio, 2005). Some of the peatlands of the RMF have been disturbed by draining, grazing and plowing, but this current analysis only documents visible changes within the peatlands over the almost 70 year period for which photos were available. Indirect influences may have been impacting the peatlands which were not revealed through this methodology.

2.1.5 *Effects of Beavers in Peatlands*

Human influences can be manifest through disturbances of ecological regimes with cascading impacts. North American beaver (*Candor canadensis*) populations were estimated between 60 to 400 million prior to European colonization (Butler & Malanson, 2005). Over-trapping throughout the 16th -19th centuries decimated beaver populations in response to demand for their fur. Beaver populations have rebounded since the 20th

century with 6 to 12 million beavers now inhabiting North America (Naiman et al., 1988).

No beaver population records exist for the Rocky Mountain Front region. However, nearby Glacier National Park (GNP), Montana, had records of beaver populations beginning around the park's founding in 1910. In 1915, GNP Superintendent Ralston (1916, 1013) stated, "colonies of beaver are to be found on almost every stream in the park." Unregulated trapping decimated the park's beaver population into the 20th century with Lechleitner (1955) estimating 1000 individuals. Current population density has since rebounded, but levels are still below pre-settlement numbers (Butler, 1991).

A study of Yellowstone National Park's (YNP) beaver population shows a similar decline in beaver numbers throughout the late 19th century and early 20th century. Smith and Tyers (2012) analyzed surveys from 1921 and numerous ground surveys from the 1980s through 2009. Their results showed abundant beaver populations in the early 1900s, then a large decline through the 1950s to the early 1990s, and finally an increase from the late 1990s to 2009. They attribute the recent recovery to the availability of willow, which is less prone to depletion than aspen (Smith and Tyers, 2012).

Beavers play a significant geomorphological role in the hydrology of wetlands. Beaver ponds trap and accumulate sediment, restrict stream velocities, and reconfigure wetland environments throughout North America. Eventually, beaver dams are abandoned and ponds drain or dry out, allowing grasses and other flora to colonize and form rich meadow communities (Turetsky & St. Louis, 2006). Building dams reduces water flows and creates large ponds and shallow lakes, sometimes killing surrounding forests and allowing further peatland development. However, Charman (2002) describes

this process as cyclical as the supply of trees declines, beavers will eventually be forced to find food and materials elsewhere. The abandoned dam will eventually collapse and may create an open meadow of wet grasses and meadows.

2.1.6 Climate History

While climate change is an ongoing process and occurs at many time scales, this project will focus on the last 100 years of temperature and streamflow change. The last major climatic cooling period occurred during the Little Ice Age (LIA: 600 to 100 cal yr B.P.; Luckman, 2000; Pederson et al., 2010). Since that time, decadal variations in temperature and precipitation have linked the Pacific Decadal Oscillation (PDO) to climate trends throughout the western United States and Canada. The El Niño \ Southern Oscillation (ENSO) and the Pacific Decadal Oscillation represent variation in sea-surface temperatures and sea-level atmospheric pressure in the equatorial and northern Pacific Ocean that primarily affect winter temperature and precipitation regimes in the western United States and Canada (Cayan et al., 1998; Schoennagel et al., 2005).

The emerging relationship between PDO and glacial patterns has probably led to a reduced mass balance of glaciers throughout the northern Rockies (Moore et al., 2009). Of the 150 glaciers that existed in Glacier National Park in 1850, less than 37 remain today (Hall & Fagre, 2003). The remaining glaciers have been reduced to one-third or less of their previous surface area, and total ice and permanent snow coverage of the park has declined by 72% since (Key et al., 2002; Hall & Fagre, 2003). Warming trends may have increasing effects on regional water supply throughout the northern Rocky Mountains.

Rood et al. (2008) concluded that eastern-slope rivers of the northern Rocky Mountains are seeing peak flows occurring earlier in the calendar year, with earlier spring runoffs resulting in late summer discharge declines. These late summer flows have decreased by around 20% over the twentieth century and extending this pattern into the twenty-first century, may result in a further decline of about 10% by 2050 (Rood et al., 2008). Pederson et al. (2013) determined a regionally “synchronous and persistent” decline in snowpack beginning by the 1980s, and as early as 1958 in the northern Rockies, driven primarily by warmer springs and earlier peak streamflows. The linkage between the PDO, glacial ablation rates, and seasonal stream flow changes raises questions of whether wetlands distributed along the RMF could be permanently altered by changes in hydrologic flows.

2.2 Study Area

The study area is located in west-central Montana along the eastern front of the Rocky Mountains (Figure 1). The RMF represents a narrow ecotone between the northern Rockies and foothill grasslands, which is largely controlled by a 1500 m drop in elevation over just tens of kilometers. Climate gradients follow elevation with mean annual precipitation increasing from 30 cm on the plains to 300 cm among the highest mountain peaks, and mean monthly minimum temperatures decreasing from 0 to -8 °C over the same elevation range. The climate of the RMF is influenced by continental patterns, bringing cold winters and warm summers. These patterns consist of winter temperatures falling well below 0 °F (-17 °C), and summer temperatures averaging above 80 °F (27 °C; Nimick, 1983). The RMF is also known for strong, warm, dry Chinook

winds that develop on the lee side of mountain ranges and provide relief from the Front's winter cold spells (Wylie, 1991). The harsh climate associated with the edge of the RMF limits peatland development because of low humidity and prolonged dry periods (Chadde et al., 1998).

Development of these fens is primarily dependent on the flow of groundwater and the presence of surface bedrock consisting of shale and limestone (Reichmuth, 1981). The RMF consists of such bedrock with numerous thrust faults known as the "Disturbed Belt" which produced the rugged reefs and ridges that make up the East Front. Nimick et al. (1983) suggest that since the end of the Pinedale glaciation approximately 14,000 years BP, melt water and surface flow recharged the local aquifer, creating areas of ground water discharge. Once vegetation began to develop in these wet areas, peat began to accumulate (Wylie, 1991).

The Nature Conservancy, (TNC) provided the list of nine locations of peatland sites along the RMF which were analyzed for this project (Figure 1). Most of Pine Butte Fen and McDonald Swamp have been owned by TNC since 1979, with two small private land holdings bordering each system. TNC also holds conservation easements in the Scoffin Creek Fen, Cow Creek Wetland, and Blackleaf Wetland Complex, though these are privately owned and have ongoing "traditional use" (TNC, 2010). The Wagner Basin Wetland is located on the Lewis and Clark National Forest and is protected in a Research Natural Area (RNA), while Blackleaf Management Area is owned by the State of Montana. The remaining two peatlands are privately owned without conservation easements.

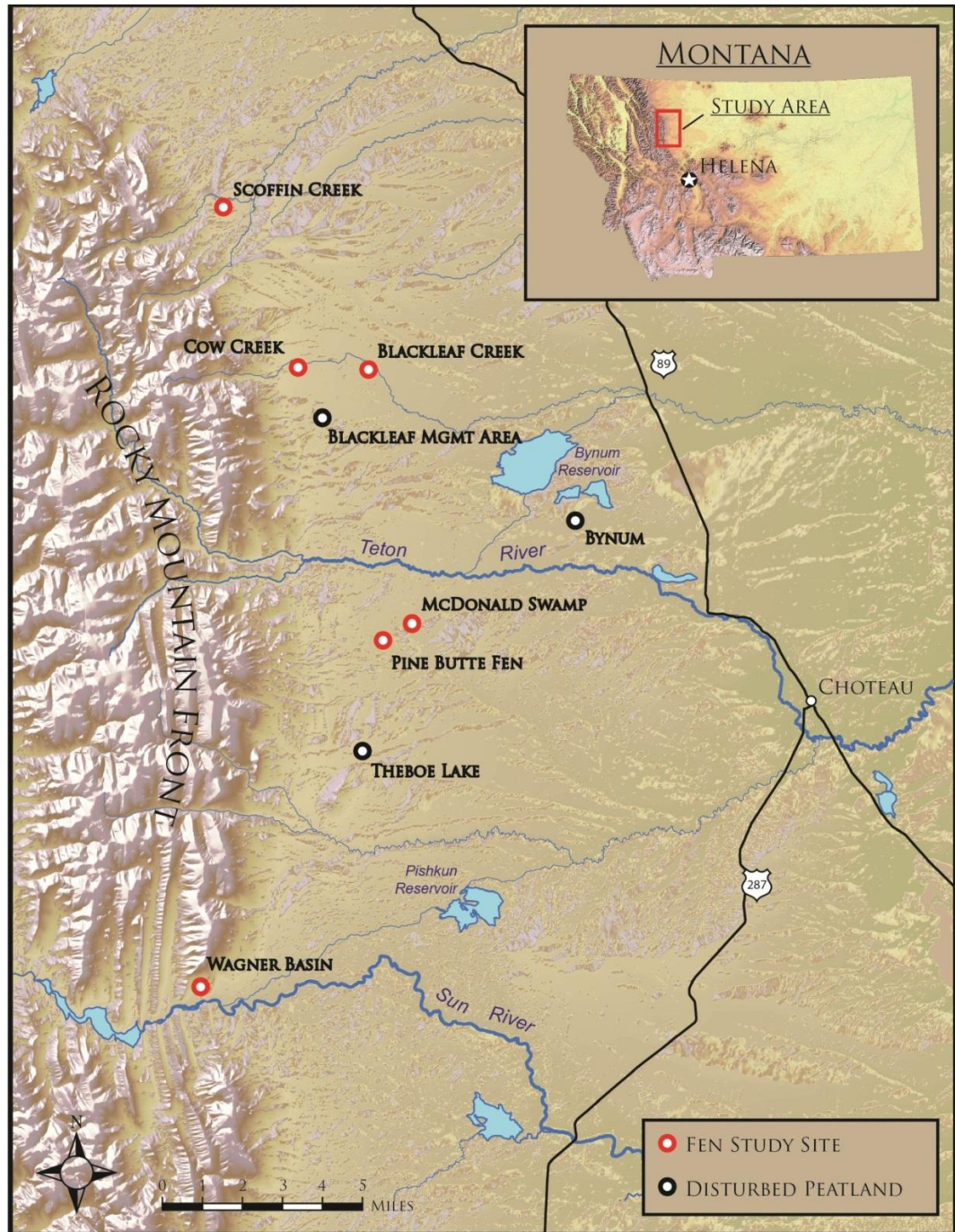


Figure 1. Map of the study area showing the location of nine peatlands found on the RMF, including six intact and three disturbed fens. Locations provided by The Nature Conservancy.

2.2.1 *Pine Butte Fen and McDonald Swamp*

The most notable peatland site along the RMF is Pine Butte Fen (47°50'39" N, 112°33'43" W), which is part of the Pine Butte Preserve, a 7,285 ha refuge dedicated in 1979 established by The Nature Conservancy to protect the last area in the continental United States where grizzly bears (*Ursus arctos*) still migrate to the plains (Lesica, 1986). The fen is also part of the territory of a pack of gray wolves (*Canis lupus*), recently delisted from the federal Endangered Species Act. This 450 ha, undisturbed, patterned fen is the most documented on the RMF (McCallister, 1990). The fen is home to 93 species of vascular plants, including seven of Montana's Plant Species of Concern (SOC; Lesica, 1986). The Pine Butte Fen lies on glacial drift derived from limestone and calcareous shales. This permeable drift, layered on top of impermeable bedrock, is saturated by water flowing from the Teton River. The continuously flowing, cold and nutrient-rich water intercepts the ground surface at the fen. Mean annual precipitation is 430 mm and total annual evapotranspiration is estimated to be 1195 mm (Figure 2; Potts, 1989), while mean annual temperature is 6.0 °C (42.8 °F), and an average of 90 days are frost free (Cooper & Jones, 2003). Peatlands are quite rare in regions with such a large annual water balance deficit (Figure 2).

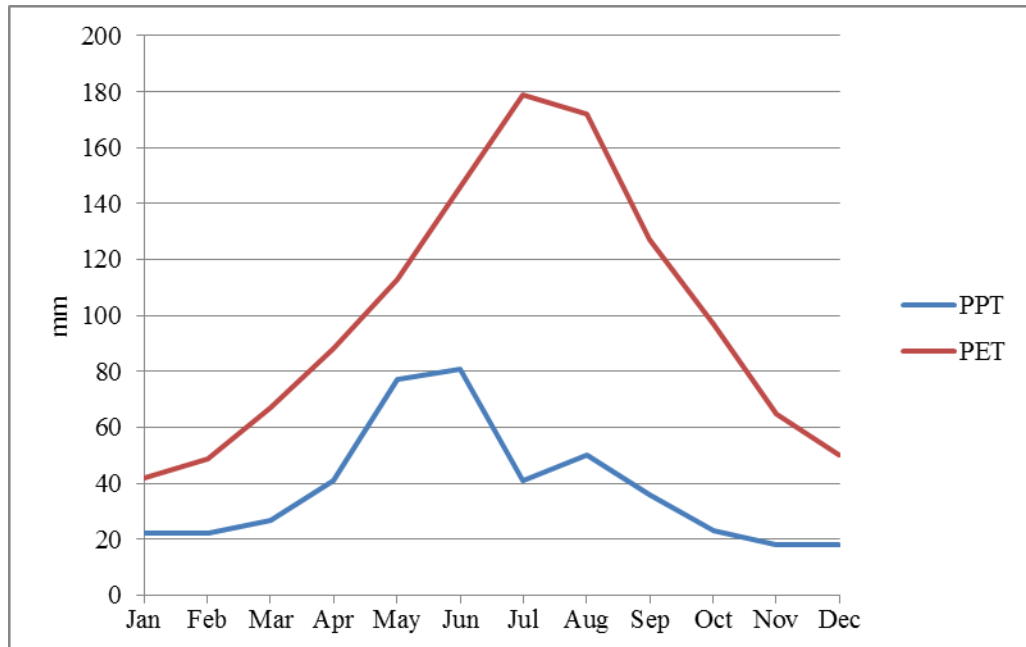


Figure 2. Monthly precipitation and potential evapotranspiration for Pine Butte Fen, adapted from Potts (1989). The area between the potential evapotranspiration and observed precipitation is a deficit.

The vegetation of Pine Butte Fen is organized into three distinct communities, including open fen, dwarf-carr, and carr (Lesica, 1986). The open fen vegetation is dominated by graminoids and bryophytes. Much of this area exhibits flark and string patterning, with flarks containing standing water and strings dominated by sedge, (*Carex simulata* and *C. aquatilis*), baltic rush (*Juncus balticus*), spiked muhly (*Muhlenbergia golmerata*), American dwarf bush (*Betula glandulosa*), and shrubby cinquefoil (*Potentilla fruticosa*; Lesica, 1986). The open fen also includes large patches dominated by bulrush (*Scripus acutus*). The carr community occurs within a hummock-hollow surface topography, with hummocks dominated by 1 to 3 meter shrubs that attain total cover of greater than 50% (Lesica, 1986). A large number of species found in the Pine Butte Fen are derived from adjacent upland communities and have adapted to the regional aridity (Lesica, 1986).

McDonald Swamp is a complex wetland ecosystem and covers a significant portion of the Pine Butte Swamp Preserve. The central and eastern portions of McDonald Swamp are not underlain by peat and are densely forested.

2.2.2 Anthropogenic Disturbance of RMF Peatlands

Pine Butte Fen and McDonald Swamp have been used as a source of irrigation water since at least 1910 (Nimick et al., 1983). Nimick et al.'s, (1983) investigation of the geology and hydrology of the Pine Butte Preserve indicates that by 1947 extensive use was made of surface waters from the Teton River, Willow Creek, Pine Butte Fen, and McDonald Swamp. Their study also suggests that use of the Teton River has increased since 1947, while use of Pine Butte Fen and McDonald Swamp has decreased.

Interviews by Nimick et al. (1983) indicate diversion of surface water from Pine Butte Fen and McDonald Swamp had been unsuccessful due to the continuous maintenance necessitated by beaver activity. However, local resident Harold Yeager had the only active diversion from McDonald Swamp at that time.

In the southern area of Pine Butte Fen, the Durr Ranch constructed numerous ditches into the wetland. The ditches had been abandoned and occupied by beaver dams, and could still be seen from aerial photographs (Nimick et al., 1983). On the northwest side of Pine Butte Fen, a ditch was constructed by resident Joe White in 1950, but was not effective because of insufficient flow rates (Nimick et al., 1983). Field observations from Nimick's study indicated the individual drainage ditches did not have an effect on the water levels in the peat near the ditches, except on the downgradient side (Nimick et al., 1983). The vegetation was said to be typical of an open fen and the water table was

not affected. Downgradient, for approximately 200 ft, the ground was dry and firm, although it is peat (Nimick et al., 1983). According to Nimick's study, this drainage ditch seemed to interrupt water flow through the peat and had created local patches of dry ground.

2.2.3 *Other RMF Peatland Sites*

The remaining peatland sites along the RMF exhibit a range of sizes, patterning, and degrees of alteration from anthropogenic influences. A site near Scoffin Creek, ~20 miles north of Pine Butte, is the northern most peatland area in this study. This site has no visible signs of anthropogenic disturbance and represents a relatively small peatland system with an area of ~35 ha. Also included are two sites along Cow Creek and the adjacent Blackleaf Creek, ~10 miles west of the town of Bynum. These sites run west to east along their respective drainages, and are divided by a secondary rural road. The Cow Creek site has some minor anthropogenic influences which altered the landscape sometime after 1937. The Blackleaf Creek peatland has experienced a myriad of disturbances throughout the past eighty years, and represents a potential restoration opportunity. Overall, these effects were minimal enough to allow analysis of changes through time at both Cow Creek and Blackleaf Creek for this study. The southernmost site is a wetland in Wagner Basin, located along the Sun River, about 17 miles south of Pine Butte. Representing the smallest wetland in this study, the Wagner Basin area covers ~24 ha, and is topographically isolated from development and inaccessible by vehicle due to two reef walls and the adjacent Sun River, and is protected by the USFS.

Three other peatland environments were difficult to analyze in this study because of major anthropogenic disturbances. A site near Bynum Reservoir was disturbed by

agricultural practices, making the boundary of the wetland virtually indistinguishable from surrounding fields. A site near Theboe Lake also had been disturbed by intensive agriculture. A site within the state-owned Blackleaf Wildlife Management Area lacked 1930-40 aerial photographs and could not be fully evaluated for the entire study period.

In summary, Pine Butte Fen, McDonald Swamp, and four other sites were assessed to quantify changes within the boundary of each peatland. The three other sites were evaluated to quantify their total extent from the first available photograph, at the first time step where they were not visible on the landscape due to anthropogenic disturbance, through to the most recent imagery. As a whole, these sites include patterned and un-patterned fens that represent a range of characteristics of fens along the RMF (Table 2).

Table 2. Ownership, size, and condition of known fens within the Rocky Mountain Front study area from north to south as of 2009. Bold indicates the six fens which are intact and had data available for the full period from 1937 to 2009.

RMF Fen Sites	Ownership	Area (ha)	Anthropogenic Disturbance
Scoffin Creek	Private; TNC Easement	32.5	None
Cow Creek	Private; TNC Easement	118.5	Minimal - Ranch/House development
Blackleaf Creek	Private; TNC Easement	303.0	Moderate - Heavy disturbance
Blackleaf Mgmt Area	State of Montana	138.0	None
Bynum	Private	160.0	Substantial - Heavy disturbance due to agriculture
Pine Butte Fen	TNC; Private	495.0	Minimal - agriculture is southern reach
McDonald Swamp	TNC; Private; State	719.0	None
Theboe Lake Site	Private	9.0	Substantial - Heavy disturbance due to agriculture
Wagner Basin Fen	USDA; National Forest	21.0	None

2.3 Mapping Wetland Land-cover from Aerial Photographs

Aerial photographs are ideal for mapping fine-scale landscape changes in habitats, such as riparian areas because they contain a high level of spatial and tonal detail (Morgan et al., 2010). Aerial photographs also offer the longest available, spatially continuous and complete record of landscape change. Aerial photographs can reduce the costs of mapping, inventorying and planning, and are used for studies ranging from wetland mapping, forest inventories, and disturbance mapping, to wildlife management (Avery and Berlin, 1992; Morgan et al., 2010).

Aerial photographs provide one of the few ways to temporally measure wetland dynamics (e.g. Dissanska et al., 2009), especially at sites where monitoring has not been done through time by other methods. Remote sensing is ideal for monitoring peatlands because it allows measurements and analysis without disrupting the sensitive ecosystems (Kelly & Tuxen, 2009).

Aerial photointerpretation of wetlands can address questions from a number of scientific fields. With increasing pressures of climate change, studies have evaluated changing peatland landscape near areas of permafrost (Vitt & Halsey, 1994; Vitt et al., 2000), carbon sequestration and greenhouse gas exchanges in peatlands (Dissanska et al., 2009). Examination of vegetation change over time has been a focus of Jauhiainen's et al. (2007) peatland study throughout Finland. Bakker et al. (1994) examined a floating wetlands transition from open water through *Carex*-dominated vegetation, to *Alnus*-dominated vegetation.

Examples of wetland mapping using aerial photography are especially prominent throughout Europe (Aaviksoo, 1993; Bakker et al., 1994; Connolly et al., 2007;

Jauhiainen et al. 2007; Nungesser, 2011), and north-central and eastern North America (Tiner, 1990; Barrette et al., 2000; Pellerin & Lavoie, 2000; Vitt et al., 2000; Johnston & Meysembourg, 2002; Dissanska et al., 2009). Byrd et al. (2004) used aerial photographs to assess the degradation of coastal salt marshes. Glaser et al. (1990) used aerial photography to base hydrological and stratigraphic studies at the Lost River peatland in northern Minnesota, to determine the influence of groundwater on peatland development and ecology.

To assess the ecological, social, and economic value of wetlands, the United States Department of the Interior, Fish and Wildlife Service conducted a nationwide inventory consisting of 105.9 million acres in the conterminous United States (Dahl & Johnson, 1991). Cowardin et al. (1979) developed a very detailed wetland classification system for the National Wetlands Inventory (NWI). They classified Palustrine Systems as all non-tidal wetlands dominated by trees, shrubs, emergent wetlands, emergent mosses and lichens. Palustrine Systems were developed to group terms mentioned in section 2.1.1, such as marsh, swamp, bog, and fen. The NWI interpreted aerial photographs and topographic maps based on Cowardin's 14 detailed categories (Dahl & Johnson, 1991). In the early 1990's, analysis of nationwide wetland change showed the status and trends of wetlands in the conterminous United States from the mid-1970's to mid-1980's. That study compared some of the first color-infrared imagery with traditional black and white aerial photographs.

3 METHODOLOGY

Traditionally, aerial photography has been the most widely used data source for mapping and inventorying wetlands (Tiner, 1990; Barrette et al., 2000). Reconstructing historic ecosystem conditions from archived aerial photographs can be important for characterizing the historic range of variability within ecosystems (Morgan et al., 2010). This thesis interprets aerial photographs from 1937 to 2009 to delineate wetland extent and land-cover change within each peatland system over time. In order to analyze each image, extensive processing (orthorectification) was done to correct planimetric distortion in the images prior to 1995. Images after 1995 had already been corrected. Next, polygons were manually digitized in ArcGIS using Nimick et al.'s delineation (1983) as a guide for Pine Butte Fen and McDonald Swamp. Ground-truthing of each site was also conducted to ensure the quality of aerial interpretation.

3.1 Aerial Photography

Aerial photographs were obtained from three sources (Table 3). Black and white aerial photographs dating from 1937 to 1941 were the earliest photos available from the National Archive and have a scale of 1:20,000. Images from 1937 to 1941 were initially photographed with film, processed into 10" x 10" prints and then digitally scanned before obtained from the Archive.

Digital aerial photographs downloaded from the USGS EarthExplorer archive had images from 1955, 1977, and 1995. Aerial photographs from 1955 were taken on film by the Army Map Service with a scale of 1:60,000, then digitized by the USGS and made available for free download. Images from 1977 have a scale of 1:83,000 and were

digitized by the USGS. The scale associated with the 1977 images make interpreting vegetation changes very difficult and may result in substantial error. The images taken in 1995 were created by the USGS and have a 1 meter ground resolution (USGS, 2001). Those photos were orthorectified by the Montana State Library to comply with the National Aerial Photography Program (NAPP) standards.

The 2009 images were created by the U.S. Farm Services Agency National Agricultural Imagery Program (NAIP), and are natural-color MrSID images with a ground resolution of 1 meter, which meets USDA program requirements. Images were projected into the State Plane Coordinate System with units in meters, using the North American Datum of 1983 (Barrette et al., 2000). The 2009 digital orthophotographs (DOQs) were used as the base imagery for the orthorectification of imagery prior to 1995.

Table 3. Aerial images used for each site, including date, source, and image scale.

	National Archive		USGS EarthExplorer		Montana Natural Resource Information System (NRIS)			
	Photo Date	Image Scale	Photo Date	Image Scale	Photo Date	Image Scale	Photo Date	Image Scale
RMF Fen Sites								
Scoffin Creek	10/24/1941	1: 20,000	9/4/1966	1: 31,000	9/1/1995	1: 40,000	9/29/2009	1: 40,000
Cow Creek	8/8/1941	1: 20,000	9/15/1955	1: 37,200	9/1/1995	1: 40,000	9/29/2009	1: 40,000
Blackleaf	8/8/1941	1: 20,000	9/15/1955	1: 37,200	9/1/1995	1: 40,000	9/29/2009	1: 40,000
BLMA	NA	NA	9/19/1955	1: 37,200	9/1/1995	1: 40,000	9/29/2009	1: 40,000
Bynum	NA	NA	7/23/1954	1: 27,600	9/1/1995	1: 40,000	9/29/2009	1: 40,000
Pine Butte Fen	8/16/1937	1: 20,000	7/6/1953	1: 60,000	9/1/1995	1: 40,000	9/29/2009	1: 40,000
McDonald Swamp	8/16/1937	1: 20,000	7/6/1953	1: 60,000	9/1/1995	1: 40,000	9/29/2009	1: 40,000
Theboe Lake	8/16/1937	1: 20,000	7/13/1955	1: 37,200	9/1/1995	1: 40,000	9/29/2009	1: 40,000
Wagner Basin	9/13/1937	1: 20,000	8/21/1955	1: 37,200	9/1/1995	1: 40,000	9/29/2009	1: 40,000

3.2 Photogrammetry

Aerial photographs have systematic and unsystematic distortion inherent in their acquisition. To remove these distortions so that the image can be treated like a map, they must go through a process known as orthorectification to remove the distortion. An orthorectified image (orthophoto) is one where each point represents a true ground location and all geometric, terrain, and sensor distortions have been removed within a specified accuracy. Scale remains constant throughout the orthophoto, regardless of elevation, providing accurate measurements of distance and direction (Avery & Berlin, 1992; Dissanska et al., 2009).

Images from 1995 and 2009 had already been orthorectified before they were downloaded. All images prior to 1995 were registered in space using ArcGIS to match the geographic coordinate system and projection of the 2009 orthophotos (Pellerin & Lavoie, 2000). Ground control points (GCPs) were used to adjust the locations of sites on the incorrect image to their corresponding locations on the orthorectified image (Rocchini et al., 2012). Road intersections, building corners, bridges, dams and boulders were used to match images, with emphasis around the perimeter of each peatland study site (Figure 3). Once GCPs have been chosen, 2nd-order polynomial functions correct the original image to the orthorectified image (Rocchini et al., 2012). The Federal Geographic Data Committee suggests a minimum requirement of a root mean square error (RMSE) of less than 5 m for images with a scale of 1:12,000 (FDGC, 2009). Photos for this project have a scale of 1:20,000 or coarser, so a minimal horizontal RMSE accuracy value of 10 m was used for accuracy purposes. Once processed, visual

inspection suggests that the error was much smaller than 10 m. In addition, a polygon was created on each aerial photograph using GCPs to measure the percent error between repeat photographs. Error values were individually assessed on each photograph, then averaged for each site and provide guidance on the errors due to orthorectification and errors due to digitization.

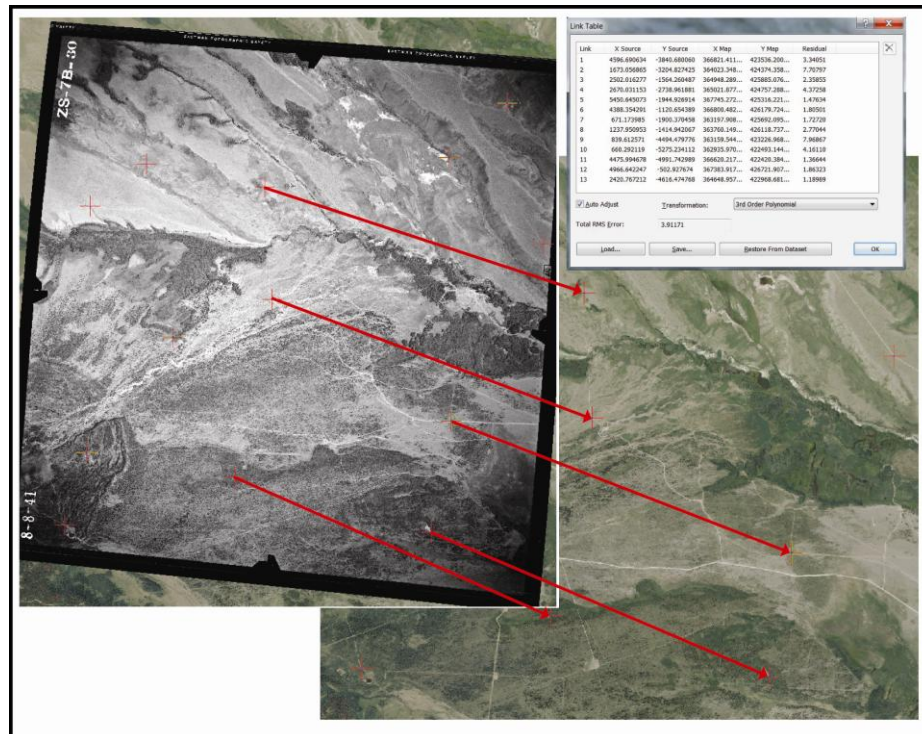


Figure 3. Example of locating ground control points (GCPs) to use for orthorectification of an aerial photograph from 1941 using a digital orthorectified image from 2009 as a reference.

3.3 Peatland Land-Cover Classification

While manual interpretation can be quite subjective and dependent upon the knowledge and perceptions of interpreters (Dissanska et al., 2011), guidelines were established and utilized to ensure consistent digitization and categorization (Table 4). Key characteristics were used to delineate and classify each polygon including, tone or

color, texture, shape, size, pattern, and context (Avery and Berlin, 1992). This project adopted a broad form of classification developed by Cowardin et al. (1979) along with observations of the local vegetation type developed by Lesica (1986). Quality control ground-truthing visits to each site provided confirmation of the aerial-photo interpretation.

Photointerpretation techniques used by the NWI to delineate wetland boundaries and land-cover categories along with background research also served as a guide for analyzing each system (Dahl & Johnson, 1991). Polygons were digitized by hand to delineate the total area within each wetland complex and separate each system into two vegetation communities and open water (Table 4). Vegetation communities were separated into open fens (described by Lesica (1986) as dominated by herbaceous flora) and woody vegetation (carr and dwarf-carr shrub environments). Where possible, this study also identified pools and streams of open water, and inventoried individual ponds.

3.4 Constraints

A number of issues arose throughout this study that limited the scope of analysis and influenced the results and their implications. First, the resolution and quality of aerial imagery have a profound effect on photo interpretation (Morgan et al., 2010). Two sets of aerial photographs taken in 1953 (Table 3) were only available at a scale of 1:60,000. Interpretation of these images does not have the same accuracy or precision of the images with a scale of 1:20,000.

Seasonality can have a profound effect on many wetland characteristics. The aerial imagery used for this study was chosen from a very limited selection and was captured at varying times throughout the year, ranging from July to October. This

seasonality may have affected photo interpretation of the amount of ground and surface water in each wetland, as well as the visibility of agricultural practices such as animal grazing or haying in the late fall months.

Table 4. Criteria used to assess spatial classifications of peatland vegetation developed using work from several authors (Cowardin et al., 1979; Lesica, 1986; Chadde et al., 1998; Barrette et al., 2000).

		Photo Interpretation	
		Black & White	Color NAIP
Total Wetland Area		Distinct edges can be seen between darker gray wetland and nearly white dry surrounding grasslands, along with textured vegetation versus untextured surrounding grasslands	Distinct edges between greener tones in wetlands and yellow-brown grasslands; wetland vegetation contains more texture and shadows versus highly homogenous “soft” grassland textures
Vegetation Community Delineation	Open Fen	Dominantly smooth, can be patterned or unpatterned, light gray tone, lacks shadows of woody vegetation	Light smooth green coloring with patterned ridges, lacks shadows of woody vegetation
	Open Water	Very smooth, darker reflectance signature, straight to convex borderlines (often representing a beaver dam)	Very dark, nearly black color often seen with abruptly straight edges from beaver activity
	Woody Vegetation	Moderate to highly textured, darker gray tone	Dark green; very textured; trees or shrubs appear spotty; often can see shadows

4 RESULTS

Six peatland sites were able to be fully mapped and analyzed for change between 1937 and 2009. Areas of the entire wetland, as well as open fen, open water, and woody vegetation were quantified and analyzed within each site's system. Where agricultural disturbances were present that was included. Also, when open water "ponds" were evident, they were counted and the number evaluated over the duration of the study.

Landscape-scale trends were observed for the peatlands of the RMF, but relied primarily on those intact sites for which figures were available for the entire study period. The total area of peatlands within the RMF changed very little from 1937 through 2009 (Figure 4). However, within the peatlands, two distinct changes were observed; 1) a 323% increase in open water and, 2) a 54 % decrease in non-wetland/agriculture area (Table 5.) Each site displayed a unique set of characteristics of size, areas of land-cover and open water, and degree of agricultural disturbance.

Three other sites were mapped and analyzed with the limited imagery available. Blackleaf Wildlife Management Area appears to be relatively stable, however, Bynum Wetland, and Theboe Lake Wetland have been heavily disturbed. About two-thirds of Bynum wetland has been converted to agriculture during the study period, while almost the entire area of the Theboe Lake wetland appears to have been heavily altered for agricultural usage prior to the earliest available images in 1937. If the original area of Bynum wetland and an estimation of Theboe Lake wetland area prior to 1937 were included, approximately 27.5% of the total peatlands in the RMF have been lost due to human activity.

Results are discussed in Chapter 5.

Table 5. Overall spatial change and percent change in peatlands along the Rocky Mountain Front, Montana, 1937-2009, including total area, woody vegetation, open fen, open water, non-wetland/ agriculture.

		RMF Peatland Totals									
		Total Area		Woody Vegetation		Open Fen		Open Water		Non Wetland/ Agriculture	
		m ²	%	m ²	%	m ²	%	m ²	%	m ²	%
Photo Year	1937-41	16,824,954	100.0%	12,667,603	75.3%	2,715,210	16.1%	104,594	0.6%	1,337,735	8.0%
	1953-66	17,009,712	1.1%	12,943,056	76.1%	2,545,976	15.1%	170,542	1.0%	1,350,138	7.9%
	1995	16,898,503	0.4%	13,448,483	79.6%	2,624,815	15.5%	281,549	1.7%	543,654	3.2%
	2009	16,886,943	0.4%	13,129,209	77.7%	2,694,533	16.0%	442,613	2.6%	620,588	3.7%

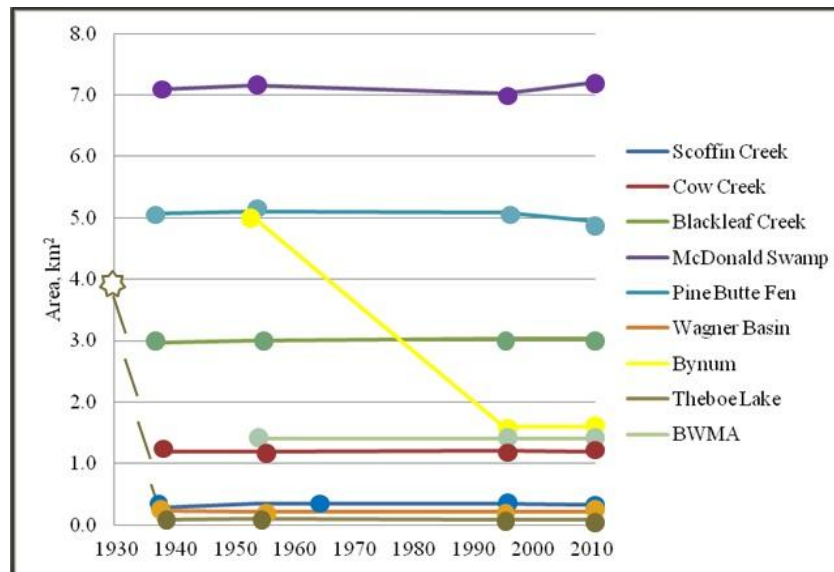


Figure 4. Graph of the change in total area at each peatland site along the Rocky Mountain Front from 1937 to 2009.

4.1 Scoffin Creek Wetland Complex

Orthorectified images from 1941, 1966, 1995, and 2009 were interpreted and analyzed to distinguish a wetland boundary, areas of open water, open fen, woody vegetation, and the number of ponds (Table 6). The Scoffin Creek Wetland Complex showed an increase in area and woody vegetation from 1941 to 1966, but then a gradual decline in spatial extent up to 2009 (Figure 5). There was an increase in overall area of 13.1% and a 5.1% increase in open water area (Table 6) from 1941 to 2009. A similar trend shows an increase in the number of pools over time from one in 1941 to 35 in 2009. While each pool is quite small, they clearly show a change in the hydrological regime of this wetland. Ponds were mainly located along the low-lying drainages, surrounded by woody vegetation. Open fen area stayed relatively steady. Errors of 3.8, 1.0, and 2.0% were found between 1941, 1966, 1995, and 2009, respectively, with an overall mean error of 2.3% due to orthorectification and digitization.

Table 6. Spatial change at Scoffin Creek including total area, open water, open fen, woody vegetation, and number of ponds from 1941 to 2009.

Photo Year	Total Area		Vegetation Community								Number of Ponds
			Woody Vegetation		Open Water		Open Fen		Non Wetland/ Agriculture		
	m ²	%	m ²	%	m ²	%	m ²	%	m ²	%	
1941	285,739	100.0%	279,471	97.8%	286	0.1%	5,913	2.1%	0	0.0%	1
1966	347,617	21.7%	332,521	95.7%	4,767	1.4%	10,329	3.0%	0	0.0%	12
1995	343,243	20.1%	325,602	94.9%	10,140	3.0%	7,501	2.2%	0	0.0%	13
2009	324,525	13.6%	300,563	92.6%	16,454	5.1%	7,508	2.3%	0	0.0%	35

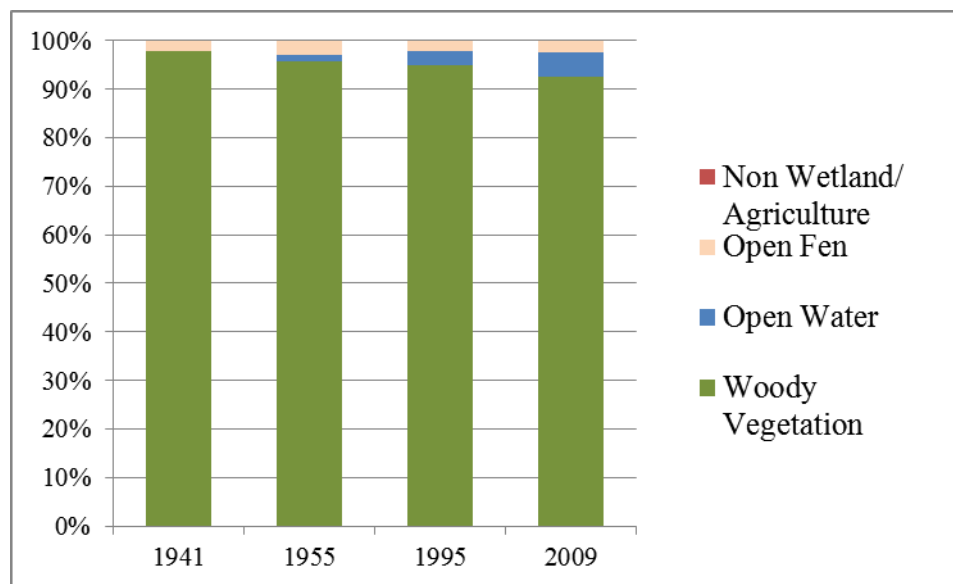


Figure 5. Percentage of land-cover types within the Scoffin Creek wetland complex from 1941 to 2009.

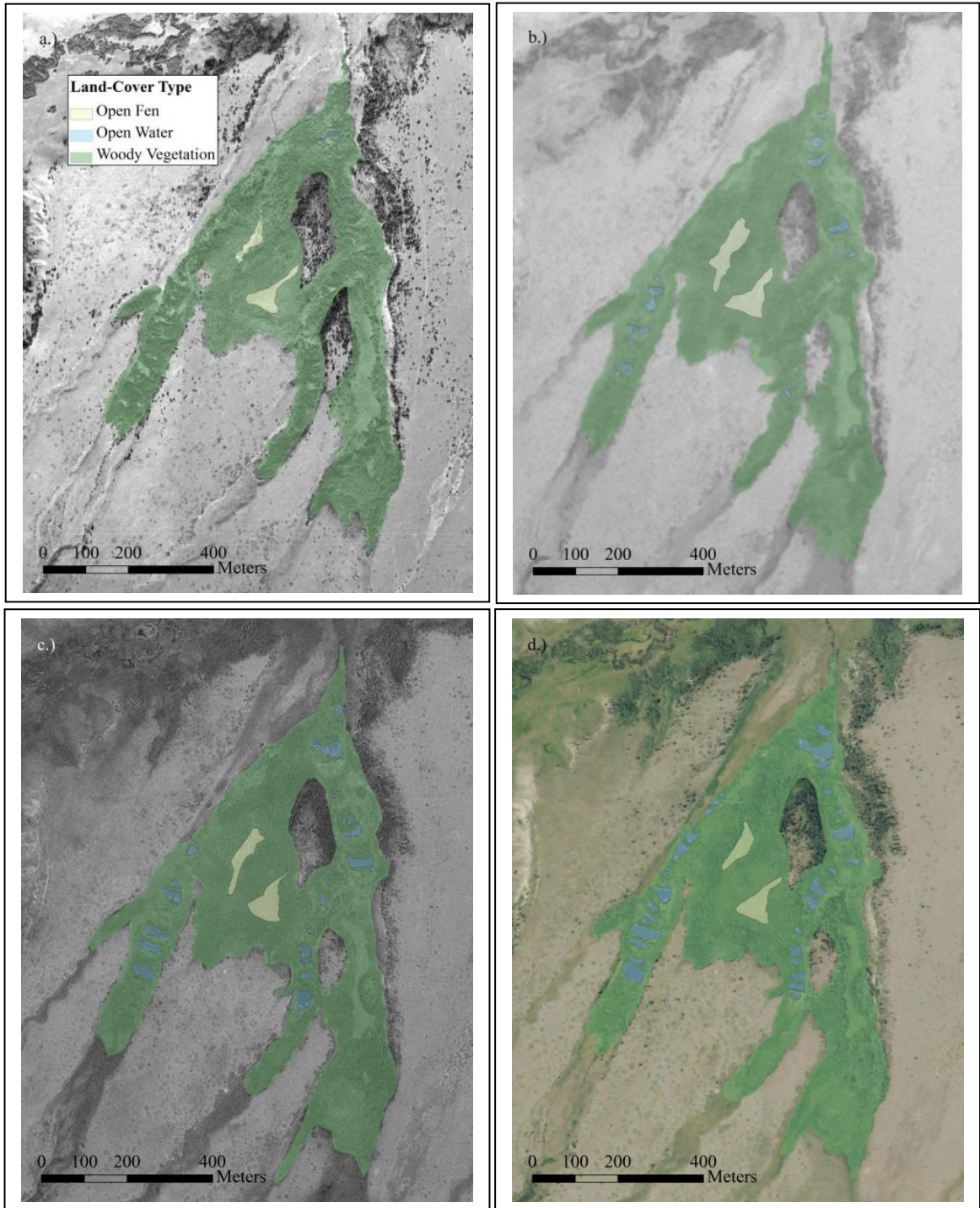


Figure 6. Change in the extent and land cover within the Scoffin Creek fen between a) 1941, b) 1966, c) 1995, and d) 2009.

4.2 Cow Creek Wetland Complex

The areal extent of the Cow Creek wetland complex declined slightly (-0.8%) from 1941 to 2009 (Table 7). Woody vegetation area maintained a steady-state throughout the study. Open water area nearly tripled from 1941 to 2009 with most of the change visible along the Cow Creek drainage. Overall, the hydrology of the Cow Creek complex seems to have gone through little change, with the exception of more distinct flow in the creek (Figure 7). Open water ponds were located along Cow Creek and other areas surrounded by woody vegetation. The development of a homestead at some time between 1955 and 1995 led to some change in land cover in the middle of the site. This development, however, seems to have had little effect on the hydrology. Another interesting change in this fen is encroachment of woody vegetation on the open fen areas in the southeastern portion of the site (Figure 8). Errors of 0.1, 0.7, and 0.1%, were found between 1941, 1955, 1995, and 2009, respectively, with an overall mean error of 0.3% due to orthorectification and digitization.

Table 7. Spatial change at Cow Creek including total area, open water, open fen, woody vegetation, non-wetland/ agriculture and percent change over time for each category from 1941 to 2009.

		Total Area		Vegetation Community							
				Woody Vegetation		Open Water		Open Fen		Non Wetland/ Agriculture	
		m ²	%	m ²	%	m ²	%	m ²	%	m ²	%
Photo Year	1941	1,195,476	100.0%	1,084,122	90.7%	10,383	0.9%	100,972	8.4%	0	0.0%
	1955	1,197,735	0.1%	1,092,937	91.3%	15,206	1.3%	89,592	7.5%	0	0.0%
	1995	1,200,858	0.4%	1,100,323	91.6%	12,358	1.0%	88,177	7.3%	0	0.0%
	2009	1,185,514	-0.8%	1,070,627	90.3%	31,152	2.6%	83,750	7.1%	0	0.0%

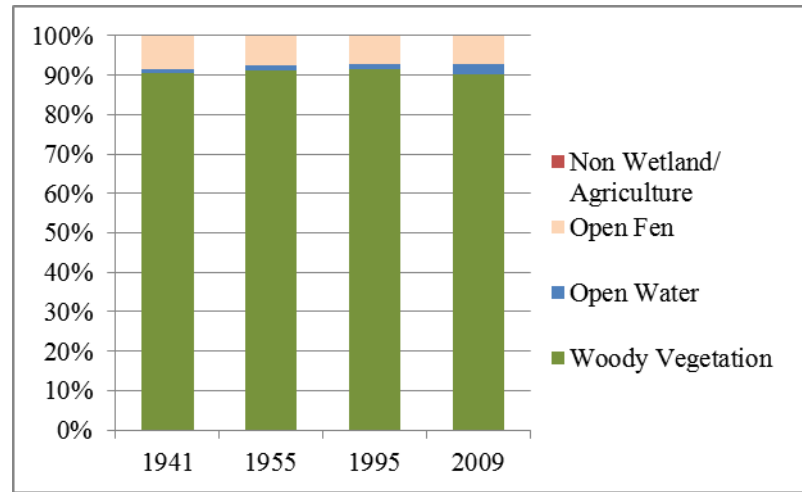


Figure 7. Percentage of land-cover types within the Cow Creek wetland complex from 1941 to 2009.

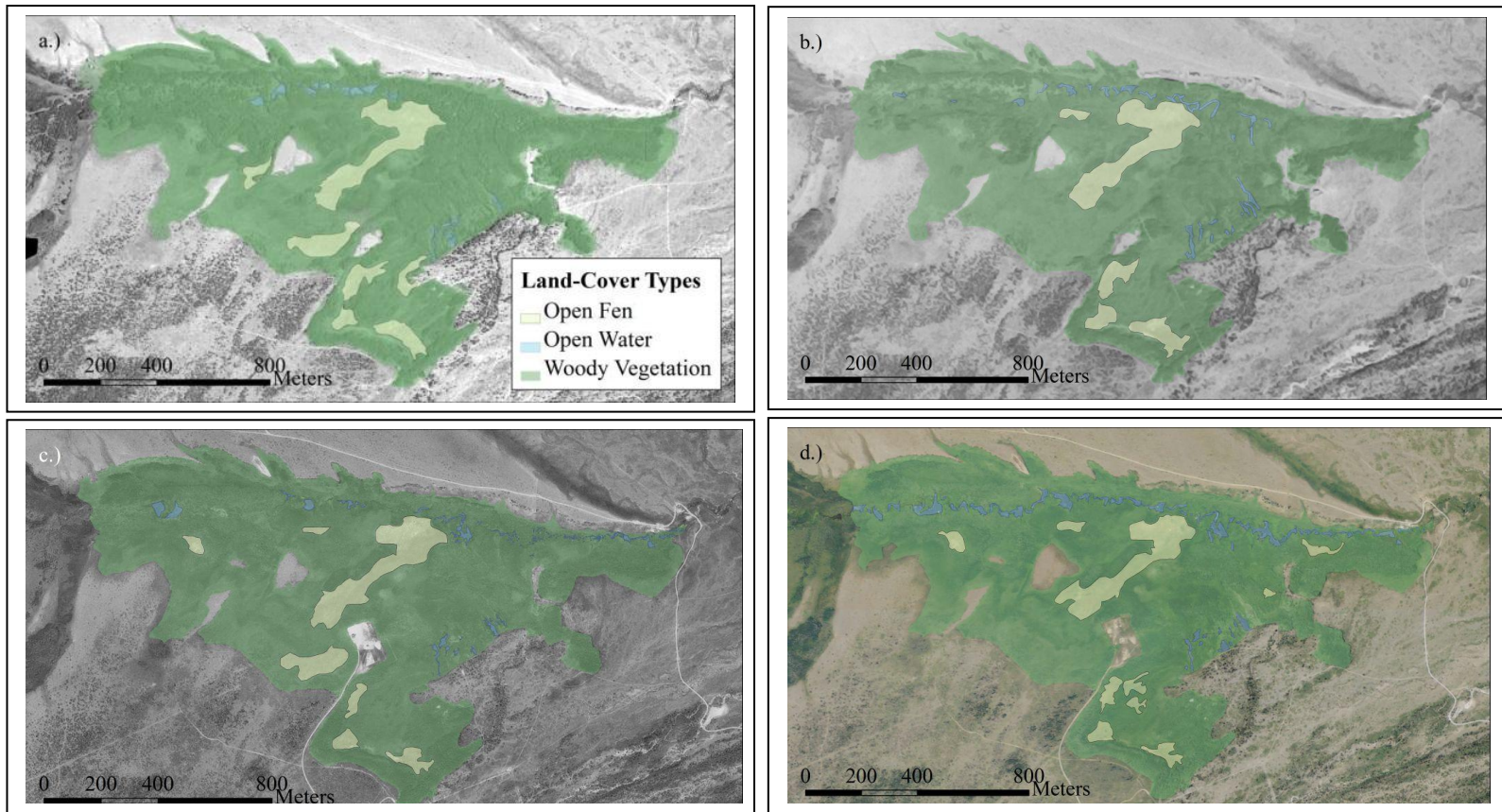


Figure 8. Change in the extent and land-cover types within the Cow Creek wetland complex between a) 1941, b) 1955, c) 1995, and d) 2009.

4.3 Blackleaf Wetland Complex

The Blackleaf wetland extends along Blackleaf Creek slightly downstream and east of the Cow Creek site. Blackleaf Creek complex exhibited little change (2.2%) in the overall area from 1941 to 2009 (Table 8). The main driver of change in this complex has been the influence of agriculture. Limited information was available regarding the agricultural practices at the Blackleaf Creek Wetland Complex, however, aerial interpretation revealed approximately 30% of the wetland was used for grazing or hay cultivation in 1941 (Table 8). By 2009 only 11.5% of the area showed disturbance. While TNC holds a conservation easement for this property, “traditional uses” may continue. Image analysis and ground observation revealed no areas of open fen throughout this complex (Figure 9). However, open water area increased 4.4% over the study period. Calculating the number of open ponds in this complex was too difficult due to the complex meanders of Blackleaf Creek (Figure 10); so quantification of pond occurrences was omitted from this site. All ponds were located either along Blackleaf Creek or in low-lying woody vegetation. Errors of 2.0, 1.0, and 0.4%, were found between 1941, 1955, 1995, and 2009, respectively, with an overall mean error of 1.1% due to orthorectification and digitization.

Table 8. Spatial change at Blackleaf Creek including total area, open water, open fen, woody vegetation, non-wetland/ agriculture, and percent change over time for each category from 1937 to 2009.

		Total Area		Vegetation Community							
				Woody Vegetation		Open Water		Open Fen		Non Wetland/ Agriculture	
		m ²	%	m ²	%	m ²	%	m ²	%	m ²	%
Photo Year	1941	2,964,999	100.0%	2,043,370	68.9%	36,094	1.2%	0	0.0%	885,763	29.9%
	1955	2,992,449	0.9%	2,115,403	70.7%	33,770	1.1%	0	0.0%	843,423	28.2%
	1995	3,034,003	2.3%	2,518,180	83.0%	70,300	2.3%	0	0.0%	445,523	14.7%
	2009	3,029,628	2.2%	2,547,918	84.1%	133,761	4.4%	0	0.0%	347,949	11.5%

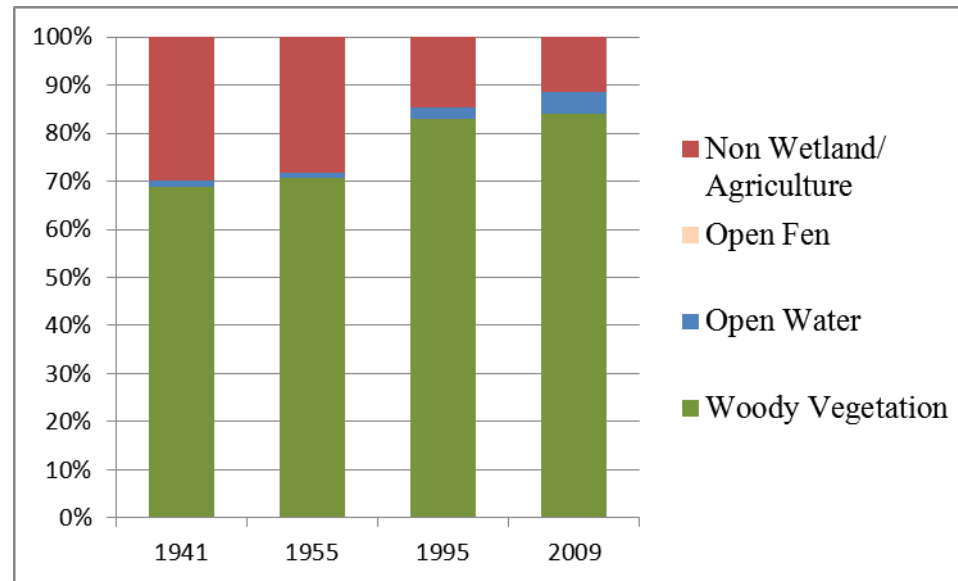


Figure 9. Percentage of land-cover types within the Blackleaf wetland complex from 1941 to 2009.

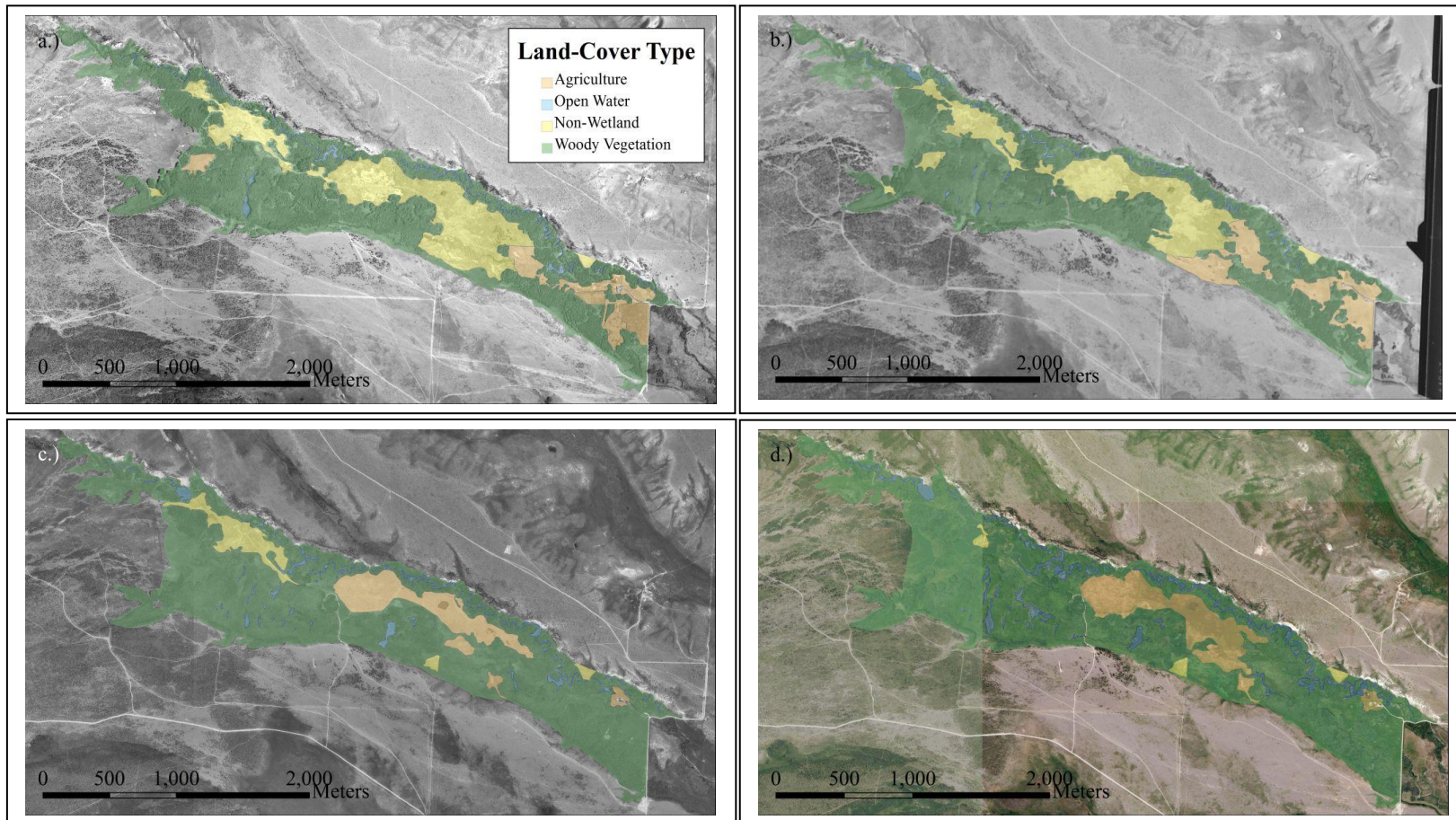


Figure 10. Change in the extent and land-cover types within the Blackleaf Creek wetland complex between a) 1941, b) 1955, c) 1995, and d) 2009.

4.4 McDonald Swamp

McDonald Swamp constitutes a large area of the Pine Butte Swamp Preserve. McDonald Swamp experienced a slight increase (1.4%) in total area throughout the study. Alterations in hydrology can be observed in McDonald Swamp as the number of ponds increased from 34 in 1937 to 92 in 2009, water area increased from 0.4% to 2.2%, and the ponds created by beavers changed some of the lower drainage depressions, and woody vegetation areas (Figure 12). Open fen can be observed in the western half of the Swamp and showed a slight decline in area (Table 9). Woody vegetation maintained similar levels since 1937 (Figure 11). Agriculture has played a heavy role in this area over time, with fluctuations from year to year based on crop utilization within the swamp, or outside its boundaries. Errors of 0.1, 1.7, and 1.4%, were found between 1937, 1953, 1995, and 2009, respectively, with an overall mean error of 1.1% due to orthorectification and digitization.

Table 9. Spatial change at McDonald Swamp including total area, woody vegetation, open fen, open water, non-wetland/ agriculture, number of ponds, and percent change over time for each category from 1937 to 2009.

		Total Area		Vegetation Community								Number of Ponds
				Woody Vegetation		Open Fen		Open Water		Non-Wetland/ Agriculture		
		m ²	%	m ²	%	m ²	%	m ²	%	m ²	%	
Photo Year	1937	7,088,713	100.0%	6,087,408	85.9%	549,914	7.8%	27,465	0.4%	423,926	6.0%	34
	1953	7,157,449	0.9%	6,083,508	85.0%	534,642	7.5%	72,784	1.0%	466,515	6.5%	33
	1995	7,033,493	-0.8%	6,360,741	90.4%	502,200	7.1%	101,964	1.4%	68,588	1.0%	83
	2009	7,188,219	1.4%	6,281,909	87.4%	499,449	6.9%	158,246	2.2%	248,615	3.5%	92

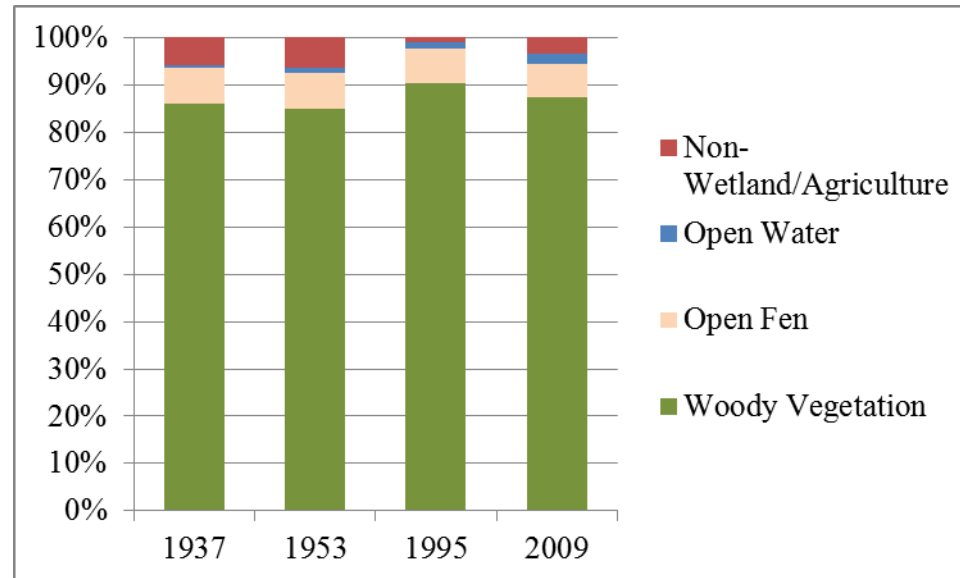


Figure 11. Percentage of land-cover types within the McDonald Swamp from 1937 to 2009.

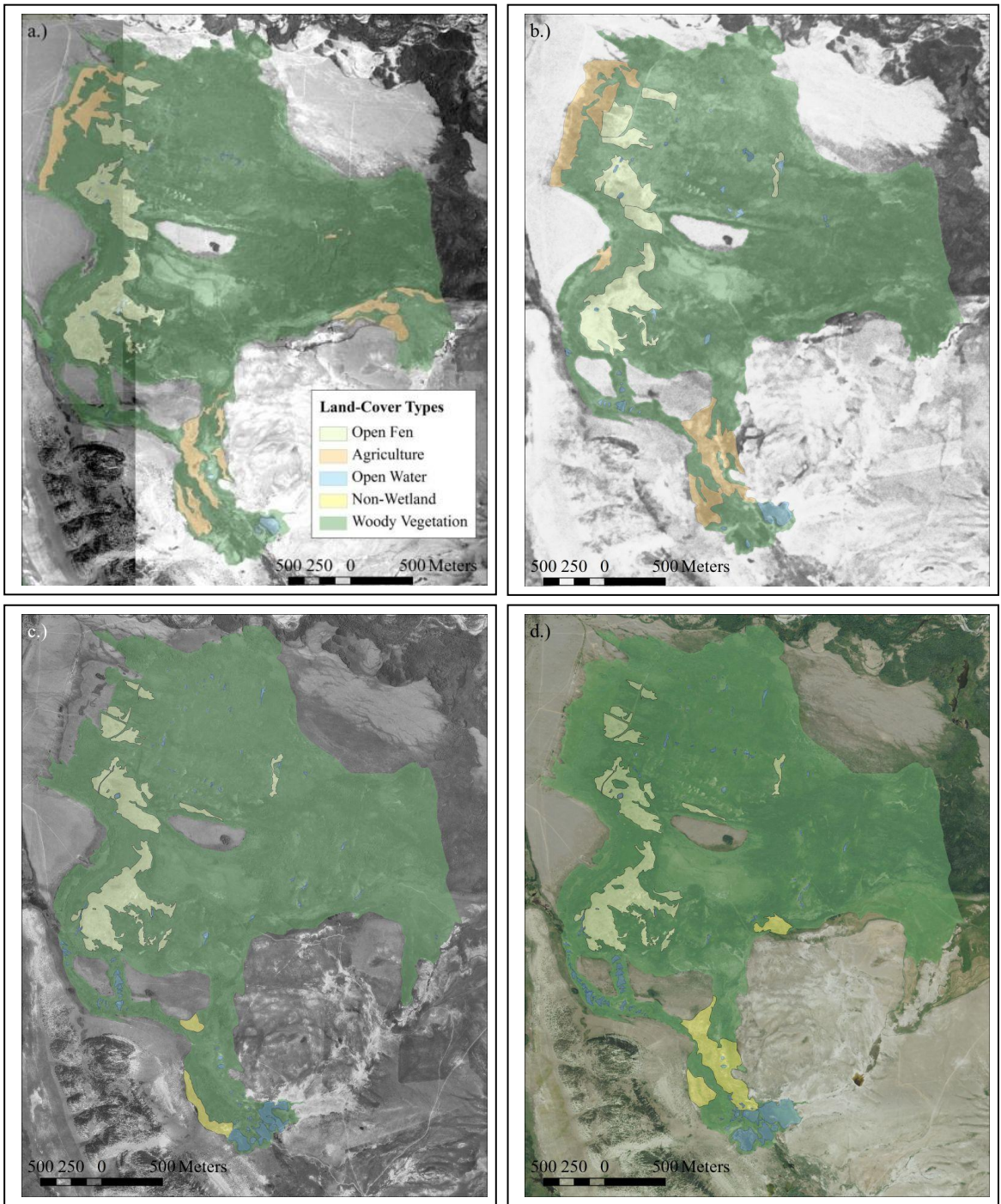


Figure 12. Change in the extent and land-cover types within the McDonald Swamp between a) 1937, b) 1953, c) 1995, and d) 2009.

4.5 Pine Butte Fen

The most established fen along the RMF, Pine Butte Fen is believed to be relatively stable (Figure 14). The total area of Pine Butte Fen saw a slight decline (-2.3%) since 1937 (Table 10). Woody vegetation also decreased slightly from 58.2% in 1937 to 55.1% in 2009. Area of open fen increased by nearly 2%, while open water nearly tripled in extent, although the latter only accounts for 1.9% of the fen (Table 10; Figure 13). The number of observable ponds increased from 33 in 1937 to 75 in 2009. Some ponds occurred within the open fen area, but most were surrounded by woody vegetation. A small private inholding in the northern portion of the fen comprises nearly one percent of the total wetland area in 2009. In 1937, 6.0% of the fen was agriculture, but that percentage dropped to 3.5% in 2009 but was categorized as non-wetland/ agriculture. From aerial interpretation in 2009, no visible agricultural practices were observed within that private inholding, but the area had not returned to woody vegetation or wetland. Errors of 0.1, 1.7, and 1.4%, were found between 1937, 1953, 1995, and 2009, respectively, with an overall mean error of 1.1% due to orthorectification and digitization.

Table 10. Spatial change at Pine Butte Fen including total area, woody vegetation, open water, open fen, non-wetland/ agriculture, number of ponds, and percent change over time for each category from 1937 to 2009.

		Total Area		Vegetation Community								Number of Ponds
				Woody Vegetation		Open Water		Open Fen		Non Wetland/ Agriculture		
		m ²	%	m ²	%	m ²	%	m ²	%	m ²	%	
Photo Year	1937	5,065,940	100.0%	2,949,278	58.2%	30,233	0.6%	2,058,411	40.6%	28,046	0.6%	33
	1953	5,102,405	0.7%	3,110,371	61.0%	40,421	0.8%	1,911,413	37.5%	40,200	0.8%	23
	1995	5,079,439	0.2%	2,941,130	57.9%	81,827	1.6%	2,026,937	39.9%	29,543	0.6%	45
	2009	4,947,993	-2.3%	2,724,135	55.1%	96,008	1.9%	2,103,826	42.5%	24,024	0.5%	75

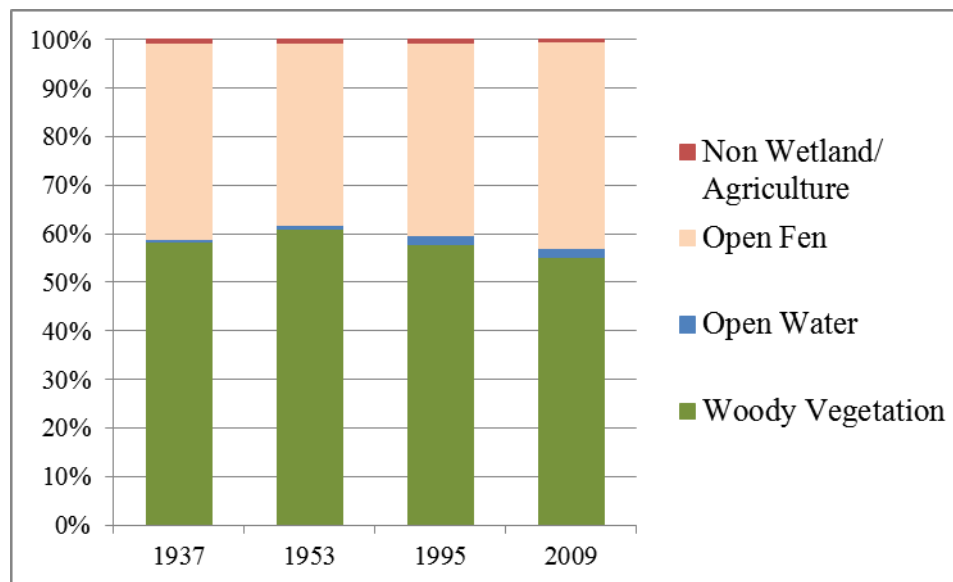


Figure 13. Percentage of land-cover types within the Pine Butte Fen from 1937 to 2009.

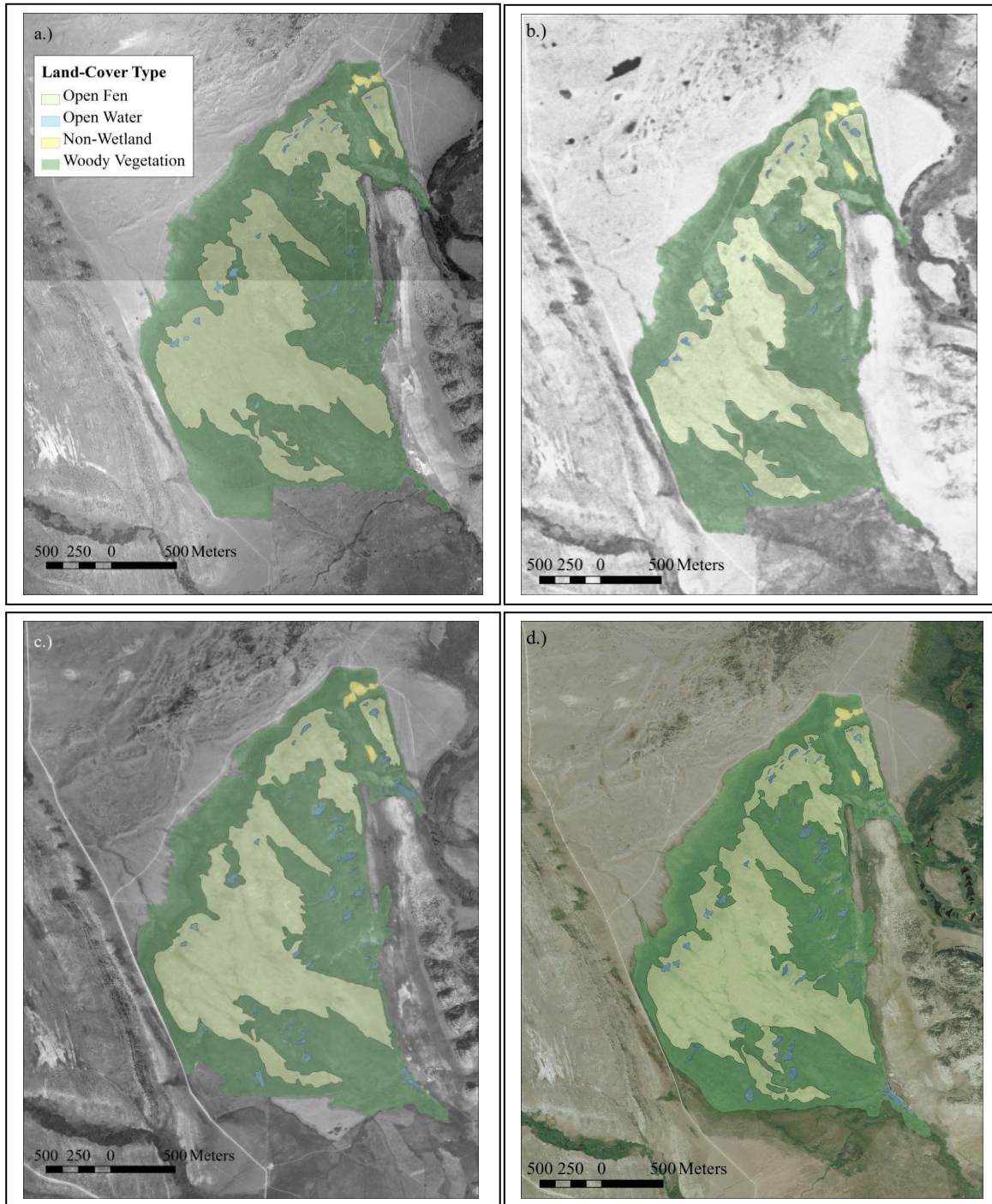


Figure 14. Change in the extent and land-cover types within the Pine Butte Fen between a) 1937, b) 1953, c) 1995, and d) 2009.

4.6 Wagner Basin Wetland Complex

The smallest peatland site along the RMF, Wagner Basin, saw a 5.8% decrease in total area from 1937 to 2009, though most of that change was from 1937 to 1995 with a recent slight rebound. This geographically isolated wetland on the Lewis and Clark NF showed a rise in open water from 1937 to 2009 (Table 11). Hydrologically, there was an increase in the number of pools, from one in 1937 to ten in 2009. The increase in open water resulted in a slight decrease in woody vegetation area. While peat was observed throughout the Wagner Basin area, no visible open fens were observed (Figure 15). Overall, the land-cover mosaic of Wagner Basin has stayed relatively unchanged, with the exception of increased open water (Figure 15 and 16). Errors of 0.2, 1.0, and 0.8%, were found between 1937, 1955, 1995, and 2009, respectively, with an overall mean error of 0.7% due to orthorectification and digitization.

Table 11. Spatial change at Wagner Basin including total area, woody vegetation, open water, open fen, number of ponds, and percent change over time for each category from 1937 to 2009.

		Total Area		Vegetation Community						Number of Ponds
				Woody Vegetation		Open Water		Open Fen		
		m ²	%	m ²	%	m ²	%	m ²	%	
Photo Year	1937	224,087	100	223,954	99.9%	133	0.1%	0	0.0%	1
	1955	212,057	5.4%	208,463	98.3%	3,594	1.7%	0	0.0%	2
	1995	207,467	7.4%	202,507	97.6%	4,960	2.4%	0	0.0%	6
	2009	211,064	5.8%	204,072	96.7%	6,992	3.3%	0	0.0%	10

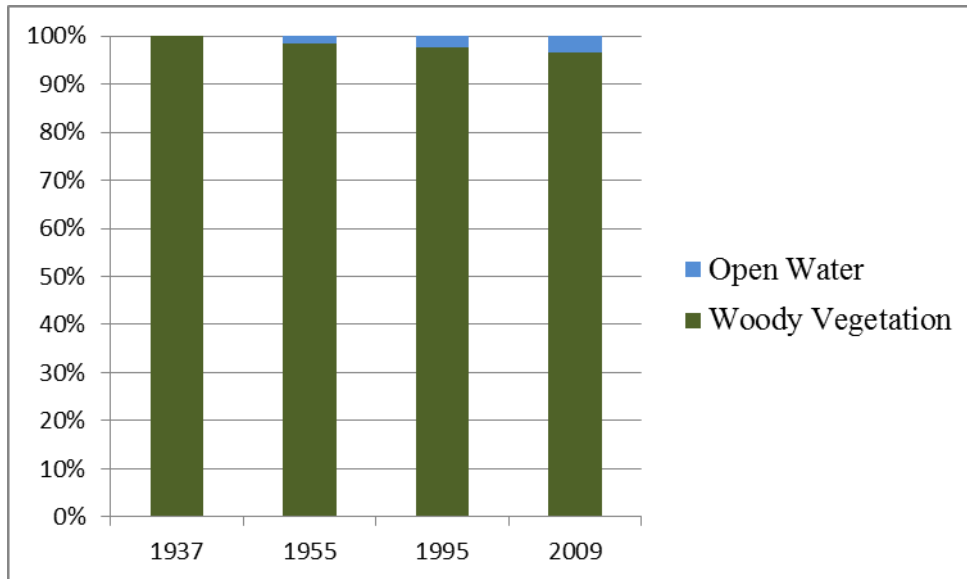


Figure 15. Percentage of land-cover types within the Wagner Basin Wetland Complex from 1937 to 2009.

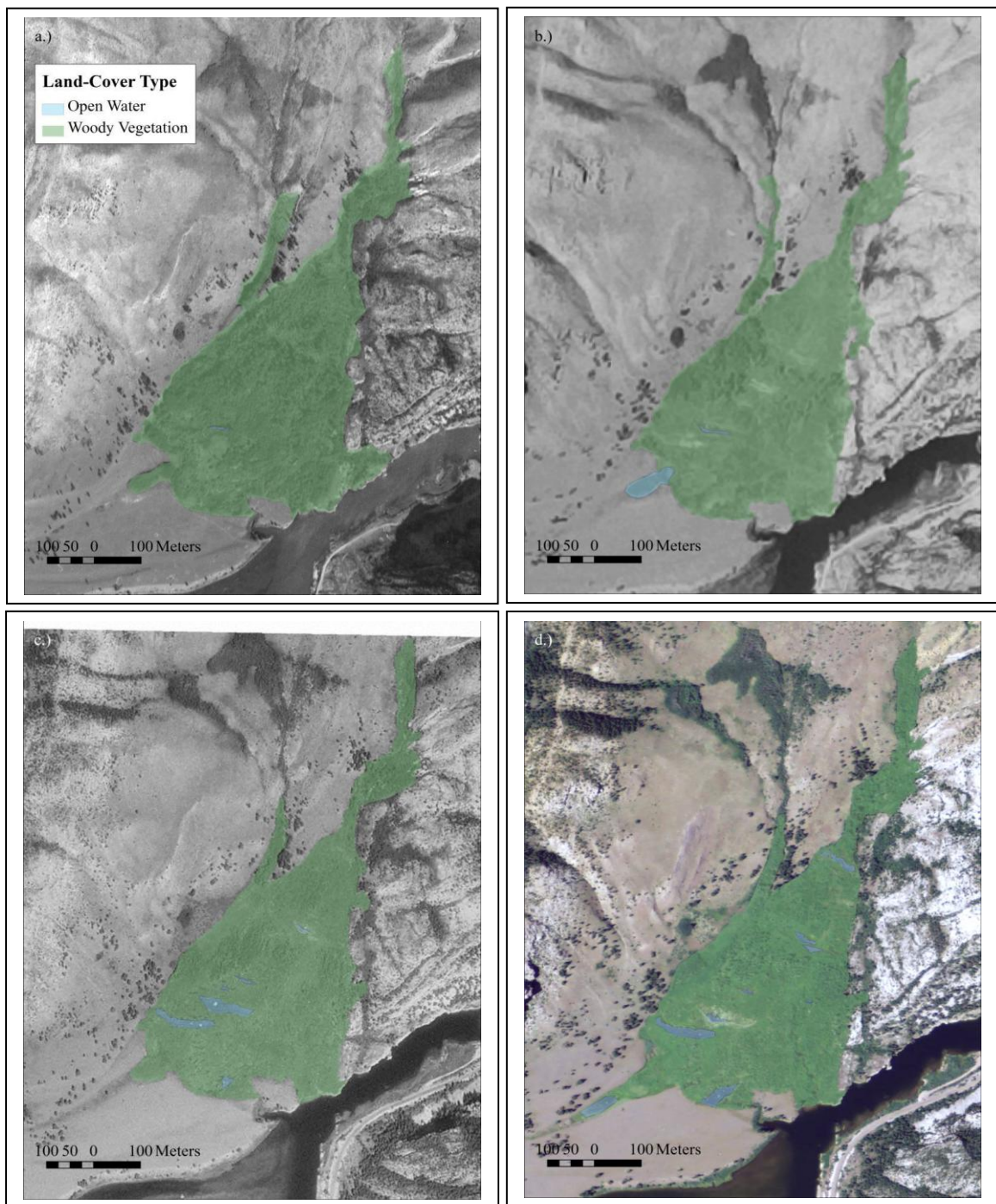


Figure 16. Change in the extent and land-cover types within the Wagner Basin wetland complex between a) 1937, b) 1955, c) 1995, and d) 2009.

4.7 Remaining RMF Peatlands

Three other peatlands along the RMF have been either highly altered by agricultural practices or had limited historical aerial imagery. These sites were included through analysis of the limited aerial images. The three sites include: Blackleaf Wildlife Management Area (BWMA) wetland, Bynum wetland, and Theboe Lake wetland.

The state-owned and managed BWMA wetland lacked the temporal scale desired for this study. However, the overall boundary was mapped with the available imagery and showed little spatial change from 1955 to 2009 (Figure 17). The BWMA areal extent covered 1.4 km² in 1955 and declined by 2.3% in 2009 (Table 12). While land-cover was not characterized for this wetland due to an incomplete aerial imagery record, little change was observed within the BWMA.

In contrast, Bynum and Theboe Lake wetlands have experienced large changes, are privately held, and TNC does not have conservation easements for them. The Bynum wetland decreased in total size by 68% since 1954, primarily due to agriculture (Table 12; Figure 18). Active cultivation continued on most of this fen in 2009.

The Theboe Lake wetland straddles the South Fork of Willow Creek, between privately owned ranches. Based upon analysis of aerial imagery, this wetland was heavily disturbed prior to the earliest images available (Figure 19). The area appears to have been drained sometime before 1937, as drainage ditches can be seen in both the 1937 and 2009 images, and extensive cultivation continued in 2009. The original areal extent appears to be as large as 3.8 km² prior to draining of the wetland (Figure 19). The current extent comprises less than 1% of the estimated original area.

Table 12. Spatial change in the Blackleaf WMA, Bynum Wetland from 1954 to 2009 and Theboe Lake Wetland from 1937 to 2009.

	Remaining Peatlands				
	Total Area, m²				Percent Change
	1937	1954/5	1995	2009	
Blackleaf WMA	NA	1,412,613	1,378,771	1,380,543	-2.3%
Bynum Wetland	NA	4,991,920	1,600,170	1,600,170	-67.9%
Theboe Lake Wetland*	88,851	NA	92,711	92,711	4.3%

*Aerial-photo interpretation of the earliest imagery indicates that Theboe Lake Wetland was 3.8 km² prior to 1937 but had already undergone extensive disturbance before the first available photograph.

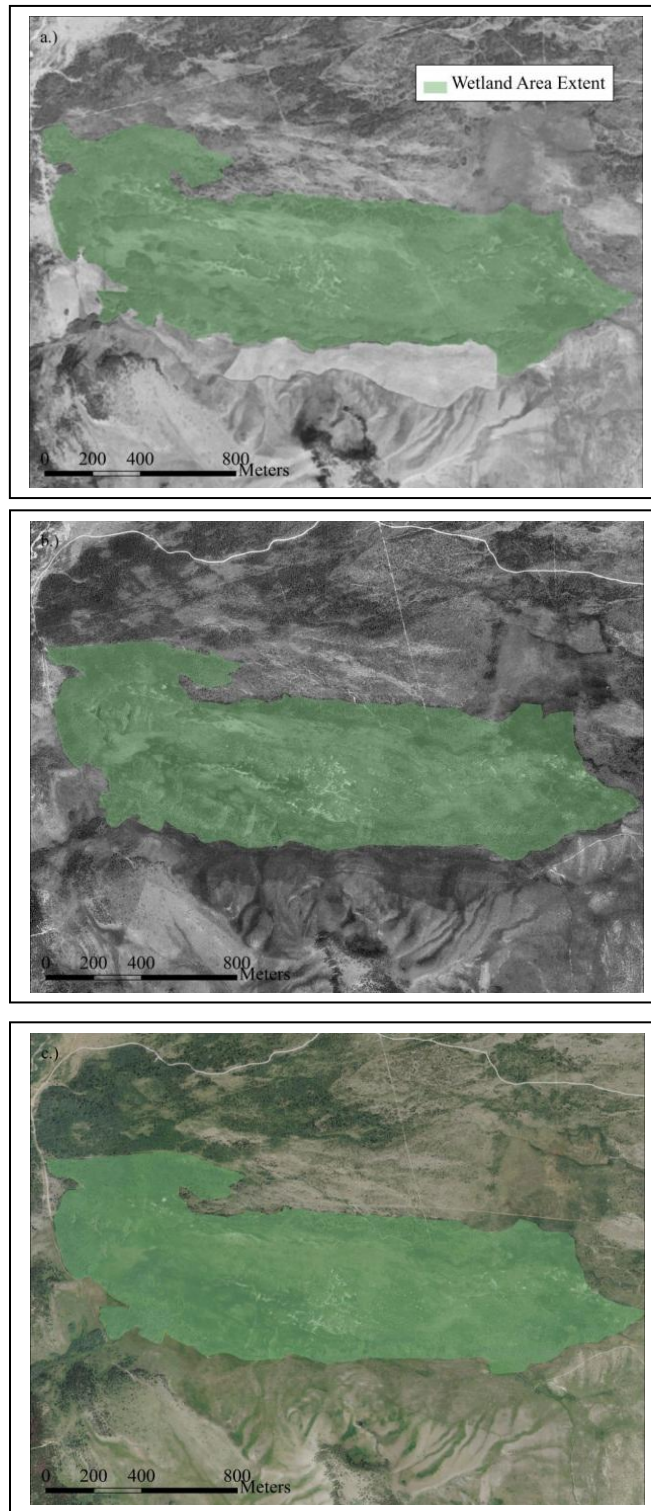


Figure 17. Change in the extent within the Blackleaf Management Area Wetland between a) 1955, b) 1995, and c) 2009.

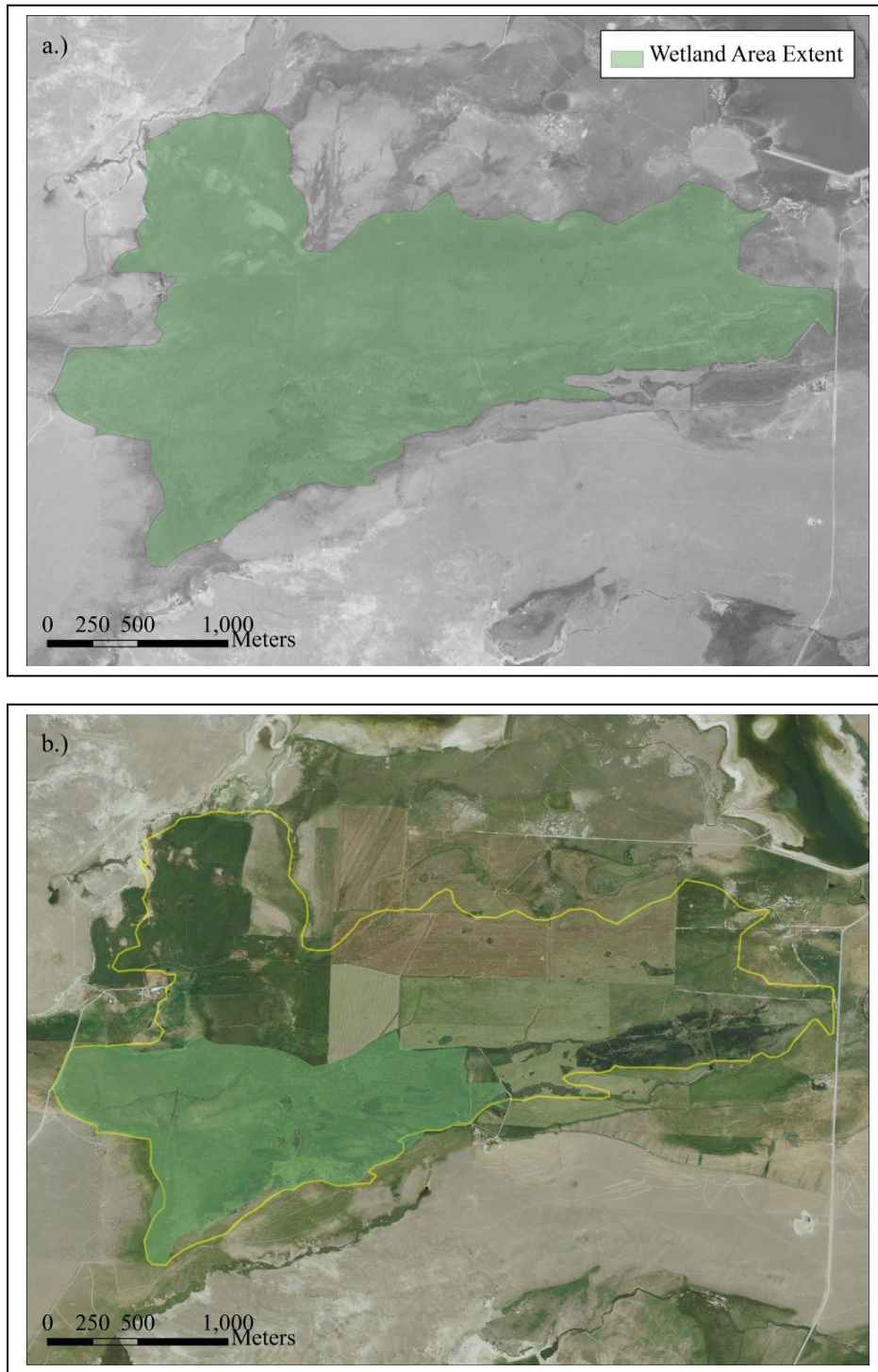


Figure 18. Change in the extent within the Bynum wetland area between a) 1954 and b) 2009 with yellow boundary delineating total area extent in 1954.

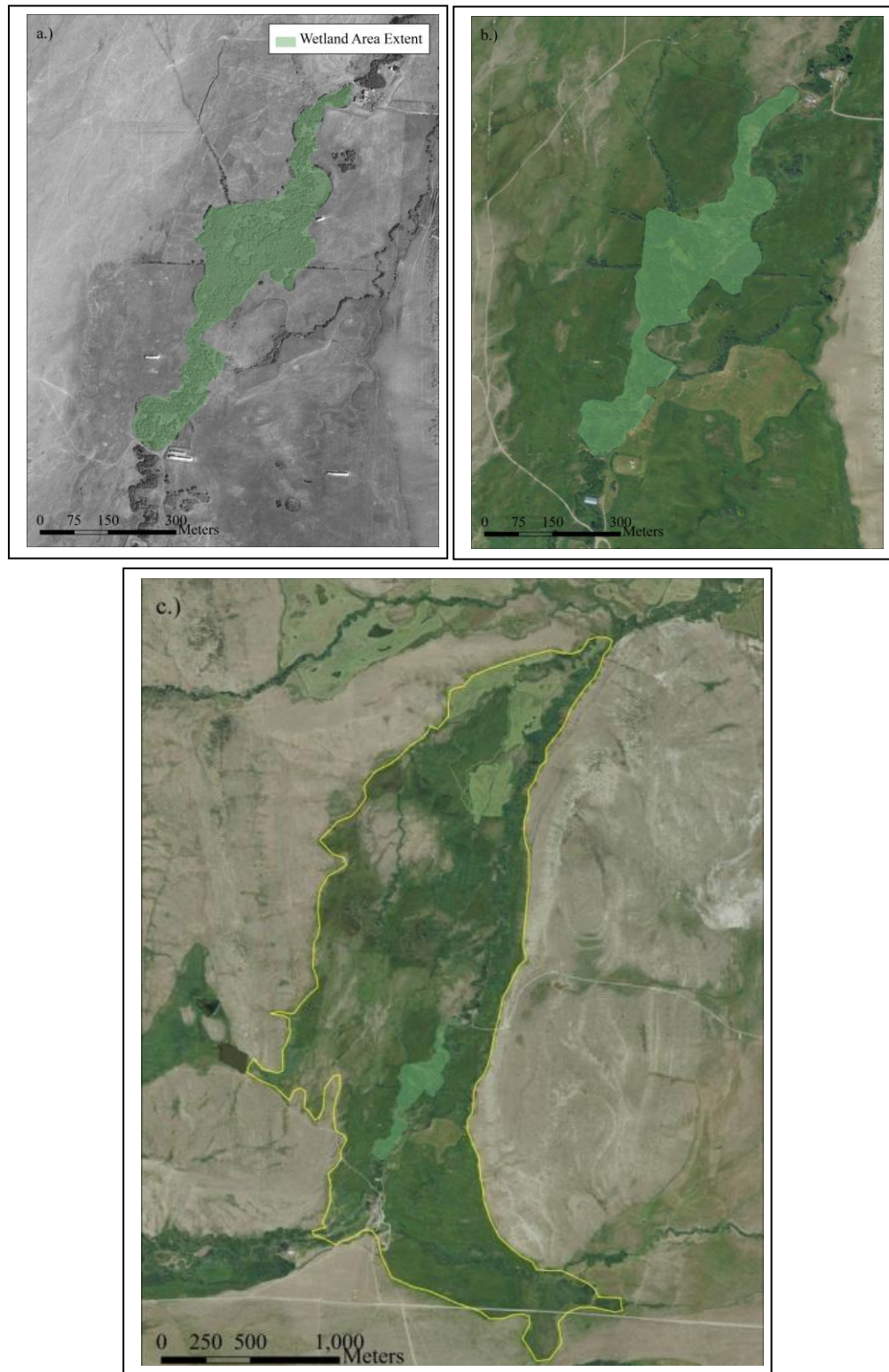


Figure 19. Change in wetland extent in the Theboe Lake wetland complex between a) 1937, b) 2009, and c) yellow boundary delineation of the estimated wetland area prior to initial cultivation.

5 DISCUSSION

Mapping the peatlands of the RMF provides a unique spatial perspective into the dynamic processes of these isolated ecosystems. By inventorying the change each system has experienced since the 1930s the following questions can be addressed: 1) did increasing temperatures correlate with slower lateral expansion rates of the Rocky Mountain Front fens, 2) did change in beaver presence or abundance correlate with changes in the distribution of vegetation community type within the fens, and 3) did decline in agricultural use of the Rocky Mountain Front fens correlate with increases in woody vegetation cover within the fens?

Regionally, little overall change was observed relating to the expansion or contraction of the peatlands, with the exception of losses related to agriculture. This stability reflects the importance of the groundwater supplying the peatlands of the RMF. Conversely, some change can be seen within the relative proportion of land-cover categories of each wetland system. The role of beavers and agriculture within each peatland revealed changing ecosystem mosaics. The following sections describe how the findings at each peatland can be integrated to address the research questions above.

5.1 Impacts of Increasing Temperatures

The direct impact of increasing regional temperatures as stated by Pederson et al. (2010) did not correlate with the expansion of the RMF peatlands. At the landscape level, the total area of intact peatlands measured since 1937 have increased in size by less than one percent (Figure 4; Table 5), which is less than the error associated with orthorectification and digitization. While some change in the hydrology and vegetation

within each fen were documented, essentially no change in the total area was observed, except those related to introduction or cessation of agriculture. This lack of spatial change is important given the context of increasing temperatures in the region. It also reaffirms the importance of groundwater in these arid RMF peatlands.

Nimick et al. (1983) and Wiley (1991) document the importance of the Teton River as a groundwater source for the Pine Butte Fen and McDonald Swamp. Their work concluded the river loses approximately 25% of its annual surface flow as the river cuts through the Pinedale glacial moraine upstream from the two fens (Nimick et al., 1983; Wiley, 1991; McCallister, 1990). This source of groundwater is especially important considering the substantial deficit of precipitation relative to evapotranspiration at the Pine Butte Fen (Figure 2). Nimick et al. (1983) stated the Pine Butte Fen and McDonald Swamp have maintained the same areal extent throughout abnormally wet and dry years. One local resident agreed with this conclusion and stated that water levels do not change in wet and dry years (Nimick et al., 1983). However, areas in the central and eastern portions of McDonald Swamp are not underlain by peat and may see some fluctuations in the water table (Nimick et al., 1983).

The largest threat to the fens of the RMF would result from alteration of the groundwater regime. Studies have deemed this threat as highly unlikely to naturally occur in the immediate future due large floods in 1964 and 1975 which scoured away most of the silt that could have decreased permeability in the unconsolidated gravel (Reichmuth, 1981; Nimick et al. 1983).

Declining snowpack in the adjacent mountains could reduce groundwater recharge in the long term. The size of the regional aquifer is difficult to quantify and no

prior studies have mapped its extent. However, mountain snow is almost certainly key to the aquifer and increasing regional temperatures leading to earlier spring snowmelt and runoff, could affect the RMF peatlands in the future.

5.2 Impact of Beaver Recolonization

Beaver activity can have a significant role in peatland hydrology and species distribution. Periodic beaver activity creates and maintains a series of successional stages within a wetland complex and contributes to the habitat and floristic diversity of peatlands (Bursik & Moseley, 1995). Crenshaw (1979, 36) states “beavers have undoubtedly played an important role in the evolution of Pine Butte Swamp.” Section 2.1.5 summarizes two studies in nearby Glacier National Park and Yellowstone National Park that document that beavers were prominent throughout each park until a rapid decline in the early to mid-1900s. Meanwhile, Crenshaw’s (1979) beaver population census contains the only records for any of the peatlands of the RMF.

In the past, trapping beavers and other fur-bearing mammals in Pine Butte was a profitable enterprise (Crenshaw, 1979). Furbearer harvesting could comprise one component of a rancher’s income on the RMF as average pelt prices ranged from \$11.35 to \$16.74 throughout the 1970s. High fur values led to the trapping of hundreds of beavers in Pine Butte Fen until 1979 when it was purchased by The Nature Conservancy. From 1970 to 1978, local resident Bud Jackson, alone, trapped 465 beavers, almost exclusively from Pine Butte Swamp (Crenshaw, 1979). Crenshaw’s (1979) study estimated a mean annual beaver population of 86.7 beavers, revealing rebounding beaver populations following their near extirpation in the early 1900s. Crenshaw speculated that

a “halt of trapping in the swamp” would eventually lead to an increase in the local population (Crenshaw, 1979, 43).

The abundance and influence of beavers on the landscape can be seen within each peatland along the RMF. Each of the six fully examined sites revealed increases in open water, and at each site where they could be mapped, increases in the number of ponds (Table 5; Figure 20). Ground observations of each site revealed countless beaver dams, lodges, signs of beaver herbivory, and other disturbances from beaver activity were widespread in the field. While the resolution of aerial images available for this study was not sufficient to map individual dams and lodges, their impact is clearly evident in the imagery from 1995 and 2009.

Analysis from this thesis shows that across the RMF, the largest change in the number of ponds was sometime between the 1950s and 2009 (Figure 20). Ponds mapped for Crenshaw’s survey in 1979 reveal similar relative locations and distribution of ponds to those observed from this study’s 1995 and 2009 imagery. Forty one ponds were located by Crenshaw’s survey within Pine Butte Fen, with a total of 68 ponds including the area near North Fork of Willow Creek and a small portion of McDonald Swamp. This study counted 45 open ponds within Pine Butte Fen in 1995. From airphoto interpretation, ground observations, and assessment of regional trends it is apparent that almost all of pond formation over the last six decades within the RMF peatlands are associated with beaver activity.

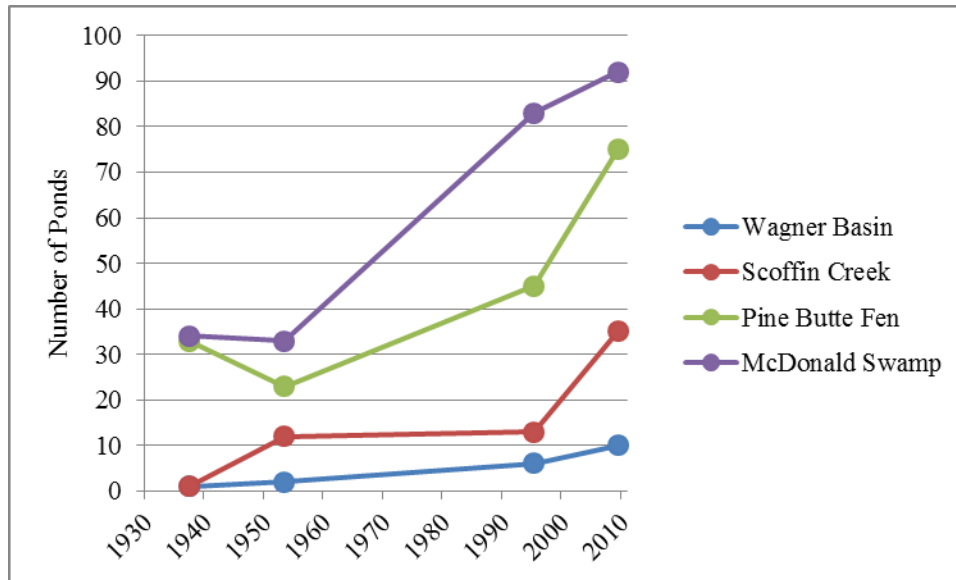


Figure 20. Number of ponds observed within the Wagner Basin Wetland, Scoffin Creek Wetland, Pine Butte Fen, and McDonald Swamp from 1937 to 2009.

Scoffin Creek and Wagner Basin could have been especially prone to the trapping and decimation of beavers in the early 1900s, as they represent the smallest peatland systems along the RMF; limiting the amount of resources available, as well as shelter from trapping and predators. Results indicated both Scoffin Creek and Wagner Basin had one pond in 1937 and now have 35 and 10, respectively. Meanwhile, larger peatlands such as Pine Butte Fen and McDonald Swamp represent the two largest wetland areas with abundant resources to support a substantial beaver population.

The influence of beaver damming and creation of new ponds may have led to a raised water table along the Scoffin Creek depression, where the total wetland area increased by 13%. The increase in ponds, however, had little effect on the areas of open fen which are located along a raised ridge dissecting the two creek tributaries which comprise the wetland complex. While no surveys have inventoried the number of

beavers in the Scoffin Creek drainage, observation of active lodges by the author in 2012 revealed the significant influence of beavers on this particular peatland.

With the exception of Pine Butte Fen, nearly every pond within the peatlands occurred along creeks (e.g. McDonald Swamp, Cow Creek, and Blackleaf Creek) or in areas surrounded by woody vegetation. This may be attributed to the availability of suitable vegetation for building dams and lodges, in contrast to the open fen areas which are vegetated mainly by graminoids and bryophytes.

5.3 Impacts of Agriculture

The peatlands of the RMF are located along or near riparian waterways where nutrient-rich groundwater resurfaces. These isolated areas within an otherwise arid to semi-arid landscape are thus an important resource for ranchers. In 1976, The Nature Conservancy (TNC), realizing the importance of these wetlands as corridors for the wildlife and refugia for rare flora, purchased Montana's first conservation easement along the RMF. Soon after, in 1979, TNC purchased the Pine Butte Swamp Preserve, consisting of most of Pine Butte Fen and McDonald Swamp. By 2010, TNC had protected 173,000 acres of private land along the RMF (TNC, 2010) through direct purchase or conservation easements.

Bynum and Theboe wetlands reveal what may have occurred across the RMF without landscape-scale conservation efforts by The Nature Conservancy, The Conservation Fund, and the U.S. Fish and Wildlife Service (Figure 18 and 19). Backed by an effort to support grizzly bear habitat and ensure historic wildlife corridors stay intact, the groups launched the Rocky Mountain Front protection campaign in 2007 to acquire conservation easements on up to 250,000 acres of private land (TNC, 2010).

Conservation easements along the RMF have allowed ranchers to maintain their agrarian uses of the land for cattle grazing and cultivating hay without pressures from outside entities looking to purchase or further develop the land. Custom agreements are made with each landowner, in which a conservation group generally pays 40 to 45% of the value of the property (TNC, 2010). In return, the landowner agrees to use traditional agricultural practices on the land while also maintaining the local wildlife habitat. It should be noted that conservation easements do not prevent ranchers from cultivating their land; however, by maintaining beneficial wildlife habitat, analysis suggests agricultural disturbances are not as widespread as they once were (Figure 21).

Agriculture at Blackleaf Creek, Pine Butte Fen and McDonald Swamp declined by over 50% (Table 5) from 1937 to 2009. In 1937, agriculture or non-wetland areas comprised 8.0% of the total area of peatlands, and by 2009 that number dropped to 3.7% (Figure 21). In contrast, woody vegetation consisted of 75.3% of the land cover in 1937 and increased to 77.7% in 2009. This increase can partially be attributed to ranchers limiting grazing activities along riparian areas; however, open water also increased. The effects of conservation easements on the RMF peatland landscape has also made a noticeable difference in the restoration of creek drainages and near established open-fen areas (TNC, 2010). However, as seen in the southern reach of the McDonald Swamp site (Figure 11), some areas used for agricultural purposes in 1937 and 1953 have not recovered to wetland vegetation as of 2009.

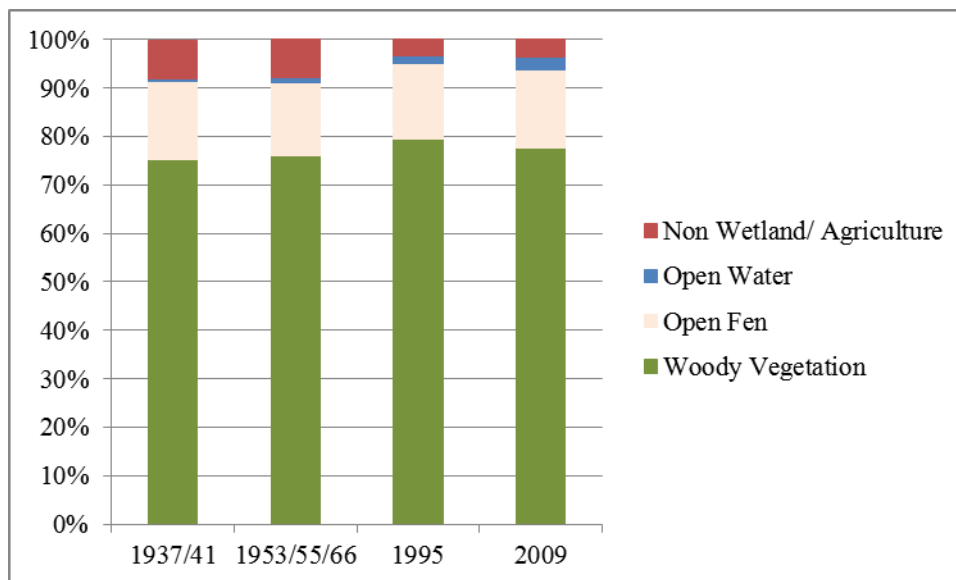


Figure 21. Overall change in distribution of land-cover types within the RMF peatlands from 1937 to 2009.

The decrease in agriculture may have resulted from land management changes that the RMF has seen since the 1990's with increasing adoption of conservation easements between the Nature Conservancy and landowners. The Blackleaf Creek Wetland Complex is currently owned by two private parties, but two conservation easements covering a majority of the Blackleaf Creek Wetland Complex were adopted in 1996 and 2000, respectively. Land-use changes from conservation easements would not have been observed until the 2009 imagery, however, results suggest that agricultural practices in this wetland were already declining in 1995, comprising 14.7% of the wetland complex, down from 28.2% in 1955 (Figure 22).

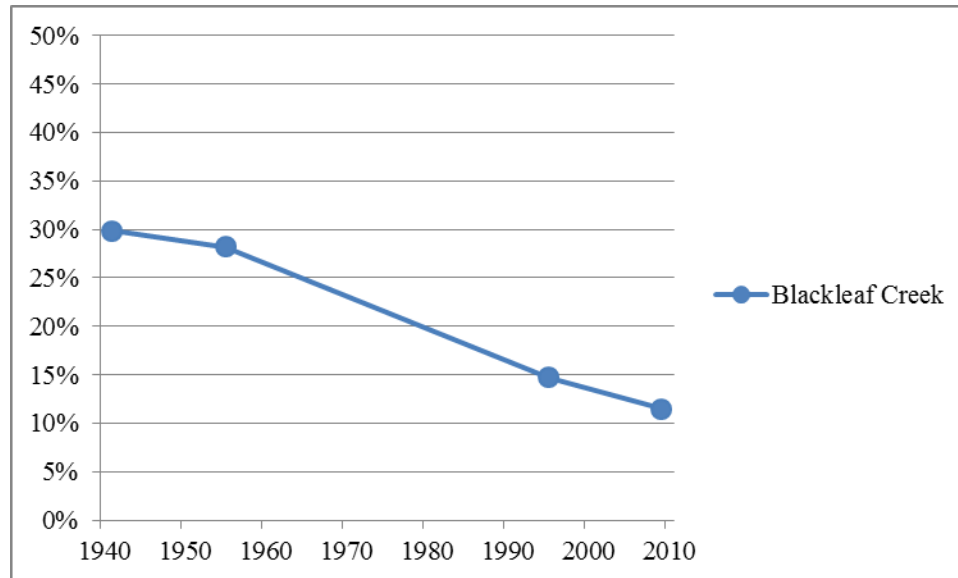


Figure 22. Percentage of agriculture or non-wetland area in the Blackleaf Creek Wetland Complex from 1941 to 2009. This land had two owners, but is under two conservation easements owned by The Nature Conservancy.

Together, McDonald Swamp and Pine Butte Fen make up the Pine Butte Swamp Preserve. These two large wetlands have been primarily owned by the Nature Conservancy since 1979, but there are still small private inholdings along the boundaries of the respected wetlands. The Nature Conservancy has used this land primarily as a refuge and for research since 1979. Agriculture is not the primary use for this land, as opposed to the Blackleaf Creek Wetland Complex. However, in the earliest imagery, agricultural disturbances could be seen in the northwest corner of McDonald Swamp near an area that was drained (ditches can still be seen in 2009 images) to water adjacent fields and along the southern drainage.

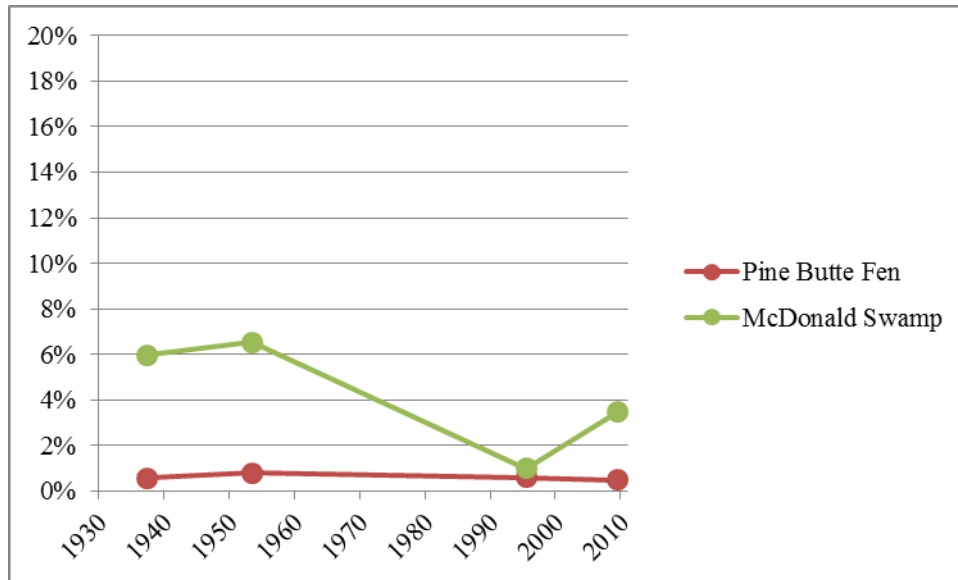


Figure 23. Percentage of agriculture or non-wetland area in the Pine Butte Fen and McDonald Swamp from 1937 to 2009. This land has been primarily owned by the TNC since 1979.

Analysis of the Theboe Lake wetland suggests little has changed from 1937 to 2009. However, the estimated area prior to agricultural usage suggests that a significant wetland has been lost. This estimate was based on the amount of wet areas visible in the 2009 images which may have been a wetland ecosystem in the early 1900s approximately 80% the size of Pine Butte Fen and Bynum wetland at that time.

6 CONCLUSIONS AND FUTURE RESEARCH

Nine peatlands were mapped for this study, with six intact sites having images available from 1937 and 1941, respectively. Each unique peatland had varying and contrasting characteristics of size, land-cover types, and amount of natural and anthropogenic disturbance. Examination of the aerial photos reveals that the total area of RMF peatlands has had very little change in overall area despite rising temperatures, reflecting the close relationship of these fens to their groundwater sources. Yet, every site has undergone hydrological change due to the rebound of beaver populations, with increased open water area and more ponding. Hydrologic alterations from beaver dams modified the spatial extent of most of the fens and the distribution of vegetation classes within their peatland boundaries. Conservation purchases and easements have led to dramatic differences in these peatlands and demonstrate both failures and success in the conservation of these unique and ecologically important resources.

Examination of the lateral expansion of the peatlands throughout the RMF shows little overall change since 1937. Therefore, increasing regional temperatures have not played an important role in the expansion of these systems over the time period of this study. This stability also reaffirms the importance of groundwater supplying these peatlands, as well as their upland watersheds. Further study is needed to predict the impacts declining snowpack and earlier spring runoff may have on the supply of groundwater upon which the RMF peatlands rely.

The effects of beavers on the peatland landscape are demonstrated by an increase in open water area and the number of ponds. Based upon aerial photo interpretation, ground observations, and regional trends, this study indicates that almost all of the new

ponds in the peatlands are due to beaver activity. With an abundance of woody vegetation available, beavers will continue to engineer the landscape. Increasing numbers of ponds and open water could also lead to increasing water table heights in depressions and basins, allowing more open fen to accumulate and expand laterally within the peatland boundaries. While no indication was seen of a loss of open fen due to beaver activity, it is possible that their efforts could change the hydrology to the detriment of open fens. Careful monitoring of the beaver impacts on these peatlands should continue as populations recover.

Finally, land management has changed dramatically along the RMF since The Nature Conservancy initially purchased the Pine Butte Swamp Preserve in 1979. The RMF still predominately supports an agrarian lifestyle, but the past twenty years has seen increasing development pressure. Conservation easements, now widespread across the RMF, allow ranchers to maintain their traditional uses of the landscape, and while they do not prevent all disturbance of peatlands, they do limit subdivision and oil development. Blackleaf Creek Wetland, McDonald Swamp, and Pine Butte Fen demonstrate the benefit of conservation easements and riparian area restoration. Conversely, Theboe Lake wetland and the Bynum wetland display the loss of riparian corridors which may be beyond restoration.

This study quantified the visible impacts of agriculture on the peatlands of the RMF and provided context for future conservation of these ecosystems. The potential for recovery of any of these disturbed peatlands to a natural condition is one area that needs further analysis. It is possible that these disturbances have permanently altered the soils and hydrology needed for peat accumulation. Peatland development can take thousands

of years, so observation of recovery of these systems with the timeframe available in this study period was unlikely.

Much of the public attention surrounding these rare, isolated ecosystems has been centered on maintaining healthy habitat for ungulates, endangered grizzly bears, and threatened gray wolves. Relatively little attention has been directed towards the rare flora and unique peat that has accumulated for nearly 2000 years, though important scientific research has been and continues to be done. Further field studies including rare plant inventories, peat coring, and monitoring of beaver populations could increase the understanding of these rare systems, and allow land management practices to evolve accordingly.

The rare flora and accumulation of peat that occurs in peatlands are some of their most interesting traits. The scale of the available imagery for this project limited the ability to analyze the occurrence of rare plants and simply attempted to map the open peat “fens” with the best available knowledge and photo interpretation techniques. However, intensive ground surveys are necessary to map the exact location of rare plant species, as well as the exact extent of peat within each system.

Peat cores from Pine Butte Fen date the initiation of peat deposits to around 1850 BP, which could also be true for other sites along the RMF (Lesica correspondence, 1987). Collecting peat cores throughout each fen would provide better insight into the actual rate of expansion of peat, and potential lateral or vertical changes.

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