INVENTORY OF PEATLAND SYSTEMS IN THE BEARTOOTH MOUNTAINS

SHOSHONE NATIONAL FOREST, PARK COUNTY, WYOMING

Prepared for:
Environmental Protection Agency
Region 8, Denver, Colorado

By: Bonnie Heidel and Eli Rodemaker
Wyoming Natural Diversity Database
University of Wyoming
Dept. 3381, 1000 E. University Avenue
Laramie, WY 82071

March 2008

In cooperation with the Shoshone National Forest
and the Wyoming Geographic Information Science Center

ABSTRACT

Peatland systems are extensive and numerous in the Beartooth Mountains of Wyoming. Peatlands were systematically inventoried across 212 mi². Over 2.1 mi² of potential peatland habitat at 326 sites were identified by a standardized photointerpretation and digitization process using digital color infrared aerial photography of the National Aerial Photography Program. Field-testing fine-tuned the photointerpretation, and 105 confirmed peatland sites representing over 75% of the area have been field verified. An attribute table linked to the Geographic Information System peatland shapefile was developed for all potential peatland sites, and expanded for storing field survey results.

Beartooth Mountains peatland systems are minerotrophic fens, most are circumneutral, and fen sites at the extremes of pH are extremely rare. The majority of fen sites formed in basin-filling processes, but there are also fens in a wide variety of sloping settings. The majority of fen vegetation structures are graminoid-dominated. Three main habitat patterns associated with peat-forming processes can be discerned on aerial photographs of the study area and were identified as consistent indications of well-developed peatland systems. These diagnostic signatures in addition to size and presence of open water zones were used to develop a peatland ranking confidence score to prioritize unsurveyed sites and compare relative attributes of surveyed sites.

Remote-sensing was simultaneously conducted to develop an efficient way to replicate the field verification of peatlands. A Classification and Regression Tree model approach (CART) was applied using ASTER satellite imagery, derived image variables, and topographic variables such as elevation, terrain slope angle, and terrain slope aspect. Eleven classification tree models were run using spectral signatures and environmental parameters to discriminate the five structural vegetation classes of peatlands: graminoid, shrub, tree swamp, aapamire, and floating mat from upland types. The best model had errors of omission and commission that reflect on gaps in the training data used in model development.

The peatland mapping results were compared in a digital analysis with National Wetland Inventory (NWI) mapping of peatland vegetation that was not available at the start of the project. NWI mapping of the saturated peat unit successfully mapped peat-forming zones with great accuracy at most high-ranked peatland sites confirmed in this study. Other differences are explained in errors of omission and commission by NWI and by this study. Application of NWI mapping and CART modeling are presented as complementary tools that can inform peatland field survey in the Rocky Mountains, with opportunities for enhanced performance identified. Essentially, this study provides a methodological framework for tailoring the remote sensing tools to the array of peatland features in a given study area, taking advantage of a fieldwork feedback loop to refine the photointerpretation and other remote sensing processes.

Report citation: Heidel, B. and E. Rodemaker. 2008. Inventory of peatland systems in the Beartooth Mountains, Shoshone National Forest, Park County, Wyoming. Prepared for:
Environmental Protection Agency. Wyoming Natural Diversity Database, Laramie, WY 82071.

Cover photo: Mud Lake Fen, by Bonnie Heidel.

TABLE OF CONTENTS

TABLES AND FIGURES

APPENDIX

INTRODUCTION

Study Overview

The goal of this study was to document peatland systems in the Beartooth Mountains. A standardized photointerpretation was developed and field-tested, and the groundwork was laid for a Geographic Information System (GIS) remote sensing methodology. The final product is a consolidated peatland database linked to GIS as documentation of peatland distribution and attributes.

Peatlands are recognized as wetlands having critical functions that cannot be protected through mitigation (USDI Fish and Wildlife Service – Region 6 1998, 1999; USDA Forest Service 2002). Information on this key wetland resource was scant in Shoshone National Forest, and in the Beartooth Mountains study area in particular, where there was the highest known concentration of rare peatland species and peatland types in Wyoming. Thus, information on peatland distribution, extent, environmental settings, and the full array of biological resources were sought.

Study Background

Prior to this study in 2000, there were six peatland sites recognized in the study area that were reported as having high botanical significance, representing the widest known array of peatland types in Wyoming, and among the highest known concentrations of peatland sites and concentrations of rare plant species in Wyoming. The six peatland sites were initially identified and evaluated in the course of botanical collecting (Evert 1982), as part of research natural area and special botanical interest area reports (Evert 1984, Fertig and Jones 1992, Jones and Fertig 1999), from the geological literature (Pierce 1961), and in surveys conducted for highway corridor mitigation purposes (ERO Resources Corporation 2000).

The results of these studies were taken in combination with peatland studies of western Montana and northern Idaho and the Wyoming Natural Diversity Database occurrence records at the time to prepare a list of peatland indicator plant species, i.e., species that are partially or exclusively restricted to peatland habitat as present in northern and central Rocky Mountain states. The peatland indicator species include many USDA Rocky Mountain Region Forest Service sensitive plant species and other Wyoming species of special concern (hereafter referred to as rare plant species), including 18 sensitive species (30% of the current Region 2 list) and 47 species of concern (10% of the current list; Heidel 2006; with 2007 updates). The rarest elements of the peatland flora tend to be restricted to peatland habitats. The fact that peatland indicator plant species of the Beartooth Mountains were much more widely distributed than the six recognized peatland sites suggested that peatland systems may be more widely distributed than known at the time.

The six peatland sites were revisited in pilot peatland studies on the Shoshone National Forest (Heidel and Laursen 2003a, Mellmann-Brown 2004). In tandem, pilot studies were conducted on the Medicine Bow National Forest (Heidel and Laursen 2003b). The purposes of these pilot studies were to document and compile information on the peatland flora and the vegetation, and evaluate the local fidelity of peatland rare species to peatland habitats. The high fidelity of most rare peatland indicator species as peatland obligates in the Rocky Mountains, and their overlaps in distribution, suggested that peatland inventory was a more effective way to locate rare peatland species than single-species inventories or models of species' potential distributions (e.g., Beauvais and Smith 2005).

Therefore, extensive peatland surveys were pursued, first in the Medicine Bow Range and Sierra Madre using color aerial photography of the U.S. Forest Service – Medicine Bow National Forest and detailed soils mapping that contained histosol units (Heidel and Thurston 2004). As a result, 154 peatland sites totaling over one square mile of peatland were documented over approximately 150 square miles. It was concluded that peatlands of the Medicine Bow National Forest are more common than previously known, while the rare plant species within them were only found in the more unusual types or well-developed habitats.

At the same time, pilot remote-sensing work was conducted in the Beartooth Mountains study area using Landsat imagery and ERDAS Imagine software (v. 8.6; Leica Geosystems) to locate peatland sites (Heidel and Smith 2004). The results suggested that infrared spectral bands or related enhancements may be useful for distinguishing peatland systems but that further analysis was needed. The present study was initiated to improve peatland inventory techniques and document the array of peatland systems as a contribution toward the development and implementation of techniques that might be applied statewide.

This study stems from and builds upon all aforementioned peatland studies in Wyoming, and other Wyoming studies that contribute significantly to a composite understanding of peatland systems in Wyoming. Documentation of peatland environmental and biological characteristics was developed for an area of the west-slope Wind River Range (Cooper and Andrus 1994), documentation of peatland environmental and biological characteristics was developed in Yellowstone National Park (Lemly 2007), and there have also been an array of single-site studies in peatlands of Wyoming (Flemming 1966, Reider 1977, 1983; Sturges 1967, 1968 a,b; Sturges and Sundin 1968).

Peatland Background

Peatlands are wetlands that have organic soil derived from dead plant material accumulating in place under anaerobic, saturated conditions. The peat substrate is placed in its own separate soil order: histosol (USDA Natural Resources Conservation Service 2006). Peat organic matter has low bulk density, so while histosols have at least 12% carbon content by weight (if 0% clay content) or at least 18% carbon by weight (if 60% clay) the fibrous plant material makes up most of the volume. Peat affects groundwater flow and conditions for perpetuating peat accumulation. Generally, depths of 40 cm or more are the minimum in defining histosols and peatland systems, though exceptions are made for intervening lithic layers (USDA Natural Resources Conservation Service 2006), and thresholds have been set as low as a 20 cm depth in other peatland classification standards (discussed in Rydin and Jeglum 2006). Peat soils overlying permafrost are documented from one study area site (Pierce 1961, 1965; Pierce and Nelson 1965) and they are classified as a separate soil order, Gelisol.

Total pore space for peat is 78-93%, which combined with other physical and chemical properties represent high water-holding capacity (Ilnicki and Zeitz 2003; cited in Rydin and

Jeglum 2006). Thus, peatlands with outlets can have large impacts on the quantity and quality of the receiving waters (Brooks 1992, Verry and Boelter 1978;). It has been demonstrated on a small scale elsewhere in Wyoming that peatland can function as early-season groundwater reservoirs and late-season stream flow stabilizers (Flemming 1966, Sturges 1967, 1968a) even though they have higher rates of evaporation than open water (Sturges 1968b). They absorb sediment and nutrient loads (Moore and Bellamy 1974), and have a filtering capacity that reduces concentrations of heavy metals (Robbins et al. 1990, Sturges and Sundin 1968).

Peatlands are self-perpetuating systems barring changes to groundwater hydrology. The anaerobic organic substrate is nutrient-poor. Under anaerobic, nutrient-poor conditions, the plant life that can survive in such settings is limited, decay is precluded, and the conditions for accumulation of dead organic matter are perpetuated. The only rate of peat accumulation data that have been published in Wyoming is that of Elk Creek Bog (Fleming 1966) where peat accumulated at rates of 0.36-0.84 cm/decade. For almost all practical purposes, montane peatland systems cannot be created *de novo* and there are major limits to restoration potential (Cooper 1990, Johnson 1996, Austin 2005, Patterson and Cooper 2007).

Peatlands are classified as distinctive wetlands among palustrine, lacustrine, and riverine systems in having saturated organic soils at the surface (Cowardin et al. 1979). They are functionally distinct in the U.S. Army Corp of Engineers classification (Environmental Laboratory 1987) with its hydrogeomorphic system (reviewed in USDI Environmental Protection Agency 2007).

The persistently moist or saturated conditions of peatlands represent a singularly cool, stable environment for a suite of vascular and nonvascular species adapted to relatively cold, wet climates. Thus, peatlands of the Rocky Mountains have a flora that includes boreal species at southern extensions of their range. The peatland systems represent botanical relicts or refugia to the extent that they have persisted throughout the Holocene since the most recent glaciation, or the initiation of their formation is more recently, respectively. Most research into their origin and requisite environmental conditions has been conducted in boreal latitudes.

The palynological significance of peatlands as archives in records of pollen, macrofossils and other microfossils is widely known (highlighted in Rydin and Jeglum 2006, reviewed in Barber 1982), but there have been a limited number of peatland palynology studies in or including Wyoming since Sears (1934). One of the most extensive was in Grand Teton and Yellowstone National Parks (Whitlock 1993). Most are unpublished (e.g., Fleming 1966). The most recent publications have included two of the study area sites in an evaluation of testate amoebae as microfossils having environmental indicator values across the Great Lakes and Rocky Mountain regions (Booth and Zygmunt 2005, Booth et al. 2005). The dates associated with peat deposits are almost non-existent from the study area, with exception of radiocarbon dates taken from the top and bottom of peat deposits at the Sawtooth Palsa Peatland of 7,570 ± 400 YBP – 8,600 ± 300 YBP (Pierce 1961, Pierce 1980) and from Yellowstone National Park at Buckbean Fen (11,500 ± 350 YBP) and Cygnet Lake Fen (8,520 ± 80 YBP); (Baker 1976, Whitlock 1993).

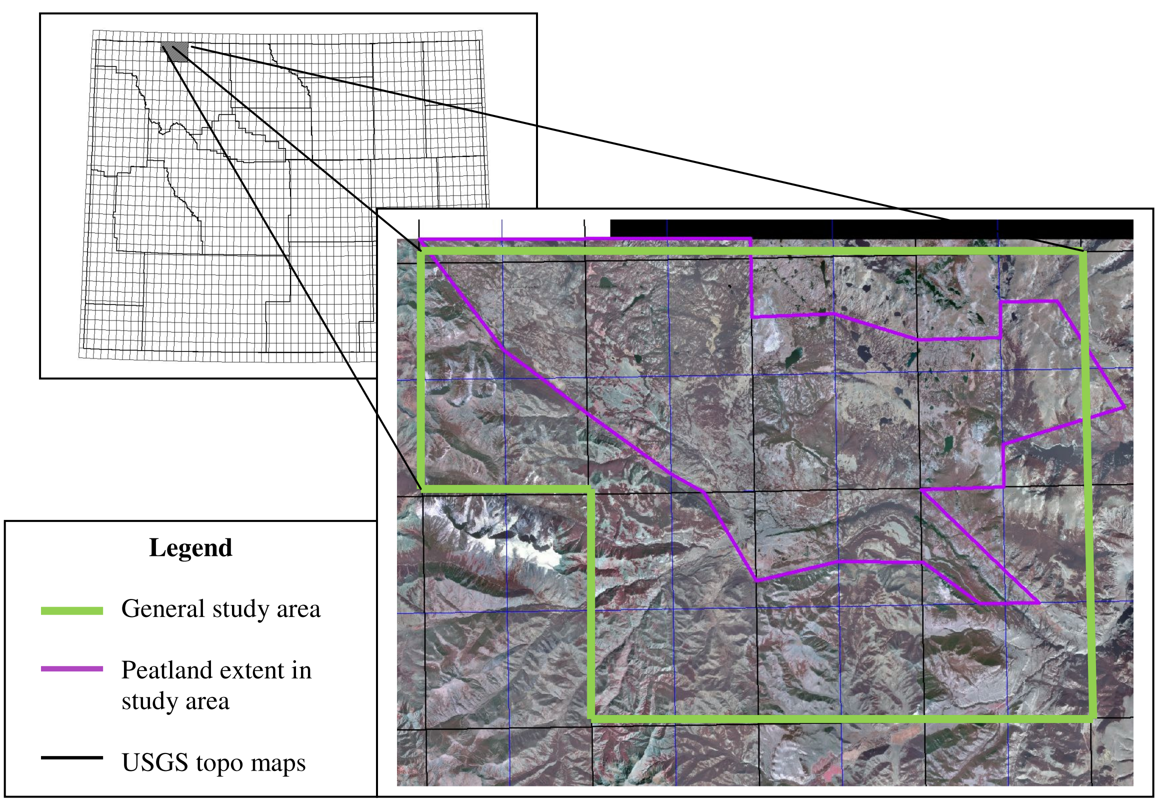
The biology of peatlands has garnered the attention of botanists and ecologists in the Rocky Mountain region in recent decades. Windell et al. (1986) provides a general overview of Rocky Mountain peatlands. More detailed regional characterizations of peatland biology are provided by Bursik (1990) and Chadde et al. (1998) for northwestern Montana and northern Idaho, and by Rocchio (2006) for Colorado. National reviews include Bedford and Godwin (2003) and various agency initiatives (e.g., National Park Service study; Weddell 2005). The biology of study area peatlands is detailed in an accompanying report (Heidel et al. 2008).

All peat-forming systems identified in the Beartooth Mountains study area were subsequently characterized as fens (a fundamental category of peatland). Throughout the rest of this report, the term "peatland" is used in presenting original objectives and in cross-referencing this study with other literature. The term "fen" is used in presenting results of this study.

STUDY AREA

The Beartooth Mountains of Park County, Wyoming are at the headwaters of the Clarks Fork of the Yellowstone watershed (10070006), part of the Missouri River watershed. They lie within the Shoshone National Forest, Clarks Fork Ranger District. The study area encompasses all of the Beartooth Mountains in Wyoming and the contiguous valley of the Clarks Fork of the Yellowstone River (hereafter referred to as the Clarks Fork; technically part of the Northern Absaroka Range). It represents less than 20% of the Beartooth Mountains; with the balance lying in Park and Stillwater counties, Montana.

Figure 1. Beartooth Mountains study area, superimposed on digital orthophotographs



The general study area is within a 300 mi² (777 km²) area that falls almost entirely within seven U.S.G.S. topographic quadrangle maps (7.5') as shown in Figure 1. It is crossed by U.S. Highway 212 (Beartooth Highway) and State Highway 296 (Chief Joseph Scenic Highway). The southern and western boundaries are at the outer margins of the Clarks Fork River valley. The northern boundary is essentially the state line, with a small extension made using digital orthophotograph that extended 1000 m north of the state border into adjoining Park and Stillwater counties, Montana. The contiguous terrain was included in photointerpretation, though only one Montana site was visited incidental to accessing Wyoming sites.

Peatlands are absent in parts of the Beartooth Mountains area, and the *de facto* study area is a contiguous 212 mi² (548 km²), distributed in mainly seven U.S.G.S. topographic maps (20 quarter-quads; Figure 1). The focus was on montane and subalpine elevations, which comprise over 95% of the Beartooth Mountains in Wyoming, only bordering alpine areas. All sites occurred on Shoshone National Forest, with exception of one mapped site on a private in-holding that was not surveyed. The study area elevations range from about 5,400-11,110 ft (m).

The Beartooth Mountains study area lies within the Beartooth Mountains Subsection (M331ah; Chapman et al. 2008). Landscapes in this area consist of steep, dissected mountains and narrow valleys, as well as high tablelands. The entire Beartooth Mountains are an 80 x 40 mi elevated crustal block of Precambrian crystalline rock (Foose et al. 1961). The Early Archean metamorphic formations contain gneiss, schist and related rocks that have been modified by strongly faulted and frost-churning geomorphic processes. There are also Mid- to Upper Cambrian sedimentary formations, Quaternary landslide deposits associated with the latter, Quaternary glacial deposits, and Quaternary alluvium along the Clarks Fork Valley (Pierce 1980, Love and Christiansen 1985; including initial documentation in Pierce 1965, Pierce and Nelson 1971). The primary geomorphic processes in these landscapes are colluvial, fluvial, faulting and frost churning. Some local glacial activity occurs at the higher elevations. Surface and groundwater flows are controlled in large part by such deformation and Quaternary events.

The study area landscape is drained mainly by south-trending tributaries of the Clarks Fork River that include (from west to east): Rock, Crazy, Gilbert, Lake, Muddy, Ghost, Beartooth (plus Sill and Little Bear Creeks at its head), Table, Canyon, Thief, and Littlerock Creeks. There are hydrological divides near the state line and the Beartooth Mountains in Montana drain to the north. Lakes are at upper or headwater positions for most of these riverine systems. Wetlands are abundant in this landscape.

The study area vegetation as mapped in the original Wyoming Gap Analysis land cover map shows a prevalence of open vegetation (subalpine meadow, mountain big sagebrush, alpine tundra, and alpine exposed rock) as well as presence of spruce fir forest, lodgepole pine woodland and douglas fir woodland (Merrill et al. 1996, Driese et al. 1997). The upland vegetation has been documented in Forest Service studies and unpublished files, baseline studies of research natural areas and special interest areas (Jones and Fertig 1998), and published literature (e.g., Billings and Mooney 1959).

The Beartooth Mountains have the highest concentration of lacustrine features in the northern Shoshone National Forest. Extensive palustrine and lacustrine areas of the Beartooth

Mountains were mapped at 1:24,000 scale as part of the National Wetland Inventory by the USDI Fish and Wildlife Service, following Cowardin et al. (1979). The palustrine habitat mapping included a unit of palustrine emergent wetland saturated at the surface (PEMB). A total of 8,178,252 m^2 (2021 acres; or 3.16 mi^2) have been mapped of this peatland unit. The NWI mapping was not incorporated in screening methods at the start of the project because it was not geo-rectified and ground-truthed. It since became available for the Cody Quad (1:100,000) and was compared in final stages of data analysis.

In addition, wetland soils of the Beartooth Mountains were mapped as part of U.S. Forest Service soils mapping (USDA NRCS 2008). A total of 32,657,060 m^2 (8070 acres; or 12.6 mi^2) have been mapped for these three histosol-containing units (302--Cryaquepts, Cryaquolls, and Cryofluvents soils, 0 to 15 percent slopes; 303--Cryofibrists, Cryaquolls and Cryaquepts; and 318--Cryaquepts-Cryaquolls-Cryofibrists complex, 0 to 15 percent slopes). This mapping, at the third order, is at a scale where polygon sizes are usually at least 5 acres. As mentioned previously, classification of peat soil includes depth criteria. The most extensive set of depth measurements are in unpublished datasets recorded as part of the environmental review study for widening of U.S. Federal Highway 212 (ERO Resources Corporation 2000).

The historic disturbance regimes in the study area and land use practices over time are not available in any single compiled reference, but documented in agency manual files. Digital mapping was available for the most recent major fire event, the Clover Mist Fire of 1988. It entered the western end of the study area and fringes along southern margins.

The annual precipitation of the Beartooth Mountains ranges from 10-62 in (25.4-157 cm) per year. Most of the annual precipitation falls as snow. There is one snow monitoring site centrally located in the area at Beartooth Lake at 8840 ft (2694 m), where average annual precipitation is 32 in (81 cm; based on 1971-2000 data) and all months from November-May average over 2.5 in (6.3 cm; NRCS 2008b).

METHODS

Potential peatland sites were first identified through photointerpretation and remote-sensing, then later verified through field surveys, resulting in digital and database products. The database was constructed as an attribute table for storing information from both photointerpretation and field surveys (Table 1). In general, it includes:

- 2 fields for peatland polygon identification
- 3 fields for location cross-reference
- 8 fields for environmental context
- 1 field for peatland ranking confidence score (indication of development/ survey priority)
- 9 fields for biological and environmental attributes derived from surveys
- 2 fields recording survey background information
- 3 fields for storing context and comments

Parts of the following table are referenced in both photointerpretation and field surveys methods, and in the respective results sections.

Table 1. Peatland attributes recorded for Beartooth Mountains sites[1]

Category	Abbreviated Column Heading	Full Column Heading	Column Entry (Picklist/Numeric/Text)	Application	Explanation of Column Content
Identification	**ID**	Polygon Identification Number	Numeric, assigned in sequence of digitizing	All sites	Assigned in the sequence of mapping with no adjustments for deleted polygons
Identification	**SITENAME**	Site Name	Text	Field sites	Place name given to those sites with conservation significance, incorporating the names of local landforms and peatland classification
Location and Identification	**QQUAD_ID**	Quarter-quad and Field Site Identification Number	Text	Field sites	Assigned by U.S.G.S. quarter quad (7.5') and the sequence of field surveys
Location	**TRS**	Township-Range Section	Text	All sites	Township, range and section (from the U.S.G.S. map; not including quarter- and quarter-quarter sections)
Location	**DRAINAGE**	Drainage Name	Text	All sites	Creek name from U.S.G.S. topo map (7.5')
Environment	**ELEV**	Elevation	Numeric	All sites	Elevation from U.S.G.S. topo map (7.5') +/- 40 ft
Environment	**AREA**	Surface Area	Numeric	All sites	Peatland surface area as mapped, determined using ArcView tools
Environment	**GEO**	Surface geology	Picklist (5 units, abbreviated)	All sites	Based on Love and Christiansen (1986)
Environment	**SETTING**	Setting	Picklist (basin, basin toe slope, riverine, valley toe slope, hillslope)	All sites	Based on published literature; discussed in report
Environment	**H2O**	Hydrological Features	Picklist (Lake, Pond, Pools)	All sites	Link to lacustrine systems or smaller open water zones
Environment	**IN**	Inlet	Picklist (X = presence)	All sites	Presence of any stream inflow part/all of year
Environment	**OUT**	Outlet	Picklist (X = presence)	All sites	Presence of any stream outflow part/all of year
Environment	**STR**	Stream Inclusion	Picklist (I = incomplete length, F = full length)	All sites	Presence of channelized flowing water within the peatland basin
Rank	**HML**	Survey Priority (high/medium/low)	Picklist (5-1; high, hm, medium, ml, low)	All sites	Survey priority based on likelihood of well-developed peat habitats, discussed in report
Environment	**PATTERN**	Bilateral/Radial Symmetry in Peatland Formation	Text	Field sites	(Expanded narrative will be developed to make distinctions between patterning as associated mainly with aapamire and floating vegetation)

[1] This table of peatland attributes is linked to the shapefile "peatfinal" that represents the product of photointerpretation and field surveys.

Table 1. Peatland attributes recorded for Beartooth Mountains sites (continued)

Category	Abbreviated Column Heading	Full Column Heading	Column Entry (Picklist/Numeric/Text)	Application	Explanation of Column Content
Environment	**HYDRO**	Hydrology	Picklist (soligenous, topogenous)	Field sites	Based on slope of peatland and patterns of linear vs radial groundwater flow
Environment	**PEATTYPE**	Peatland Type	Picklist (Graminoid, Shrub, Forested, Floating Mat, Aapamire)	Field sites	Based on vertical or horizontal structure; discussed in report
Environment	**PH**	pH	Numeric	Field sites	Peat pH sampled in surface water or 15 cm core
Footnote to Environment	**PHNO**	pH notes	Picklist (1-4; differences in instrumentation)	Field sites	Different pH meter units and practices
Environment	**VEG**	Vegetation Structure	Picklist (G=graminoid, SL=shrub low, SM=shrub medium, T=tree)	Field sites	Distinctions between vegetation structure categories
Environment	**DOMINANT**	Vegetation Dominant	Text	Field sites	Species' name(s), using 6-letter acronyms
Environment	**EO**	Number of Element Occurrences	Numeric	Field sites	Total number of different Wyoming plant species of concern at the site
Environment	**DISTURB**	Disturbance	Picklist (beaver, ditch, drought, fire, grazing, logging, road)	Field sites	Primary natural or man-made disturbance that could have shaped existing peatland conditions; adding a "?" for uncertainty; also distinguishing those that are not ongoing as historical (h), and disturbances that were partial in the peatland basin, full in the peatland basin, or above (in the surrounding catchment)
Environment	**DISTURBC**	Disturbance Comments	Text	Field sites	Secondary disturbances, and additional notes on primary disturbances
Environment	**UNIQCHAR**	Unique Peatland Characteristics	Text	Field sites	Statement of distinguishing attributes, from any environmental condition or biological feature
Source	**VISITOR**	Visitor	Picklist (bh, ee, kh, lm)	Field sites	Initials of four people participating in surveys
Source	**DATE**	Date	Date	Field sites	Date of field surveys
Caveat	**MAPNOTE**	Mapping Notes	Text	All sites	Includes notes on mapping, as based on photointerpretation and field surveys
Footnote to derived	**COMMENTS**	Comments not addressed in other fields	Text	All sites	Includes comments on all other points not addressed elsewhere

Photointerpretation Methods

The aim of photointerpretation was to produce a map of ground-truthed and potential peatland sites and associated attributes. In combination with field survey, it also led to documentation of distinct peatland signatures.

Interagency federal aerial photography was photographed late in the 2001 growing sensing as color infrared aerial photos sensitive to a band width of 400 to 900 nanometers and was provided as 1 m spatial (pixel) resolution, geo-referenced, and terrain corrected digital images.http://eros.usgs.gov/guides/napp.html#napp14. This imagery was obtained through the Wyoming Geographic Information Science Center from the National Aerial Photography Program (NAPP). Photointerpretation was started in April, 2005. The six original peatland sites (Heidel and Laursen 2003, Mellmann-Brown 2005) were plotted using digital color infrared (CIR) orthophotographs. Using the color infrared imagery, all potential peatland sites similar in appearance to the six already known, were identified and digitized across the Beartooth Unit study area (342 potential peatland sites, total). The spectral, spatial, textural and tonal properties of the sites were examined. Digitized peatland sizes ranged from 617 m^2-989,213 $m.^2$

Photointerpretation has routinely been used for peatland surveys (Heidel and Thurston 2004, Cooper and Wolf 2006, Chimner et al. 2007, Lemly 2007) though usually as a means toward a sampling objective, with limited documentation of signatures, assumptions, and iterative stages of testing. The photointerpretation employed in this study followed basic guidelines and information learned from previous photointerpretation in other parts of Wyoming and in other states. Such guidelines have been articulated and posted by Mountain Studies Institute (MSI 2007). Though the MSI guidelines pertain to color aerial photography without infrared band wavelengths, they are general guidelines subject to imagery and study area considerations, and provide a springboard for this project. The MSI encapsulated peatland identification criteria include:

1. Distinct color (brown-green in the case of natural color aerial photographs)
2. Mottled texture
3. Small irregular pools

In addition, the following points identified by MSI (2007) are helpful:

1. Optimal scales for photointerpretation are between 1:2000-1:10,000
2. Alternating within the range of optimal scales is useful to see both landscape characteristics and the fine-scale color and texture of a given wetland
3. Alternating between aerial photography and topographic maps is useful to make sure both indicate wetland habitat
4. When doing photointerpretation for many sites, it is helpful to assign ranking confidence for each site

Color in color infrared aerial photography represents near-infrared photosynthetic activity that is not visible to the naked eye. While photosynthesis patterns vary by vegetation structure, most prevailing peatland vegetation types in the study area have high photosynthetic activity late in the growing season at the time when the aerial photos were taken because soils remain saturated throughout the growing season. This color pattern stands out from surrounding vegetation. There may be texture and pattern differences between peatlands in different landscapes, so a catalogue of attributes were recorded for checking back and forth between aerial photos and field surveys.

Refinements to photointerpretation were made at each stage of ground-truthing that lead to confirmations, additions and deletions in polygons of potential peatland. In 2005, ground-truthing fieldwork was concentrated in two quarter-quad areas of high peatland density and diversity that had contrasting settings between them. In 2006, ground-truthing fieldwork was aimed at geographic breadth of survey with particular emphasis on large potential peatland sites. In 2007, ground-truthing fieldwork was aimed at surveying those areas of well-developed peatland habitat not captured in 2005-2006. A final, revised set of photointerpretation guidelines with the signatures of different peatland types and provisions for different settings was developed, and it is presented with photointerpretation results.

At the onset, peatland photointerpretation conducted in 2005 had just a unique polygon identification number and no other associated attributes for the discrete polygons identified as potential peatland sites. Three location fields were added (township-range-section and drainage; plus and quarter-quad and field survey number for those sites that were surveyed). A second complete review of peatland photointerpretation and database development was conducted after fieldwork in 2007. The attribute database was populated with nine environmental attributes for all potential or confirmed peatland sites, explained below and represented in Table 1.

1. Elevation (from U.S.G.S. topographic map, at precision +/- 40 ft)

2. Total area (m^2; determined using ArcView 9.0)

3. Surface geology (from Love and Christiansen 1984)

4. Setting: Five different settings for peatland sites were documented in the study area. Sites recorded as “basin” have typical basin-filling peat formation, while sites recorded as “basin toe slope” have flow-through peat formation on slopes above the basin. Sites recorded as “riverine” have flow-through peat formation restricted to drainage bottoms or margins, while sites recorded as “valley toe slope” were flow-through peat formation at the base of valley slopes, paralleling the valley rather than the drainage course. Sites recorded as “hillside slope” had steep, flow-through peat formation apart from any discrete drainage or basin.

5. Open water features: Water bodies or well-developed open water zones were noted as representing lake or pool features.

6. Inlet: Seasonal or permanent inflow into the peatland was noted.

7. Outlet: Seasonal or permanent outflow from the peatland was noted.

8. Stream inclusion: Presence of a stream channel running for part or the full length of the peatland was noted.

9. Wetland patterns: Presence of bilateral or radial symmetry patterns that are products of peat-forming processes

The full range of landscape settings for peatlands and the discernible characteristics of peatlands were determined over the course of fieldwork.

The results of fieldwork were also used to develop and assign peat ranking confidence scores to each polygon representing potential peatland that reflects the relative degree of peat development and survey priorities in the Beartooth Mountains, from 1 (lowest) to 5 (highest). There were no adjustments made to these photointerpretation scores after field surveys, with the exception that the scores were increased by 1 for all sites harboring Wyoming plant species of concern, as indirect indication of well-developed peat habitat.

Table 2. Peatland ranking confidence scores in the Beartooth Mountains

Score	Definition
1	Prospective peatland site smaller than 5000 m^2 and with no other feature indicating well-developed habitat
2	Prospective peatland site larger than 5000 m^2, or smaller site that possibly meets criteria 3 and 4 (cases of uncertainty in photointerpretation)
3	Prospective peatland site that also includes any lakes or pools
4	Prospective peatland site that includes any of the diagnostic peatland patterning features
5	Prospective peatland site that meets all of criteria 2-4

Remote-sensing Methods

The aim of remote-sensing was to develop an efficient way to replicate the identification of ground-truthed peatlands. From previous trials in the study area (Heidel and Smith 2004) and from a peatland remote-sensing study in Colorado (Bradley and Gerhardt 2003), it was known that remote sensing to identify potential peatlands using Landsat Thematic Mapper imagery proved less than ideal to mapping the range of peatland features and distinguishing these features for neighboring land types. Further, peatlands were visually identifiable on fine spatial resolution aerial photographs, especially color infrared photography, due to high spectral contrast to most neighboring landscape features. However, peatlands did not have distinct spectral signatures from other land types. This lack of distinction in spectral signature, whether 30m Landsat data or 1m aerial photographs showed that mapping of peatlands could require a multiple data source modeling effort. Multiple imagery options and remote-sensing options were considered at the onset of the project. They included image segmentation of 1m aerial imagery to discriminate terrain unit boundaries and decision rule modeling of remotely sensed data combined with ancillary data layers such as topographic variables or derived GIS data layers for elements such as National Wetland Inventory wetlands mapping. While image segmentation of 1m aerial orthophotographs or similar imagery should provide beneficial distinction of terrain features, including peatlands, costs of such a method for a US National Forest area would be considerable. Also, while image segmentation should provide useful feature boundaries, further analysis beyond segmentation would be needed to provide effective peatland inventory stratification. Instead of pursuing the image segmentation approach, which is basically a machine assisted or semi-automated method producing results similar to human image interpretation, we chose to explore the use of an hierarchical classification tree modeling approach.

A Classification and Regression Tree model approach (CART) was applied (Brieman et.al. 1984) for a central portion of the study area (38,237 ha). The CART model was generated in the software program See5 (Quinlan 1993) using the Classification Tree tools. A Classification Tree is a hierarchical partitioning of independent variables by a set of dependent or response variables that creates a set of decision rules to model the independent to the dependent type list (classes). The Classification Tree tools were employed with 10 Trial Boosting, Global Pruning of Classification Trees by a minimum of 2 classes with a 25% *Pruning CF* option, and using the full dependent sample set.

The spatial domain for this model was delimited to encompass 44 degrees 59 minutes 40.81 seconds North latitude, 109 degrees 45 minutes 36.50 seconds West longitude by 44 degrees 50 minutes 2.66 seconds North latitude, 109 degrees 29 minutes 15.35 seconds West longitude. The model was applied to about half of the study area, as represented by a central block covering 21.88 km E/W x 17.57 km N/S, encompassing areas of relatively intensive peatland visitation during this study and containing a full variety of common land types and peat types in the study area.

The modeling approach used ASTER satellite imagery, derived image variables, and topographic variables such as elevation, terrain slope angle, and terrain slope aspect (see Table 1). An experimental satellite imagery dataset (four images, two needed for synoptic coverage) was acquired of ASTER imagery. ASTER is an example of a new lineage of Earth Observation Satellites oriented towards acquiring fine spatial resolution data and has color infrared equivalent spectral content at 15m spatial resolution (background information posted at: http://edcdaac.usgs.gov/aster/asteroverview.asp). As U.S. federal researchers, project principals were able to acquire ASTER imagery at no cost. ASTER imagery was incorporated into the WYGISC image processing system and the dates 8 September, 2005 was chosen for the eastern portion and 21 July, 2001 for the western portion of the study area. Using ERDAS Imagine software industry standard precision (<0.5 pixel root mean square error) georectification of the imagery was performed to the NAPP CIR aerial imagery.

Two derived image variables could then be generated from the rectified ASTER imagery: band average image brightness, and a vegetation abundance index. Band average image brightness is a variable responsive to the surface albedo of features, in this case in the wavelengths 0.52 to 0.89 micrometers, and is computed as the three band average of the ASTER digital number (DN) values for each image pixel. The vegetation abundance index was computed as the industry standard Normalized Difference Vegetation Index (NDVI). NDVI for each pixel was found by subtracting the DN value of the near infrared spectrum band minus the DN value of the red spectrum band and dividing the product by the sum of the near infrared and red DN values.

Topographic information was collected from the USGS National Elevation Dataset (NED, http://ned.usgs.gov/). NED is provided at a nominal resolution of 1:24,000 scale and is distributed as 10m pixel Digital Elevation Model (DEM) raster products. NED data for the study area was ingested into the ERDAS Imagine software. The DEM was resampled to a 15m pixel coordinate system matching the ASTER imagery using the ERDAS Imagine bilinear interpolation resampling algorithm. Percent terrain slope angle and nine category terrain aspect classes (45degree range per class) were calculated from the resampled 15m DEM.

Table 3. List of model variables used in CART peatland models

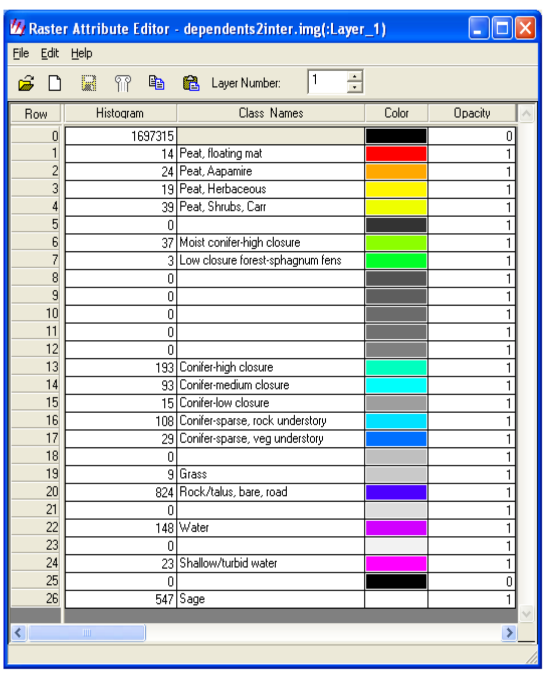
Layer #	Model Variable
Layer 1	ASTER Mosaic Band1 (Green)
Layer 2	ASTER Mosaic Band2 (Red)
Layer 3	ASTER Mosaic Band3N (Near Infrared)
Layer 4	ASTER Mosaic NDVI
Layer 5	ASTER Mosaic Brightness
Layer 6	ASTER Mosaic Source Image Extents
Layer 7	Terrain Elevation
Layer 8	Terrain Slope Angle
Layer 9	Terrain Slope Aspect

The CART model attempted to fit the response of the ASTER and topographic variables to the type strata statistics sampled from the training data collected in the field. A set of model training data was developed from field visitation data and GIS data from the US Forest Service Shoshone National Forest habitat map (Shoshone National Forest, R2Veg database). Both the field collected data and Shoshone NF GIS data were collected or mapped at a different scale than the ASTER based modeling scale. In order to generate a dependent sample set for the model a new set of samples corresponding to the ASTER pixel alignment was generated by manual image interpretation and reference to the field and Shoshone GIS data. The training data was collected incidental to the peatland survey which, in 2005, was concentrated in two quarter-quad areas of high peatland density and diversity, and in 2006, was aimed at geographic breadth of survey with particular emphasis on large potential peatland sites. Neither approach was random or representative. The Shoshone habitat map delimited terrain features of about 5 acres in size and larger. Neither delimited the spatial pattern of the landscape at the 15m pixel scale of the ASTER imagery (the smallest common spatial size of all independent data variables). So, field visitation points were extrapolated spatially across enough homogeneous neighboring terrain as to encompass at least one ASTER pixel or were eliminated. Conversely, the coarse Shoshone habitat map could only be used as a guide to discriminate homogeneous types that matched the model dependents classification and representative ASTER pixels were selected from within the 5acre minimum map unit habitat features. In either case dependent data selection was based largely on photointerpretation of 1m color infrared aerial orthophotography from the date 2001, 1m natural color aerial orthophotography from the date 2006, inference from the field visitation or Shoshone habitat GIS, and the ASTER imagery itself.

Wetland field training data, and peatland data in particular, were secured in the course of ground-truthing the aerial photointerpretation. Wetland cover type mapping was conducted in three previous studies (Walford et al. 2001, Fertig and Jones 1992, Jones and Fertig 1999), and the polygons and mapping points were all conceptual contributions but were not directly applicable in remote-sensing. Upland cover type training data were provided from unpublished Shoshone NF files. In order to use field data with ASTER imagery, the vegetation data needed to be mapped accurately (less than 15 m error), and in settings of relative homogeneity (greater than 15 m continuity on all sides). In the first field season (2005), two separate training forms were developed for collecting large volumes of wetland training data and detailed amounts of peatland data. A premium was placed on training data from peatland sites in particular in the second field season, and the training data available at the close of the 2006 field season (included 52 peat points and 33 other wetland points) was used in running classification tree models.

A principal activity in using Classification Tree techniques is the definition of the target classification. Poor classifications will result in poor models. The generation of the peatland classification followed the typing of Chadde et al. (1998) in the absence of any reference for the study area. Upland types were based on local ecology understanding and the Shoshone NF habitat mapping. A process of type ordination was used to group field visitation data. Types were added to address perceived variance in peat types, and types were deleted for those features deemed too spatially small to be discriminated at the 15m ASTER pixel level. Some field visitation sites were moved to avoid 'mixed' ASTER pixels at the edges of types. Geometric error in the peatland training data was evident at initial 2005 field sites that resulted from allowing insufficient time for the GPS unit to calibrate at freezing temperatures and they were removed for the training set. Model development produced a total of 2125 pixel samples from 85 different sites. The spread of samples per type are shown in Figure 2.

Figure 2. Training data samples used in the peatland CART models



Row	Histogram	Class Names	Color	Opacity
0	1697315			0
1	14	Peat, floating mat		1
2	24	Peat, Aapamire		1
3	19	Peat, Herbaceous		1
4	39	Peat, Shrubs, Carr		1
5	0			1
6	37	Moist conifer-high closure		1
7	3	Low closure forest-sphagnum fens		1
8	0			1
9	0			1
10	0			1
11	0			1
12	0			1
13	193	Conifer-high closure		1
14	93	Conifer-medium closure		1
15	15	Conifer-low closure		1
16	108	Conifer-sparse, rock understory		1
17	29	Conifer-sparse, veg understory		1
18	0			1
19	9	Grass		1
20	824	Rock/talus, bare, road		1
21	0			1
22	148	Water		1
23	0			1
24	23	Shallow/turbid water		1
25	0			0
26	547	Sage		1

Eleven classification tree models were run using spectral signatures and environmental parameters to discriminate the five structural vegetation classes of peatlands: graminoid, shrub, tree swamp, aapamire, and floating mat from upland types. The models were evaluated based on photointerpretation as noted above to the mapped results and agreement to the field visitation data and Shoshone habitat GIS. Usually for a model iteration additional samples were photointerpreted for those types showing low success or high confusion. These additional samples were collected from sites with no or limited typing information and were only based on inference from known sites that seemed visually similar. Ideally, additional training data would have been collected independently with field visitation and sampling. The best model and its evaluation are presented and evaluated in the results section.

Field Methods

The purposes of fieldwork were to ground-truth photointerpretation, develop training data for remote-sensing, and document peatland characteristics. The peatland characteristics include those recorded for all digitized polygons (available from maps, digital references, and photointerpretation) and ones obtained from field surveys.

The color infrared imagery and digitized potential peatland sites were printed out in sets of 20 quarter-quads that span the study area. They were printed onto 8 ½ x 11" pages, at the same scale as U.S.G.S. topographic maps for ease of cross-reference, and carried in plastic sleeves for protection in the field.

In the field, aerial photography boundaries were compared with observed wetland boundaries at each site identified as potential peatland, and GPS points taken as needed for mapping reference. The GPS readings were recorded using a Garmin eMap unit. The Garmin Unit was used in all subsequent years. Sites were traversed across their length as a rule and vegetation structure noted (dominance and relative cover of graminoid components, shrub components, tree components, floating mat, and aapamire; i.e., fine-scale patterning and juxtaposition of graminoid cover on moss mounds and swales of open water or lawn). Representative training data were collected from all wetlands (2005) in a narrow area of inventory, and subsequently only from peatlands (2006) across the full extent of inventory. In 2005, separate forms were developed for the abbreviated wetland data, and a separate form for the expanded peatland data. This resulted in having peatland sites documented on two different forms for the first year. All peatland field data was consolidated on a single peatland form in 2006-2007.

The forms and data points used for mapping and modeling are separate from the customized database that was developed for cataloguing all salient peatland information and differentiating between both field-verified and potential peatland sites (identification, location, peatland development rank, and derived and field-collected environmental attributes, as well as notes on the terms of visit or comments (Table 1). Those 14 fields that were populated during or following field surveys are presented below.

1. Site name: Site names were assigned based on the nearest named feature on the map. Site names incorporate the rudiments of peatland classification in the name ("fen" for all graminoid- and shrub-dominated sites; "swamp" for all forested sites; and "complex" for sites with both fen and swamp). They incorporated all pre-existing site names, and were assigned after completion of fieldwork only for those sites with well-developed peatland, large populations of rare plants, and/or a high concentration of unusual peatland features.

2. Quarter-quad and field site identification number: All field forms and field notes of surveyed sites were labeled by the quarter-quad on which they occur, and a field site identification number reflecting the sequence of field visits to all wetland sites. It served as an interim site name pending completion of fieldwork.

3. Hydrology: Distinction was made between two different peatland hydrological regimes. They can usually be inferred from the setting. A topogenous peatland is sometimes

referred to as a basin- or lake-fill peatland formed by paludification (peatland encroachment on an open water zone). A soligenous peatland is sometimes referred to as a flow-through peatland, where there is a continuous inflow of groundwater in a gravity-driven sloping system.

4. pH: At least one representative value was recorded per site; taken in standing water or else in peat core (15 cm depth). Additional pH values were stored in an unabridged comment field at the end.

5. pH notes: The conventions for recording pH are noted. 0 – recorded as part of a previous study; refer to original field methods. 1 – recorded in 2005 with a Hanna pH meter (Model HI 98129), calibrated daily with the closest pair of buffer solutions. Measurements were taken in standing water or otherwise at 15 cm depth in peat, 2 – recorded in 2006 with a Hanna pH meter, 3 – recorded from samples brought back to the lab (stored under refrigerated conditions), or 4 – recorded in 2007 with an Oakton pH meter (Acorn) in standing water or otherwise at 15 cm depth in peat.

6. Peatland type: Each peatland was classified by the prevailing vegetation structure, and the array of vegetation structures. There are five main vegetation structural units that were considered as representing distinctly different peatland types in remote sensing (tree-dominated, shrub-dominated, graminoid-dominated, and two variations on the latter: floating mat, and aapamire). In addition, shrub-dominated types were differentiated by height category: tall=, medium=, short=)

7. Vegetation dominant: Characterization of canopy cover dominance by species name (abbreviated) was noted for each peatland zone. The fieldwork was conducted in the latter half of the field season so as to generally have the dominants in fruit for determination. Vascular plant nomenclature follows Dorn (2001).

8. Peatland pattern: A wide variety of recurring patterns in peat mounds and associated pools were documented in the study area and that represent signatures for well-developed peatland.

9. Number of element occurrences: This is a tally of the number of Wyoming plant species of concern that were found at or previously known from the site.

10. Disturbance: The hydrological disturbance features noted from aerial photointerpretation by other peatland researchers (e.g., Chimner et al. 2007); features like ditches, drains, canals, and dikes; were rare or absent from the study area. Grazing allotments were retired over large parts of the study area, and commercial timber harvest is not practiced. Indicators of hydrological alteration from road construction, past fire or logging in the watershed or directly in the peatland were recorded. Potential alteration from beaver dams, and the affects of concurrent drought were also recorded. Only the primary disturbance was noted, so that there was a decision made as two which were more severe and extensive. The evaluation standards by Austin (2007) and Rocchio (2006) were not in place at the start of this study but considered final edits to the attribute table.

11. Disturbance comments: The scale and location of disturbance is noted (e.g., fire in surrounding uplands, or fully throughout the peatland). Additional disturbances were noted if more than one is present, and direct or inferred signs of disturbance noted.

12. Unique peatland characteristics: The one or more peatland attributes that distinguish this site from all others in the study area is highlighted.

13. Survey visitor: Initials of all visitors to the site as part of this project.

14. Survey date: Primary date of survey when field data were collected.

Sites that were found to harbor rare species also had vascular floristic lists initiated. Bryology species were documented in the 2002 pilot study and very limited collecting of bryology specimens was also conducted in 2007 at select sites. Peat depth was recorded in 2007 using an Oakfield Apparatus auger (up to 90 cm maximum), and select revisits were made to previously-surveyed sites for this purpose. Depth notes were also made at pool and channel margins where the peat profile was exposed. In addition, peat cores were collected from the upper 15 cm to confirm soil classification at the University of Wyoming Soils Testing Laboratory. The peat core samples and depth probes made in 2007 also included other wetland or riparian sites outside of peatlands where peat forms but saturated peat conditions do not predominate.

The size threshold for evaluating peatland systems required special consideration beyond initial objectives. In general, the photointerpretation signature patterns were not reliably discerned below 0.25 ac (1 ha) because of the confounding affects of shadow or the limits to interpreting color and pattern development at this scale. This was particularly true of elongate sites with shadow, and sites in which much of the wetland basin was open water (not subtracted from net area of potential peatland). A small number of peatland sites were added to the original photointerpretation set in the course of field surveys, generally less than 0.25 ac (1 ha).

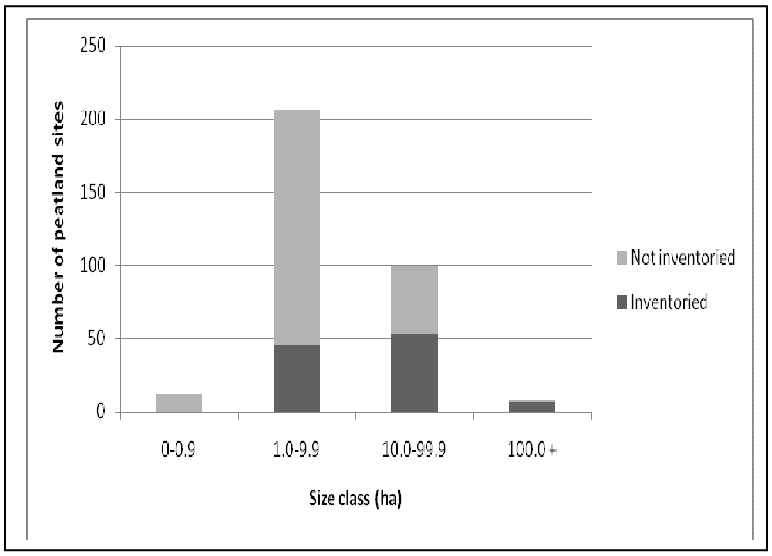
The study area also exhibits peatland systems with full gradations of peat depth, gradations between turf and peat (with possible successional implications), peat-lined stream channels, and one or more special cases of complex mosaics of peat habitat intermixed with wetland habitat that does not meet peatland definitions. Peatland delineation and delimitation information is included in the discussion.

RESULTS

Field and Photointerpretation Results

Peatlands are a recurring wetland type throughout the Beartooth Mountains. A total of 413 potential peatland sites were digitized of which 105 were inventoried in the field and 81 deleted from the digitized set (net total of 326[2] inventoried+not inventoried sites; Figures 3 and 4; Appendix A; also documented electronically in the accompanying GIS shapefile and database). The size of inventoried peatland sites range from 0.06 ha to 949 ha (0.15-234 ac), and over 96% of all sites are greater than 1 ha. The digitized peatland extent represents a total area of 5,480 ha (1354 ac; 2.1 mi²). Over 75% of this surface area has been field-verified. On this basis, the total extent of peatlands in the 212 mi² study area landscape is calculated at 1.0%.

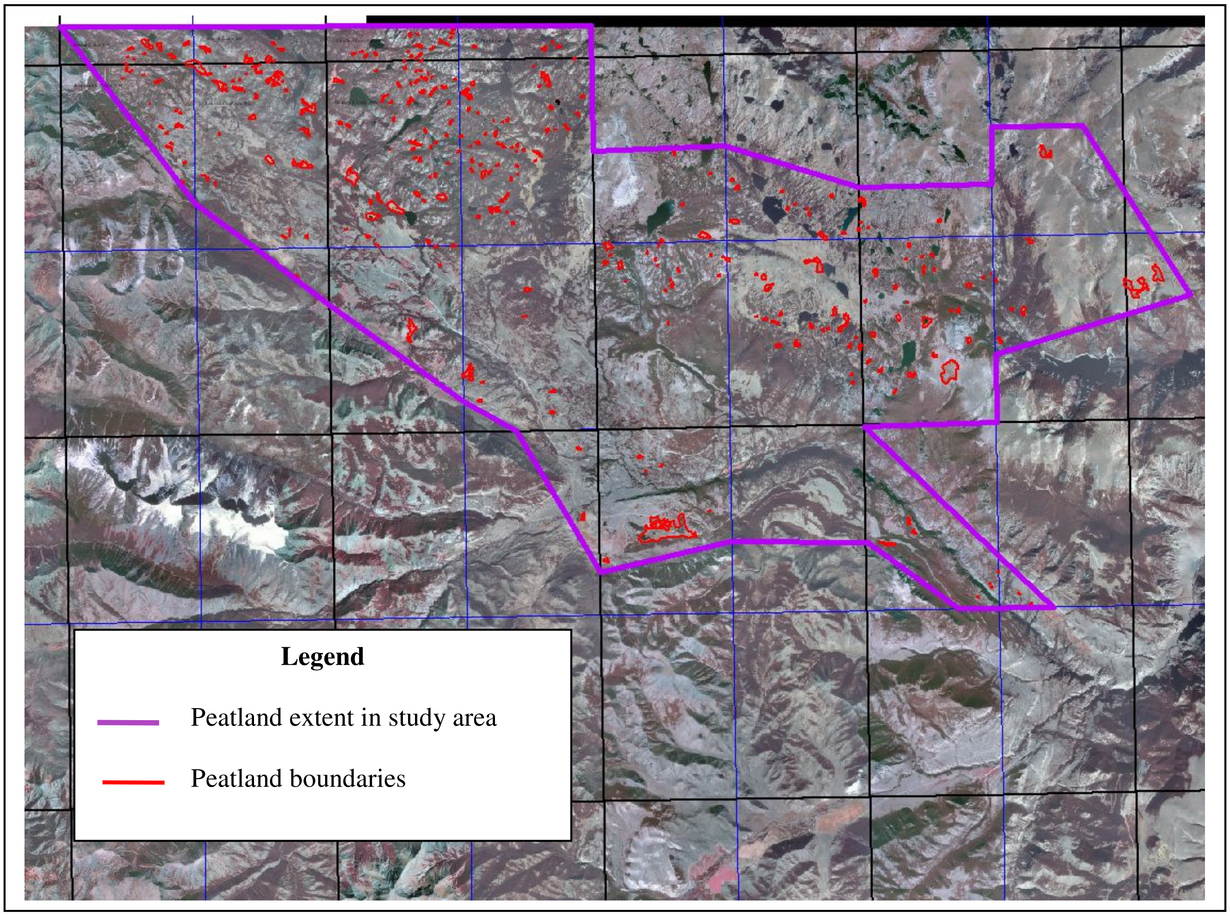
Figure 3. Number of Beartooth Mountains peatland sites, by size class



As a result of site characterization and pH data compiled (Appendix B), it was determined that all field-verified peatland systems of the study area are fens, i.e., minerotrophic peatland systems fed by groundwater, and associated with specific groundwater hydrology conditions. Fens are often classified by their nutrient status. Documented pH values ranged from 4.34-8.28, corresponding with the full array of poor to extremely rich fens. There are only two sites with pH values below 5 that also have characteristics of poor fens, and both were known prior to this study. There is only one site with pH values across much of the site near or above 8, representing an extremely rich fen, at Swamp Lake Fen. Spruce swamps in the study area approach the pH value of extremely rich fens. The mean pH reading of all measurements was circumneutral at 6.34 (n=64). While pH values are not available for all sites or for all zones at each site, and cation concentration data are wanting, the results suggest that intermediate conditions characterized as rich fen or transitional fen are prevalent (see Cooper and Andrus 1994, U.S. Fish and Wildlife Service 1999).

[2] Of the 326 digitized peatland sites, 304 are in Wyoming and 22 are in Montana.

Figure 4. Peatlands mapped in the Beartooth Mountains[3]



Fens are not distributed evenly throughout the study area but associated with Quaternary deposits (glacial/alluvial) or else with fractured Paleozoic bedrock. All extremely rich fens are associated with Quaternary deposits and all poor fens are associated with fractured Paleozoic bedrock. The fens found in Paleozoic bedrock fractures were generally smaller and restricted to confined basins compared with fens on Quaternary deposits.

Photointerpretation Guidelines

Photointerpretation informed by field survey resulted in a characterization of peatland settings and vegetation structure. In turn, they served to develop photointerpretation guidelines for use of NAPP CIR aerial photography in the study area that address fen signatures, based on color, texture and patterns. The complete set of study area quarter-quads showing digitized peatland boundaries are presented in Appendix B, and a set of examples are presented to illustrate the cases.

Fens are classified by groundwater movement. Of the verified sites, there were over twice as many topogenous fens (level fens) as there were soligenous fens (sloping fens). All

[3] The rectangular areas in this map correspond with the 20 quarter-quad enlargements presented with more detailed peatland boundaries in Appendix A; also submitted as GIS shapefiles.

topogenous fens are in basin settings. Both poor fens and extremely rich fens are primarily topogenous fens. A few fen sites have both soligenous and topogenous hydrology (Swamp Lake and Lake WGN). All soligenous fens are sloping. The majority of sites are in basin settings but have groundwater discharging above the basin level, so that setting alone is not adequate to distinguish the hydrological regime(s). Most soligenous fens are gently-sloping except for steep hill slope fens. The settings of Beartooth Mountains fens and their prevailing groundwater direction are represented in Figures 5-9.

Figures 5-9. Peatland settings and hydrologies in the Beartooth Mountains (cross-hatch denotes peatland; arrows indicate primary direction of groundwater movement)

Figure 5

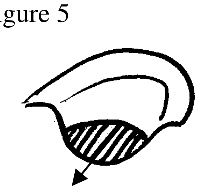


Figure 6

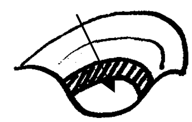


Figure 7

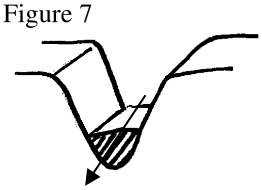


Figure 8

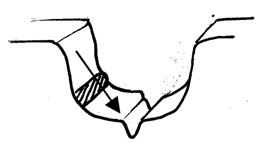


Figure 9

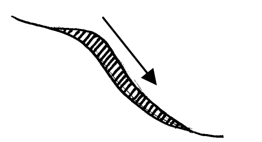


Figure 5. Basin setting - topogenous
Figure 6. Basin toe slope setting - soligenous
Figure 7. Riverine setting - soligenous
Figure 8. Valley toe slope setting - soligenous
Figure 9. Hill slope setting - soligenous

Several other hydrological characterizations can be made of Beartooth Mountains fen systems collectively. They are primarily in headwater positions. Among the field-verified sites, most do not have inlets (over 80%), and almost all of those that do are fed by first-order streams. Over half of the sites have distinct outlets (54%). Channelized flow that traverses part or all of fen length is present at less than 33% of the sites.

Of the vegetation categories, graminoid fens are by far the most numerous and graminoid vegetation is typically prevalent. Shrub fen is a common vegetation feature but usually restricted to an outer zone, or if prevalent, then occupying small sites. There is one exception of a medium-sized shrub fen site. Tree-dominated fen vegetation consistently occurs separate from other fen vegetation categories, except at very small sites with graminoid openings, and at the largest site, Swamp Lake, site of the best-developed forest vegetation in the study area. Graminoid and shrub peatland vegetations are found in both soligenous and topogenous fens, tree-dominated vegetation and aapamire are found only in soligenous fens, and floating mats are found only in topogenous fens. There were no wetlands where moss cover was high across the wetland, though mosses are locally prevalent in or adjoining floating mat zones and on aapamire mounds (dominated by *Aulocomnium palustre* in association with other mosses). The only places where there was extremely high *Sphagnum* moss cover were found at relatively acidic sites with floating mats and at relatively sheltered corners of large riverine fens (Muddy Creek and Gilbert Creek).

Distinct patterns emerge in a review of the resulting combinations of fen vegetation with hydrology and setting (Table 4). The most frequent form of fen is the graminoid basin fen. The other settings (basin toe slope, valley toe slope, riverine) harbor the only fen sites with aapamire and with forest cover. Soligenous aapamire fens in basin settings are relatively common, and all other soligenous fen vegetation and setting combinations are present at five or fewer sites.

Table 4. Relative fen vegetation frequency by hydrology and setting, Beartooth Mountains[4]

Hydrology	**Topogenous**	**Soligenous**			
Setting/ Vegetation structure	**Basin**	**Basin toe slope**	**Valley toe slope**	**Riverine**	**Hill slope (steep slope)**
Graminoid Fen	1		6		6
Shrub Fen	2				
Forested Fen			5	6	
Aapamire Fen		3			
Floating Fen	4				

The NAPP CIR imagery represents photosynthetic activity, which is a function of phenology and composition. Fen color on this imagery is a characteristic deep pink often with an underlying gray tone. Elsewhere in the landscape, mesic meadows, mesic forest margins, seeps and some zones of burned landscapes exhibit similar color. They can generally be ruled out by landscape context. The characteristic deep pink coloration was subdued in some imagery, and dim in some fen sites and zones. In special cases of floating mats, there is a thin pale gray with or without pink superimposed on a deep gray tone matrix, and most of these cases reflect floating peat mat vegetation.

The combination of color and texture on NAPP CIR aerial photography are extremely useful in identifying and delimiting fens in the study area. Texture on aerial photography represents vertical and horizontal vegetation structure and composition at various scales. Tree crowns are distinct on the NAPP CIR imagery as dark radial patches. Forested fens could not be discerned from other forested terrain, except where there were openings with distinct understory coloration, or partially-forested fens. Shrub cover color resembles graminoid cover color except as distinguished by a tightly-spaced “cotton-like” texture and accompanying bright colors. Graminoid cover has a diffuse, “soft” texture, without sharp lines except as interrupted by drainage channels or peat-formation patterns. In the MSI photointerpretation guidelines (2007), mottled patterns were ascribed to peatlands. This refers to wetland vegetation patterns with diffuse edges rather than jagged edges, whereas highly mottled patterns in the study area usually had jagged edges and were usually associated with semi-permanent palustrine marsh systems. Marl deposits appear as white spots within the pink matrix. Color and texture examples are illustrated in Figures 10-12.

[4] The frequency of vegetation structural categories is listed from 1-7 in the matrix of different hydrological conditions and settings, representing how many times they are present among the 105 survey sites; with 1 as the most frequent and 7 as least frequent, i.e., found at only a single site.

Figure 10. Unnamed fen vegetation patterns in basin toe slope setting; two main vegetation zones Arrows: Pink peatland color, with sparse tree cover in south, bright pink shrub cover, and dull pink graminoid cover (Muddy Creek SW)

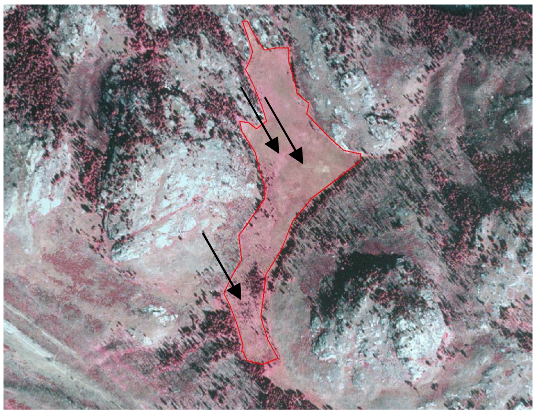


Figure 11. Poke Lake Fen and unnamed fen in basin setting; two main vegetation zones Arrows: Grayish pink peatland color of floating mats within graminoid vegetation (Muddy Creek NE)

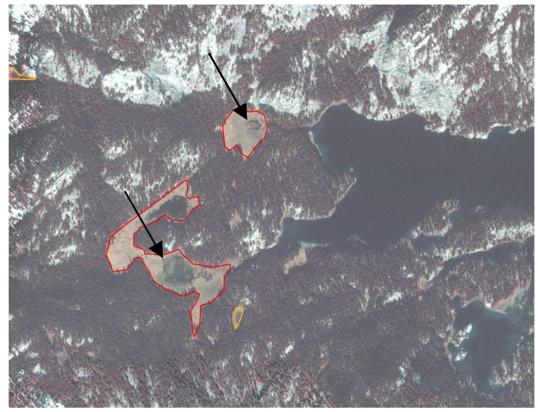


Figure 12. Swamp Lake Fen vegetation patterns in basin and valley toe slope settings. Arrows: Marl deposits appear as high-reflectance white spots within the pink matrix (center); forest swamp is along the south, and semi-permanent marsh and open water cover large areas (north).

Patterns on the NAPP CIR aerial photography are products of the peat-forming process as well as external influences. While some sites had “irregular pools”, one of the MSI criteria, many had fine-scale fen patterns that are distinct on this imagery, exhibiting symmetry or orientation relative to water movement. Fens are most readily distinguished from non-peatland wetlands if they have microhabitat patterns. While such patterns are not in all sites, they are absent from non-peatland sites, so they serve as high-precision indicators. Four fen patterns are discussed in some detail as diagnostic features that are discernible on the NAPP CIR aerial photography. The fifth has not been tested in the field.

1. Semi-rounded lake and pool outlines, set off by sharp borders with no relation to basin outline or drainages
2. Paludification pattern of floating mat on lakes or pools
3. Solifluction patterns of string mounds and narrow or broad intervening flats or pools
   a. Narrowly-spaced strings with lawn flarks
   b. Widely-spaced strings with pool flarks
4. Solifluction patterns of terraced slopes
5. Palsa (associated with permafrost)

Not all fens have these patterns. Not all places where fens occur have these patterns. They were essentially absent from the 154 fens inventoried in the Medicine Bow Mountains of the Medicine Bow National Forest (based on Heidel and Thurston 2004). However, they were much more common in fens of the Beartooth Mountains study area as described further below. A paired set of aerials and schematic cross-sections are shown for the four on the following pages (Figures 13-23).

Sites with semi-rounded lake and pool outlines are topogenous fens reflecting a past or ongoing basin-filling process, found in montane zones. Semi-rounded lake and pool outlines within a graminoid matrix are often indication of peat formation. An autogenic peat-forming process is indicated by the symmetry in their shape, abrupt transitions from graminoid vegetation to open water, and an openwater outline that may not reflect the overall basin outline (Figures 13-14). Occasionally such smooth outlines are dissected by wildlife trails.

Sites with floating mats are also topogenous fens reflecting a past or ongoing basin-filling process in montane zones. Floating mats with predominantly moss cover are narrow zones that appear like a pale ribbon or "eye-ring" border along open water zones. There are no lakes in the study area that have floating mats around their entire perimeter, but there are small pools encircled by floating mats and segments of lakes with floating mats (Figures 15-16). Floating mats formed by vascular plants like mud sedge (*Carex limosa*) and buckbean (*Menyanthes trifoliata*) appear in central pools and appear as thin pale gray superimposed on a deep gray. The *Carex limosa* mat may be in the center of the basin, or part of concentric zones near the center.

Sites with many fine bands and a hill slope setting distant from basins and valleys are a form of aapamire vegetation in soligenous fens, reflecting past or ongoing solifluction processes, found in subalpine zones. They have terraced patterns on relatively slopes at the heads of drainages. The widely-spaced mounds are abrupt rises that run perpendicular to the slope, separated by slightly-sloping intervening graminoid expanses and occasional pools behind the mounds (Figures 17-18). The example represents a subalpine fen that straddles a divide and drains in both north and south directions.

Peatland Patterns[5]

Figure 13. Mud Lake Fen (Muddy Creek NW)
Basin setting.

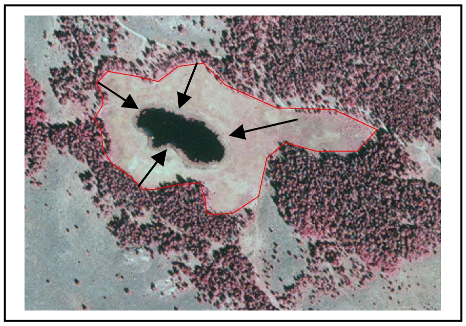


Figure 14. Rounded pool margins, anchored peat

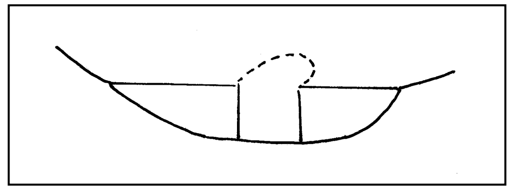


Figure 15. Rock Creek Fen (Jim Smith Peak NW)
Basin setting.

Figure 16. Rounded pool margins, floating peat mat

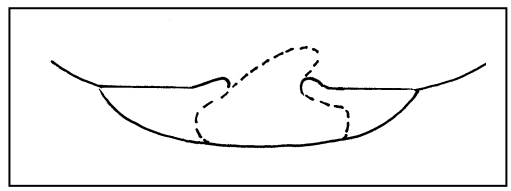


Figure 17. South Fantan Fen
(Beartooth Butte SE). Hill slope setting.

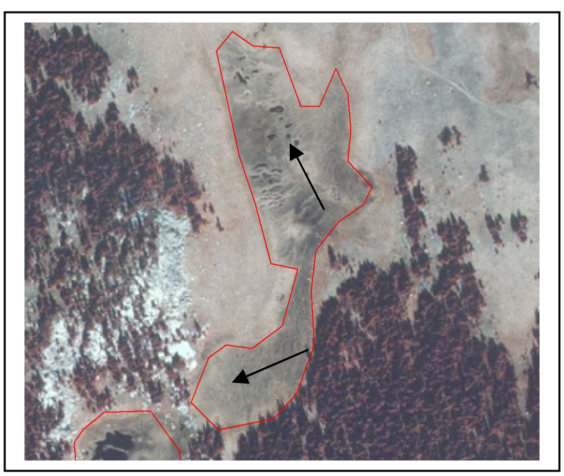
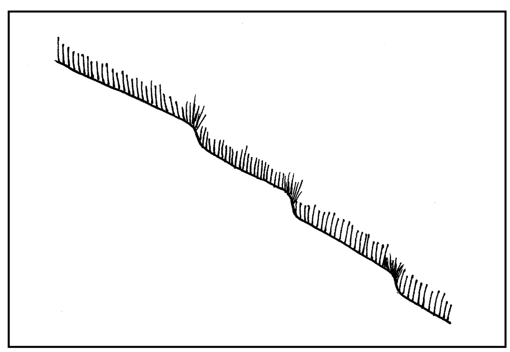


Figure 18. Terraced peat (w/o pools)
Steep slope.



[5] Arrows indicate the prevailing direction(s) of groundwater movement on this page and the following page.

Figure 19. Meadow Lake Fen (Beartooth Butte SE)
Basin toe slope setting.

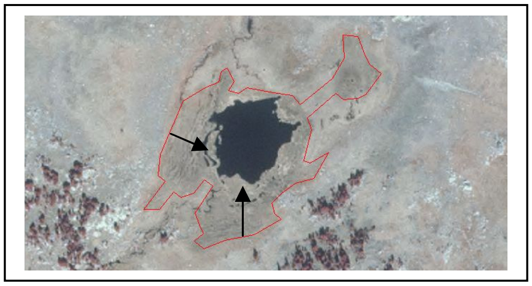


Figure 20. Narrowly-spaced strings and flarks
Gentle slope.

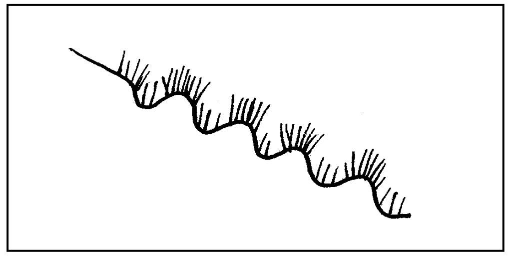


Figure 21. North Fantan Fen (Beartooth Butte SE)
Basin toe slope setting.

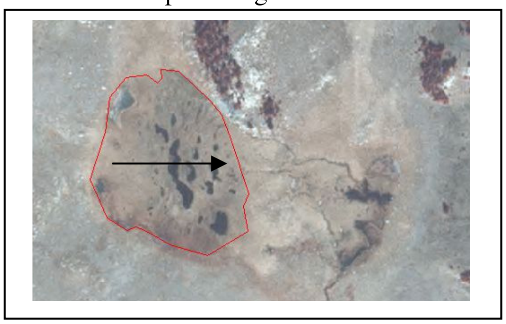


Figure 22. Widely-spaced strings with pool flarks
Gentle slope.

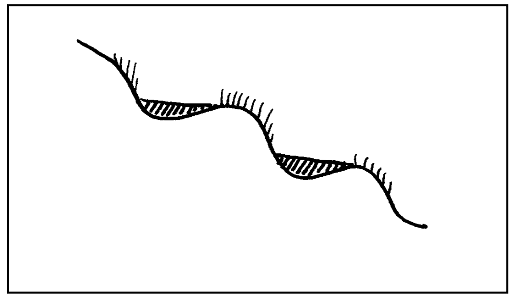


Figure 23. Lily Lake Fen (Muddy Creek NW) -
Basin toe slope setting.

Sites with many fine bands in basin or valley settings are also a form of aapamire vegetation in soligenous fens, found in subalpine zones. The series of mounds and intervening swales appear like striped bands. They are products of solifluction and run perpendicular to the slope and to the flow of water. Even though many are in basins, the peat is formed above the water level in the center. The string-flark term originated in Sweden and refers to mounds (strings) and intervening swales (flarks). The mounds have high moss cover and rise above the water table. The intervening swales vary in depth relative to the water table, with flats of short, sparse graminoid cover and saturation at or near the surface, or “pool” conditions. There were many permutations, but the ones that filled basins had either narrow flats or else wide pools (Figures 19-23). All were in the subalpine zone with possible exceptions of Lily Lake Fen (Figure 23) and fine-scale patterns at the east end in Swamp Lake (Figure 12).

Palsa patterns are peat accumulations over permafrost, visible on the ground as mounds. There is only one widely-recognized palsa peatland/fen in the study area (Pierce 1961, Collins et al. 1984) though there was one site with what appeared to be small collapsed mounds with no permafrost (Littlerock Fen), and there are four more unconfirmed sites with patterns of collapsed pool relicts that appear on aerial photographs that may indicate palsa fens.

Peat mounds potentially form at spring heads but were not found in the study area. There were relatively few discrete springs at any of the peatlands of the study area (with a couple striking exceptions). They had no mounds associated with them. By comparison, peat mounds are occasional features in Medicine Bow fens (as reported by Heidel and Thurston 2004) and in Yellowstone National Park fens (Lemly 2007).

Development and Disturbance

All peat cores collected from peatland sites were determined at the University of Wyoming Soils Testing Lab to be in the fibrist suborder, except that samples collected at the bottom of pools were in the hemist suborder. In addition, there is one area mapped as Gelisol soil order (mean annual temperature lower than 0º C, overlying permafrost). Outside of peatlands, fibrist cores were also collected and confirmed from stream borders, shrub thicket mounds, and seeps.

The documentation and analyses of peat depth profiles are preliminary. As indicated by soils mapping on Shoshone National Forest (USDA Natural Resources Conservation Service 2008), there are extensive portions of the study area where soils are mapped as soils unit complexes of cryoaquepts and cryaquolls with histic horizons that do not meet the depth requirement. There was only one alpine peatland site included in this study, and the deepest peat depth found in preliminary sampling of the alpine site was 29 cm depth. It does not meet the standard threshold of a 40 cm minimum peat depth, but otherwise maintained composition and pattern features characteristic of peatland. There were subalpine peatland sites that had less than 40 cm peat depth, but the two places where this was found were in small sites of less than 1 ha (0.25 ac). There were montane peatland sites with less than 40 cm peat depth, but these were in transitional willow communities. Preliminary comparisons have been made of peat depth in places where fen sites are clustered and that differ by size. Results indicate that the larger sites have the deeper peat profile. There were no peat depth profiles taken across the entire hydrological gradient of a given peatland site, but the abruptness of the environmental gradient was evident. For example, preliminary depth measurements taken in the upper margins of soligenous subalpine fens documented peat depths of over 70 cm less than 4 m from the upper margin.

The measurement of depth to groundwater is a key measurement for documenting peatland vegetation (e.g., Cooper and Andrus 1994, Lemly 2007). This would have been all the more significant during the study period when there were multiple signs of drought conditions noted during field surveys. In general, the driest conditions observed were in peatlands that had burned across the basin or at least at the margins in the Clover Mist Fire of 1988.

An interesting observation coming out of peat cores was documentation of an aerobic basement under string mounds and an anaerobic basement under lawn flarks side-by-side

(Figures 24-25). It appears that there are oxidizing condition zones beneath an anaerobic wetland that correspond with surface patterns. A review of hypothesized primary and secondary mechanisms for peatland patterns and the associated interplay of biotic/abiotic process are presented by Rydin and Jeglum (2006).

Figure 24. Peat core below mound

Figure 25. Peat core below swale adjoining mound

Seven disturbance factors were noted during field surveys. Grazing was the most common factor (primary disturbance factor at 24 sites) including all forms of influence (herbivory, trampling, eutrophication), generally by livestock (cattle, sheep, horses) more than by pack animal traffic, and most of which were disturbed in the past and reflected in vestigial signs like hummocks. There are no longer sheep allotments. Many sites are no longer part of grazing allotments, though there was at least one accidental entry of livestock in an area withdrawn from grazing. Fire was the second most frequent factor (primary disturbance factor at 17). Fire posed one of the most challenging disturbances to evaluate because it has the longest history and was highly variable on its extent if not intensity, and had the greatest influence on fen photointerpretation signatures. Some fens only burned at the borders, but other sites burned across the wetland surface. All surveyed fen sites in the Clover Mist Fire of 1988 burned across most or all fen surface areas. In addition, surface run-off may have flooded and floated areas of peat habitat. Roadway hydrological alterations were noted at 7 sites, most of which lie within the U.S. Hwy 212 (Beartooth Highway) corridor slated for road widening. The largest of these fen sites bordering the highway, Clay Butte Fen and Little Bear Fen, have already been identified (ERO Resources Corporation 2000, Mellmann-Brown 2004). Most disturbances were found in trace amounts. Ditching accompanied by plowing and possibly irrigation are present on private lands upstream from Swamp Lake and from the Crandall Ranger Station Swamp. Signs of on-site ditching were present at one small site where a ditch was in place to divert water from what is now an abandoned road. Signs of historic logging are present in the forested swamps. Beaver houses were present at low elevation sites with aspen (*Populus tremuloides*) but dams did not impound the fens except at three sites (two in the Clarks Fork River valley and one at the upper end of an unnamed Lake Creek tributary). There did not appear to be any current signs of beaver activity, and the impoundments appeared to be many decades old. The inundation zones later dried and in some cases were grazed, leaving peatland persisting below the long-abandoned beaver dams at two of the three sites.

The largest fen site, Swamp Lake, has multiple hydrological alterations that have not been systematically evaluated. Its water level was elevated by highway construction that raised its culvert outflow, at about the same time as a crown fire across steep slopes above the wetland, and accompanying drought intervals fostered surface runoff and water level fluctuations. It has anchored peatland vegetation, most of which is in a flat basin setting except for sloping segments that rise to the south.

Despite unanswered questions about disturbance patterns at any given site and across the study area as a whole, what may be even more significant is the paucity of detected disturbance at the majority of sites. It is noteworthy that there were no disturbance factors detected at almost half of the sites (44 sites), nor evidence of peatland sites that were destroyed. This was true even in the case of a newly-documented floating mat sites that showed no disturbance even though it was less than 3 air mi (5 km) from the former lowhead dam and power plant of Western Smelting & Power Company (built in 1916), and there was a very old stone foundation of a cabin was found less than 0.25 mi (less than 0.5 km) away.

Signs of disturbance that could not be ascribed to any one factor were also noted. Some of these signs might relate to the current drought period or to climate trends in addition to disturbance events. Downcutting in peat was noted where there were vertical exposures of peat and stream channel height equaled or exceeded stream channel width. Some sites had vegetation typical of floating mats that appeared to be anchored. Some sites seemed to lack intact transitions from peatland vegetation to upland vegetation, where the outer peatland perimeter was filled by monodominant swards of bluejoint reedgrass (*Calamagrostis canadensis*). While this grass is native, it is robust, clonal and tolerant of aerobic conditions such that it may have the potential to displace other peatland vegetation.

In general, the paucity of non-native species is noteworthy. Sites along the Clarks Fork Valley, at lowest elevations in the study area, generally had the most consistent presence of non-native species like Canada thistle (*Cirsium arvense*). Incursion of non-native species like clovers (*Trifolium* spp.) was noted in those Clarks Fork Valley sites that also had a history of grazing.

Remote-sensing Results

Eleven classification tree models were run using spectral signatures and environmental parameters to identify the five classes of peatlands: graminoid, shrub, tree swamp, floating mat and aapamire. The ASTER imagery and peatland mapping produced by Model 11 are represented in Figure 26. The peatland areas calculated by the model are represented in Table 5.

Figure 26. ASTER imagery and Peatland CART Model 11 for the central study area

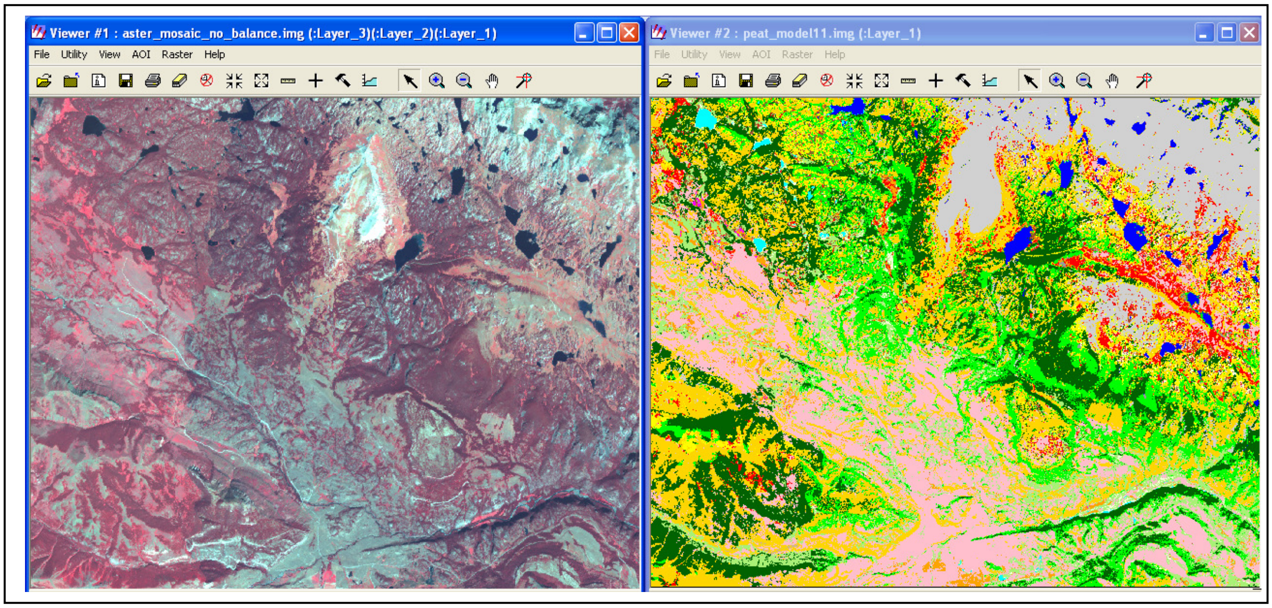


Table 5. Peatland CART Model 11 attribute table showing by modeled type: the classification names, display color used in Figure 26, histogram of the number of 15m pixels modeled, and area in hectares

Raster Attribute Editor - peat_model11.img(:Layer_1)

Row	Class Names	Color	Histogram	Area
0			0	0.00
1	Peat, floating mat		17617	396.38
2	Peat, Aapamire		21284	478.89
3	Peat, Herbaceous		56251	1265.65
4	Peat, Shrubs, Carr		34036	765.81
5			0	0.00
6	Moist conifer-high closure		123424	2777.04
7	Low closure forest-sphagnum fens		1359	30.58
8			0	0.00
9			0	0.00
10			0	0.00
11			0	0.00
12			0	0.00
13	Conifer-high closure		287823	6476.02
14	Conifer-medium closure		206169	4638.80
15	Conifer-low closure		1590	35.78
16	Conifer-sparse, rock understory		322798	7262.96
17	Conifer-sparse, veg understory		103641	2331.92
18			0	0.00
19	Grass		914	20.57
20	Rock/talus, bare, road		180835	4068.79
21			0	0.00
22	Water		22055	496.24
23			0	0.00
24	Shallow/turbid water		5362	120.65
25			0	0.00
26	Sagebrush-bunchgrass		314282	7071.34

Two analyses of results are presented for Model 11. A contingency table (Table 5) represents the analysis of a ”F-Fold” test performed in the CART software. The approach quantifies model class accuracy via statistics from a “Monte Carlo” routine, where ten independent CART models each containing a fraction of the original dependent set are run and model deviance is compared across runs. It shows fair accuracy for the five peatland classes (67%-89%) except for the peatland class having the smallest sample size, i.e., low closure forest fen (33%). Nearly all upland vegetation classes had higher accuracy levels (83%-100%).

The second analysis is a tabulation of vegetation types within digitized peatlands compared against the vegetation classes in which they have been placed by the model (Table 6). This analysis points to a serious misidentification of confirmed peatland as sagebrush-bunchgrass. A review of the particular sites that the model identified as sagebrush-bunchgrass points to the source of the problem. The largest area of misidentified peatland is in Swamp Lake, a site where no training data was collected because it was already well-documented. This is perhaps the only site with a large central marshy area, which had extreme levels of standing dead emergent vegetation when ASTER imagery was taken in the drought year of 2001. Likewise, a large Hunter Peak ridge peatland of extreme levels of standing dead emergent vegetation was modeled as having all upland vegetation. The latter was noted as having highly-productive vegetation of beaked sedge (*Carex utriculata*) in an unusual mat that was suspended, i.e., floating in places. Expansion of the training data or replacement of the ASTER imagery by a future source, provided that it was not in drought, would have the effect of eliminating these two very large site-specific errors.

Table 6. Peatland CART Model 11: 10 F-Fold test contingency table

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	<-classified as on Map	No.	CLASS NAME	No.	Producers Accuracy			
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----					%			
11				1			1			1						(a):	1	Peat, floating mat	14	79			
1	16		3	3						1						(b):	2	Peat, Aapamire	24	67			
		13	5						1							(c):	3	Peat, Herbaceous	19	68			
	1	5	31												2	(d):	4	Peat, Shrubs, Carr	39	79			
2	1			33			1									(e):	6	Moist conifer-high closure	37	89			
		1	1		1											(f):	7	Low closure forest-sphagnum fens	3	33			
						191	2									(g):	13	Conifer-high closure	193	99			
						2	89	1		1						(h):	14	Conifer-medium closure		96	96		
								15								(i):	15	Conifer-low closure	15	100	100		
									107			1				(j):	16	Conifer-sparse, rock understory	108	99			
						2	1		2	24						(k):	17	Conifer-sparse, veg understory	29	83			
									2		7					(l):	19	Grass		78		9	78
									2		1	820			1	(m):	20	Rock/talus, bare, road		100	100		
													148			(n):	22	Water	148	100			
1													2	20		(o):	24	Shallow/turbid water	23	87			
															547	(p):	26	Sagebrush-bunchgrass	547	100			
																							%
15	18	19	40	37	1	195	94	16	114	27	8	821	150	20	550	2125							
73	89	68	78	89	100	98	95	94	94	89	88	100	99	100	99	%							

The zone tabulation in Table 7 also indicates significant error in differentiating upland forest types from peatland. Only one confirmed peatland site was misidentified as an upland forest, at the floating mat zone in particular of Lake WGN. It is a small peatland, and the scattered clumps of vegetation may have been responsible for this basic error. Of the seven documented sites of spruce forest, none were wider than 100 m, i.e., 3 pixels. The narrowness of and heterogeneous canopy of forested swamp habitat was responsible for the failure of the model to identify spruce swamp. It may be possible in other landforms and in settings where spruce swamps are more extensive, but not in the Beartooth Mountains.

Table 7. Peatland CART Model 11 summary

No.	Class Name	Count	%	Hectares
1	Peat, floating mat	483	3.06	10.87
2	Peat, aapamire	2163	13.73	48.67
3	Peat, herbaceous	1924	12.21	43.29
4	Peat, shrub carr	3492	22.16	78.57
6	Moist conifer-high closure	2343	14.87	52.72
7	Low closure forest-sphagnum fens	571	3.62	12.85
13	Upland conifer-high closure	497	3.15	11.18
14	Upland conifer-medium closure	465	2.95	10.46
15	Upland conifer-low closure	185	1.17	4.16
16	Upland conifer-sparse, rock understory	110	0.7	2.47
17	Upland conifer-sparse, veg understory	460	2.92	10.35
19	Grass	2	0.01	0.04
20	Rock, talus, bar, road	72	0.46	1.62
22	Water	169	1.07	3.8
24	Shallow/turbid water	399	2.53	8.98
26	Sagebrush-bunchgrass	2424	15.38	54.54

The most far-reaching error in Model 11 is not reflected in either tabulation, that being the lack of distinction between peatland and productive meadows (mostly wet meadows; but also including upland meadows at woodland margins, and in other sheltered settings). There were no general wetland training data collected in this area, and this landscape had peatland microhabitats embedded in other wetland types (peat-lined channels, shallow-depth peat overlying seep). The broad swath mapped as graminoid peatland across the central righthand portion of the model map (Figure 4) is in fact a glacial meltwater trench with broad subirrigated and seep-fed valleys in the Little Bear Creek and Chain Lakes areas.

DISCUSSION

This study addresses peatland systems throughout a landscape. It provides a methodological framework for tailoring the remote sensing tools to the array of peatland features in a given study area, taking advantage of a fieldwork feedback loop to refine the photointerpretation. It parallels concerted statewide peatland inventory efforts in other regions of the country (e.g., Pearson and Leoschke 1992) and in the state (Heidel and Thurston 2004).

A diversity of fens is present in a diversity of fen settings in the Beartooth Mountains, providing classification and context for known sites and significant additional new site information. Three sets of conclusions emerge.

1. Peatlands are numerous and extensive, but large fens and "extreme" pH conditions are very rare, pointing to the significance of previously-documented sites. The unparalleled significance of Swamp Lake among all other study area fens is established in its size (over 2.5X larger than any other well-developed site), extent of each vegetation component, and total number of Wyoming species of concern (21 at present). It appears to be the only extremely rich fen in the study area and among the few with dual hydrologies (topogenous and soligenous).

2. There are heretofore undocumented solifluction patterns in the Beartooth Mountains. Some contrasting patterns are side-by-side in adjoining wetlands. They may be explained by differences in environment, origin or length of development, but this remains to be determined.

3. The overall distribution pattern of peatland systems in the Beartooth Mountains is hypothesized as representing two fundamentally different groundwater sources, associated with unconfined aquifers in Quaternary deposits (mainly glacial, but including alluvium in the Clarks Fork Valley); and confined aquifers associated with a latticework of faults and fractures in Precambrian bedrock. The latter has fens that are only in basin settings, while Quaternary deposits have fens in all five fen settings.

The field inventory has not addressed the majority of potential peatland sites identified through photointerpretation in the study area (201 of 326). But it has addressed about 75% of the peatland surface area in the study area, and is taken as a qualitatively robust characterization of the peatland systems across the landscape. Most of the unsurveyed potential peatland sites in the study area are small sites on rugged Precambrian bedrock in the Absaroka Beartooth Wilderness area located between Muddy Creek and Lily Lake.

This inventory does not provide an intensive documentation of the abiotic and biotic features at any given site, which is potentially pursued as an intensive followup study and stratified sampling (e.g., Heidel and Jones 2006). Elsewhere in the country, the intensive inventory stage has been merged into initial study plans where there is already a compendium of expertise or other baseline circumscription of fen types and distribution (e.g., Chimner et al. 2007, Cooper and Wolf 2006).

The other highest remaining potential priorities for site-specific peatland systems inventory and verification in the study area include:

- evaluate four putative palsa fens, to verify potential smaller additions to the only confirmed palsa fen in the lower 48 states,
- evaluate a large peatland complex at the eastern end of the study area, at the upper end of subalpine habitat, to survey what may be the only subalpine site with a tree canopy component
- evaluate a unique pattern involving very broad mounds and swales, at a site near Reed Lake (Montana)
- evaluate the potential fen sites on Precambrian bedrock for the best of additional poor fens (which can be well-developed in spite of small size)
- evaluate the largest peatland mosaic at the upper end of Muddy Creek, to map and consider disturbance history at what may be the second largest peatland in the study area

This study only included one alpine site, and alpine sites may also be priorities for an expanded inventory whether separate or in combination with the above. The preliminary results from it suggest that the alpine sites have species and vegetation not found elsewhere in the study area. Furthermore, the alpine peatland habitat may provide stable groundwater microhabitat for Wyoming plant species of concern, along fen perimeter seeps and subirrigated wet meadow margins.

In addition, the origin of the different fen types is subject for further investigation, along with the fire disturbance regimes of large fens, the hydrological affects of road construction, and the relative stability or vulnerability of peatland systems to disturbance events or climate shifts in general. The GIS product and linked attribute table represent a robust reference, but additional documentation of vegetation characteristics, vascular and nonvascular floras in an intensive inventory approach is warranted. To date, there are 36 Wyoming plant species of concern known from study area peatlands. The survey of vascular species of concern and general flora is incomplete and the survey of bryophytes is scant. The Columbian spotted frog was noted in one of the soligenous subalpine fens (site represented in Figure 21) and is a U.S. Forest Service sensitive species. Surveys of reptiles and amphibians are rudimentary and surveys of invertebrates are scant. The preliminary botanical results of the peatland inventory to date, including Wyoming plant species of concern, are presented in greater detail in a U.S. Forest Service report (Heidel et al. in progress).

This inventory would not have been possible or at least not nearly as effective without the high-resolution digital NAPP CIR aerial imagery. This imagery only recently became available. The feedback loop between fieldwork and photointerpretation proved particularly important in a study area where the range of fen settings and diagnostic characteristics discernible on aerial photos were not known at the onset. A minimum of two years of fieldwork was needed to: 1) identify sites of questionable peatland determination and conduct field analysis to circumscribe color, texture and pattern features and revise the initial photointerpretation, 2) catalogue the array of settings and hydrologies present in the study area, and incorporate them in revising the initial photointerpretation, 3) develop and test a working list of diagnostic peatland patterns present in the study area as discernible on aerial photos, and incorporate them, too, in revising the initial photointerpretation, and 4) Compile all field-verified and inferred determinations in an attribute table linked to photointerpretation.

In the past, Wyoming peatland significance has often been characterized by the unique biological attributes and plant species of concern. The ranking confidence system that was developed provides a systematic framework for considering the degrees of peat development at a given site, without the benefit of field data. As it turns out, the rare plant species affinities are highly skewed to the topogenous fens, while there are well-developed soligenous systems present that have no Wyoming plant species of concern. This is all the more significant because there are well-developed peat-formation patterns in many of the soligenous fens, and because the formation of discrete zonation and pool complexes is generally taken to represent habitat specialization and a flora that includes microhabitat specialists (Fontaine et al. 2007).

One of potentially the important, unplanned contributions of this study is a comparison of a robust, ground-truthed dataset against National Wetland Inventory (NWI) mapping of peatland vegetation that was not available at the start of the study in its current form. The only NWI wetland type with saturated hydrological conditions as mapped in the study area is identified as a unit of Palustrine-Emergent-Saturated (PEMB). It is a new resource for Wyoming and this study indicates that is has merit as a tool for peatland inventory in the state.

A digital analysis of NWI mapping of the PEMB unit compared with the peatland photointerpretation product shows only 48% overlap (2,657,724 m^2 of 5,480,714 m^2). This limited overlap is partially an artifact of the differences in purposes and standards, and that would be brought into much closer alignment if they were applied consistently at the two largest peatlands. Swamp Lake was mapped in the current project as a single large peatland system, while the marshy central zones with standing water were mapped separately in NWI mapping. Likewise, all other photointerpreted peatland sites with open water zones had these inclusions mapped separately from PEMB vegetation in NWI mapping. The second largest area of peatland as mapped in NWI mapping is the Muddy Creek wetland complex. It was found in field surveys to be a mosaic of peatland and non-peatland, which for purposes of this project was omitted and only areas identified as contiguous from preliminary surveys were mapped in this project.

An initial review of all peatland sites greater than 10 ha, as mapped in this study, shows 100% correlation between NWI identification of PEMB presence in the same sites. However, there is a far greater area mapped by NWI as peatland (8,178,252 m^2) compared with that mapped in this study. This much more extensive mapping of peatland in NWI mapping is explained by a combination of conservative and incomplete mapping in this project (as in the Muddy Creek example, above), and by possible errors of omission at small sites. In addition, the NWI mapping of peatland is also interpreted as including non-peatland sites like wet meadow flats, riparian corridors and upland swales, as well as seeps; as visited in several surveys. The NWI mapping recognized many peatland sites less than 0.05 ha, but no peatland sites of this size were found in surveys. The only consistent omission in NWI peatland mapping was exclusion of solifluction peatlands that contained large pools.

The aforementioned comparison highlights the fact that total peatland acreages and proportions depend heavily on the conventions for delimiting peat habitat, including differences between mapping of peat systems/basins vs. mapping of vegetation zones within them. Regardless of the conventions, the results document that peatland systems are a significant proportion of the landscape approaching or exceeding 1%.

An idealized approach to systematic peatland inventory would start with NWI mapping, digital orthophotos, and data from confirmed peatland sites to date to produce an initial photointerpretation product. The next step would be to determine if there are any discernible characteristics apart from peatland size that can be used to elevate confidence in peatland determination for assigning a peatland confidence rank. In this study, the presence of an open water zone and the presence of fine-scale patterning associated with peatland development proved particularly effective. Then the peatland verification would address those of largest size, further stratified by location, and salient environmental parameters (potentially including elevation and surface geology) factoring in any indicators of peatland development to efficiently and effectively document the full array of peatland types throughout a given area.

It is important to note that this incremental process and stratified sampling would also be expected to produce the most reliable training data for remote sensing. A stratified sampling of peatlands and training point collection for under-represented wetland types represent the most important tasks to improve model accuracy and utility. The remote sensing was not able to replicate field inventory at present. It proved to be beyond the scope of this study to re-document known sites and develop complete peatland/wetland training data without knowing the systems in advance. The gaps in gathering vegetation training data from Swamp Lake, and the inclusion of non-peatland in mapped peatland sites (including standing water and emergent mash), were sources of error. Swamp Lake (Figure 12) and a large unnamed fen were interpreted as sagebrush-bunchgrass. The latter may also point to the idiosyncrasies of ASTER imagery for wetlands in a drought year. The skewed sampling, with gaps in gathering subalpine wet meadow training data was the source of serious commission in remote sensing of peatlands south of Island Park, modeled as vast areas of peatland. The omission of large areas in the Muddy Creek wetland complex from peatland mapping may also have contributed to the error rate. It is likely that ground-truthing of NWI peat polygons, ideally in combination with remote sensing, would improve fieldwork effectiveness and efficiency. With these tasks accomplished, it would then be feasible and effective to couple photointerpretation of NWI fen mapping with remote sensing and field data collection feedback to produce a final analysis more robust than any single method. This product and process is presented as a model for application elsewhere in Wyoming and in the rest of the Beartooth Mountains.

There are challenges to any approach at mapping peatland sites in this particular study area that were not found in the Medicine Bow Mountains. First, there are well-developed peat deposits in forested swamp sites that are not distinguishable from upland by any available photointerpretation or CART analysis. They are generally small patch features on the landscape within forested uplands, and apt to be excluded from wetland or peatland mapping. Most of the confirmed forested swamp sites were documented incidental to survey of peatland features or other wetlands in the vicinity. Second, there are fibrists present as microhabitat features in an array of other wetland and riparian sites that are not peatlands. Soil samples collected in 2007 were made from streams passing through wet meadows, in seep systems, and in thickets that were confirmed as fibrists. In some cases, the fibrist depth reached or exceeded 40 cm, and in many cases, they were in continuous patterns. In a few cases, they were part of wetland mosaics, problematic settings which met all the soils criteria (depth and fibrist structure) and have extensive peat, but they have highly irregular boundaries or narrow zones. For example, peat depths were taken at Chain Lakes, a giant seep landscape laced by streams, that ranged from 76-24 cm (76 cm @ upper/northern end vs. 24 cm @ lower/southern end close to open water; and intermediate values in between), but only at the lower end was peatland a prevalent wetland habitat. Chain Lakes and one smaller site were problematic mosaics mapped as peatland sites.

There are special challenges in use of CART modeling based on remote sensing and environmental parameters may warrant further consideration for peatland research in particular. CART modeling has been applied to map vegetation units of all sizes from matrix to small patch units, but not necessarily for "systems" made up of multiple vegetation features that often have high pattern heterogeneity (e.g., 90% water cover, or "striped" patterns as present in some fen sites of the study area). Moreover, it is entirely possible that the specific environmental parameters that have been used to model contemporaneous vegetation features so well may not reflect the paleo-environment that dictated over the origin of peatland habitat, or the subsurface hydrological stability parameters that dictate over contemporary peatland habitat perpetuation.

The remote sensing described in this report was experimental and represents an incremental step in identifying peatland systems. The project attempted to address two principal remote sensing issues for mapping peatlands: the viable spatial scales for peatland discrimination and the biophysical properties of peatlands that are spectrally distinguishable. Three spatial scales of imagery were analyzed: 30m Landsat, 15m ASTER, and 1m CIR aerial photos. Techniques employed seem to show that the Landsat is too spatially coarse, while the 15m ASTER may represent a threshold scale for landscape level analysis. The strongest support for the 15m scale was successful discrimination between peatland types (e.g. aapamire vs. carr-shrubs, etc). Further, discrimination of peatland types by the remote sensing model approach also supports spectral sensitivity of the ASTER imagery. Most peatlands types occurred on similar topographic features, but were successfully discriminated with the ASTER spectral signature. The preponderance of model error was in discriminating true peatlands from non-peatland types, pointing to a need for additional model improvement.

Model performance shows good distinction of the five peatland types but limited capacity to distinguish peatland from select upland types, pointing to some needed avenues for improvement. For instance, areas of wildfire burns frequently contained committed peatland model error (burned areas mapped as peatland). Another example is committed peatland model error within shadowed conifer stands. Additional model layers such as burn area strata or forest strata delimitations could easily be added to the model or analysis process. Much work could also be incorporated by additional remotely sensed data, such as texture measures from very fine resolution images, temporal change analysis, active remote sensing (LiDAR), or multiple look angle imagery. Finally, improved terrain modeling, such as slope position, would have been beneficial in the Beartooth Mountains. Given appropriate resources, a more robust model approach would be needed to accurately discriminate peatlands, and these models would need to be tuned to the mapping area of interest. For instance, peatlands of the San Juan or Sierra

Nevada mountains are distributed much differently than those in this study area (Chimner et al. 2007, Cooper and Wolf 2006).

There was no analysis of peat contributions to the watershed or their potential function as groundwater reservoirs. However, it was established that they are generally in headwater positions, and the majority have outlets. The orientation of many sites along pronounced fracture lines suggests there could be contributions from deep water sources. In a couple cases, peatlands straddle a divide and feed outlets in opposite directions. This information taken together with hydrology studies elsewhere indicates that they could delay or prolong water release, thus moderating stream flows. The permanence or seasonality of outlet flow has not been determined. A framework for addressing ecological isolation or connectivity of such peatlands is provided by Leibowitz (2003). The functional role of peatland systems in the Beartooth Mountains landscape is an additional research possibility.

In conclusion, this study provides a framework for closer analysis of peatland biological resources, functionality, and their relationships in the Beartooth Mountains. It also provides a model for systematic peatland inventory elsewhere in Wyoming.

ACKNOWLEDGEMENTS

This study was coordinated by Brent Truskowski, U.S. Environmental Protection Agency. The interest and administrative support of the Shoshone National Forest and Kent Houston, Ecologist, were integral to the research at all stages. The foundations laid by previous peatland researchers working in the study area are reflected in this report, including studies by Erwin Evert, Walter Fertig, George Jones and Sabine Mellmann-Brown. This study developed from pilot remote-sensing studies conducted with the help of Ken Driese and Rebekah Smith. Mark Andersen kindly provided later GIS analyses. Field assistance and field collaboration of Leslie Marty, Emily Elliott and Brian Elliott are acknowledged with appreciation. The editorial review of Gary Beauvais is acknowledged with appreciation. Special thanks are extended to all other colleagues who have shared information and provided opportunities to collaborate on and contribute to Rocky Mountain peatland research. Project funding was provided by the U.S. Environmental Protection Agency, Region 8 (Denver) and the University of Wyoming.

LITERATURE CITED

Austin, G. 2005. Draft U.S. Forest Service Rocky Mountain Region Fen White Paper. Prescott College, Prescott, AZ.

Austin, G. 2007. Fen inventory and evaluation form. Unpublished data sheet. San Juan National Forest, Gunnison, Colorado.

Baker, R.G. 1976. Late Quaternary vegetation history of the Yellowstone Lake Basin, Wyoming. Geological Survey Professional Paper 729-E. United States Geological Survey, Washington, D.C.

Barber, K.E. 1982. Peat-bog stratigraphy as a proxy climate record. In: A.F. Harding, ed. Climate change in Later Prehistory. Edinburgh University Press, Edinburgh, Scotland.

Beauvais, G.P., D.A. Keinath, and R. Smith. 2005. Predictive distribution models for 54 taxa of management concern in USDA Forest Service region 2. Electronic report and models submitted to U.S. Geological Survey. Wyoming Natural Diversity Database, Laramie, WY.

Bedford, B. and K. Godwin. 2003. Fens of the United States: distribution, characteristics and scientific connection versus legal isolation. Wetlands 23: 608-629.

Billings, W.D. and H.A. Mooney. 1959. An apparent frost hummock-sorted polygon cycle in the alpine tundra of Wyoming. Ecology 40:16-20.

Booth, R.K. and J.R. Zygmunt. 2005. Biogeography and comparative ecology of testate amoebae inhabiting *Sphagnum*-dominated peatlands in the Great Lakes and Rocky Mountain regions of North America. Diversity and Distributions 11:577-590.

Booth, R.K., J.R. Zygmunt and S.T. Jackson. 2005. Testate amoebae as paleoclimatic proxies in the Greater Yellowstone Ecosystem. University of Wyoming – National Park Service Research Center Annual Report.

Bradley, J.B. and T.D. Gerhardt. 2003. Mapping and characterization of mires and fens in North Park, Jackson County, Colorado. Johnson Environmental Consulting. Prepared for USDI Bureau of Land Management. Fort Collins, CO.

Breiman, L., J.H. Friedman, R.A. Olsen, and C.J. Stone. 1984. Classification and Regression Trees. Wadsworth and Brooks, Monterery, California.

Brooks, K.N. 1992. Surface hydrology. In: Wright, H.E., B.A. Coffin and N.E. P. Asseng, eds. The patterned peatlands of Minnesota. pp. 153-162. University of Minnesota Press, St. Paul.

Bursik, R. 1990. Floristic and phytogeographic analysis of northwestern Rocky Mountain peatlands, U.S.A. Masters Thesis. University of Idaho, Moscow, ID.

Chadde, S. W., J.S. Shelly, R.J. Bursik, R.K. Moseley, A.G. Evenden, M. Mantas, F. Rabe and B. Heidel. 1998. Peatlands on national forests of the Northern Rocky Mountains: ecology and conservation. Gen. Tech. Rep. RMRS-GTR-11. Ogden, UYT: USDA Forest Service, Rocky Mountain Research Station.

Chapman,S.S., Bryce, A. A., Omernik,J.M., Despain, D.G., ZumBerge, J., and Conrad, M., 2003. Ecoregions of Wyoming (color poster with map, descriptive text,summary tables, and photographs): Reston, Virgina, U.S. Geological Survey (map scale 1:1,400,000).

Chimner, R.A., J. Lemly, D.J. Cooper, K. Northcott. 2007. Final Report: Regional assessment of fen distribution, condition, and restoration needs, San Juan Mountains, Colorado. Prepared for the Environmental Protection Agency. Colorado State University, Fort Collins, CO.

Collins, E.I., R.W. Lichvar and E.F. Evert. 1984. Description of the only known fen-palsa in the contiguous United States. Arctic and Alpine Research 16(2):255-258.

Cooper, D. J. 1990. An evaluation of the effects of peat mining on wetlands in Park County, Colorado. Unpublished report prepared for Park County, Colorado.

Cooper, D.J. and R.E. Andrus. 1994. Patterns of vegetation and water chemistry in peatlands of the west-central Wind River Range, Wyoming, U.S.A. Can. J. Bot. 72:1586-1597.

Cooper, D.J. and E.C Wolf. 2006. Fens of the Sierra Nevada, California. Prepared for the USDA Forest Service. Department of Forest, Rangeland and Watershed Stewardship, Colorado State University, Fort Collins, CO, Cowardin, L.M., V. Carter, F.C. Golet and E.T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. FWS/OBS-79/31. Office of Biological Service, U.S. Fish and Wildlife Service. Washington, D.C.

Dorn, R.D. 2001. Vascular Plants of Wyoming. Mountain West Publishing Co., Cheyenne, WY.

Environmental Laboratory. 1987. Corps of Engineers Wetlands Delineation Manual, Technical Report Y-87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

ERO Resources Corporation. 2000. Final report: plant species of concern – portions of U.S. Hwy 212 (FH 4), The Beartooth Highway, Park County, Wyoming and Park County, Montana. Prepared for the Federal Highway Administration, Central Federal Lands Highway Division. Denver, CO.

Evert, E. F. 1982. Noteworthy collections, Wyoming. Madroño 29 (2): 124-125.

Evert, E.F. 1984. A research natural area proposal and suitability investigation report for the Cathedral Cliffs Wetland Complex. Unpublished report prepared for The Nature Conservancy and the Wyoming Native Plant Society.

Fertig, W. and G. Jones. 1992. Plant communities and rare plants of the Swamp Lake Botanical Area, Clarks Fork Ranger District, Shoshone National Forest. Unpublished report prepared for the Shoshone National Forest by the Wyoming Natural Diversity Database.

Fleming, W. 1966. Geohydrology of a mountain peat wetland, Medicine Bow Mountains, Wyoming. Masters thesis. Department of Watershed Mangement, Colorado State University, Fort Collins, CO.

Fontaine, N., M. Poulin and L. Rochefort. 2007. Plant diversity associated with pools in natural and restored peatlands. Mires and Peat 2:1-17.

Foose, R.M., D. U. Wise and G.S. Garbarini. 1961. Structural geology of the Beartooth Mountains, Montana and Wyoming. Geological Society of America Bulletin 72(8): 1143-1172.

Heidel, B. 2006. Glacial refugia and relicts. *Castilleja* 25(3): 6-7, 10-11.

Heidel, B. 2007. Wyoming plant species of special concern. Wyoming Natural Diversity Database, University of Wyoming, Laramie, WY.

Heidel, B. and S. Laursen. 2003. Botanical and ecological inventory of peatland sites on the Shoshone National Forest. Prepared for the Shoshone National Forest. Wyoming Natural Diversity Database, Laramie, WY.

Heidel, B. and R. Smith. 2004. Remote sensing to locate peatlands on Shoshone National Forest. Prepared for Shoshone National Forest. Wyoming Natural Diversity Database, Laramie, WY.

Heidel, B. and R. Thurston. 2004. Extensive inventory of peatland sites on the Medicine Bow National Forest. Prepared for the Medicine Bow-Routt National Forest. Wyoming Natural Diversity Database, Laramie, WY.

Heidel, B. and G. Jones. 2006. Botanical and ecological characteristics of fens in the Medicine Bow Mountains, Medicine Bow National Forest, Albany and Carbon counties, Wyoming. Prepared for the Medicine Bow-Routt National Forest. Wyoming Natural Diversity Database, Laramie, WY.

Heidel, B., W. Fertig, S. Mellmann-Brown, and K. Houston. In progress. Biology of Beartooth Mountains Fens. Prepared for the Shoshone National Forest. Wyoming Natural Diversity Database, Laramie, WY.

Ilnicki, P. and J. Zeitz. 2003. Irreversible loss of organic soil functions after reclamation. Pp. 15-32. In: L.E. Parent and P. Ilnicki, eds. Organic soils and peat materials. CRC Press, Boca Raton.

Johnson, J.B. and T.D. Gerhardt. 2003. Mapping and characterization of mires and fens in North Park, Jackson County, Colorado. Report prepared for Bureau of Land Management. Johnson Environmental Consulting, Fort Collins, Colorado.

Jones, G.P. and W. Fertig. 1999. Ecological evaluation of the potential Lake Creek Research Natural Area within the Shoshone National Forest, Park County, Wyoming. Unpublished report prepared for the Shoshone National Forest, USDA Forest Service by the Wyoming Natural Diversity Database, University of Wyoming.

Leibowitz, S.G. 2003. Isolated wetlands and their functions: an ecological perspective. Wetlands 23(3): 517-531.

Lemly, J. 2007. Fens of Yellowstone National Park, USA: regional and local controls over plant species distribution. Master of Science Thesis, Colorado State University, Fort Collins, CO.

Love, J. D. and A. C. Christiansen. 1985. Geologic Map of Wyoming. U.S. Geological Survey, scale 1:500,000.

Mellmann-Brown, S. 2004. Botanical and ecological inventory of selected peatland sites on the Shoshone National Forest. Prepared for Shoshone National Forest. Wyoming Natural Diversity Database, Laramie, WY.

Moore, P.D. and D. Bellamy. 1974. Peatlands. Springer-Verlag, NY.

Mountain Studies Institute. 2007. Identifying Fens in the San Juan Mountains with Digital Air Photographs. Downloaded in 2007 as posted at: http://www.mountainstudies.org/Research/fenProject.htm

Patterson, L. and D.J. Cooper. 2007. The use of hydrological and ecological indicators for the restoration of drainage ditches and water diversions in a mountain fen, Cascade Range, California. Wetlands. 27(2): 290-304.

Pearson, J.A. and M.J. Leoschke. 1992. Floristic composition and conservation status of fens in Iowa. Iowa Acad. Sci. 99(2):41-52.

Pierce, W.G. 1961. Permafrost and thaw depressions in a peat deposit in the Beartooth Mountains, northwestern Wyoming. U.S. Geological Survey Professional Paper, 424B: B1544-B156.

Pierce, W.G. 1965. Geological map of the Deep Lake Quadrangle, Park County, Wyoming. Geological quadrangle maps of the United States. U.S. Geological Survey, Washington, D.C.

Pierce, W.G. and W.H. Nelson. 1971. Geological map of the Beartooth Butte Quadrangle, Park County, Wyoming. Geological quadrangle maps of the United States. U.G. Geological Survey, Washington, D.C.

Pierce, W.G. 1980. Geological map of the Cody 1 x 2 Quadrangle, Wyoming. 1:250,000. (Compiled 1978). U.S. Geological Survey. Washington, D.C.

Quinlan, J.R. 1993. *C4.5:* Programs for machine learning. Morgan Kaufmann, San Mateo.

Reider, R.G. 1977. Radiocarbon dates from carbonates of soils on Bull Lake and Pinedale tills of the Libby Creek area, Medicine Bow Range, Wyoming. Contributions to Geology, University of Wyoming, 15:67-62.

Reider, R.G. 1983. A soil catena in the Medicine Bow Mountains, Wyoming, U.S.A., with reference to paleoenvironmental influences. Arctic and Alpine Research, Vol. 15(2): 181-192.

Robbins, E.K., R.A. Zielinski, J.K. Otton, D.E. Owen, R.R.Schumann, and J.P. McKee. 1990. Microbially mediated fixation of uranium, sulfur, and iron in a peat-forming montane wetland, Larimer County, Colorado. In: USGS Research on Energy Resources – 1990 Program and Abstracts: U.S. Geological Survey Circular 1060, pp. 70-71.

Rydin, H. and J. Jeglum. 2006. The Biology of Peatlands. Oxford University Press, Oxford, England.

Sears, P.B. 1935. Types of North American pollen profiles. Ecology 16(3): 488-499.

Sturges, D. L. 1967. Water quality as affected by a Wyoming mountain bog. Water Resources Research 3(4): 1085-1089.

Sturges, D. L. 1968. Hydrologic properties of peat from a Wyoming mountain bog. Soil Science 106:262-264

Sturges, D. L. and R. E. Sundin. 1968. Gross alpha and beta radiation in waters at a Wyoming mountain bog. Water Resources Research 4(1): 159-162.
USDA Forest Service, Rocky Mountain Region. 2002.

USDA Forest Service. 2002. Wetland protection – fens. Memo of 19 March 2002 from Marisue Hillard, Director of Renewable Resources in the Rocky Mountain Region, to Forest Supervisors. Regional directive. Denver, CO.

USDA Forest Service, Shoshone National Forest. 2005. CVU NRIS FSVeg: Natural Resources Information System: Field Sampled Vegetation, with FSVeg Data Dictionary, Version1.7.

USDA Natural Resources Conservation Service. 2006. Keys to Soil Taxonomy, 10th ed. Posted electronically at: http://soils.usda.gov/technical /classification/taxonomy/.

USDA Natural Resources Conservation Service. 2008a Soil classification in Shoshone National Forest, Wyoming. Unpublished data.

USDA Natural Resources Conservation Service. 2008b SNOTEL Precipitation Data Table - Monthly Data (Previous Water Years). Posted electronically at: http://www.wcc.nrcs.usda.gov/cgibin/state-site.pl?state=WY&report=precsnotelmon

USDI Environmental Protection Agency. 2007. Classification of Wetlands. Chapter 3. In: Nutrient Criteria Technical Guidance Manual. EPA-822-R-07-004. Posted electronically at: http://www.epa.gov/waterscience/criteria/nutrient/guidance/ .

USDI Fish and Wildlife Service. 1998. Regional policy on the protection of fens. Unpublished memo from Mary Gessner, Region 6 Director, sent to project leaders for ecological services, refuges and wildlife, and fish and wildlife management assistance in Region 6.

USDI Fish and Wildlife Service. 1999. Regional policy on the protection of fens, as amended, from the Regional Director (Region 6), to project leaders for Ecological Services, Refuges and Wildlife, and Fish and Wildlife Management Assistance. Denver, CO.

Verry, E.S. and D.H. Boelter. 1978. Peatland hydrology. *In:* Greeson, P.E., J.R. Clark, and J.E. Clark, eds. Wetland functions and values: the state of our understanding. American Water Resources Association. Proceedings of the National Symposium on Wetlands, November 7-10, 1978.

Walford, G., G. Jones, W. Fertig, S. Mellmann-Brown and K. Houston. 2001. Riparian and wetland plant community types of the Shoshone National Forest., Rocky Mountain Res. Stn. Gen. Tech. Report RMRS-GTR-85. USDA Forest Service, Ogden, UT.

Weddell, B.J. 2005. Peatlands: potential national natural landmarks in the Northern Rocky Mountains. Prepared for the Idaho Cooperative Fish and Wildlife Unit, Moscow, ID. Submitted to the National Park Service, Pacific West Region, Seattle, WA.

Whitlock, C. 1993. Postglacial vegetation and climate of Grand Teton and Southern Yellowstone National Parks. Ecological Monograph 63:173-198.