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Soils of Peatlands: Histosols and Gelisols

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CONTENTS

Introduction

Peatlands are a subset of wetlands that have accumulated significant amounts of soil organic matter. Soils of peatlands are colloquially known as peat, with mucks referring to peats that are decomposed to the point that the original plant remains are altered beyond recognition (Chapter 6, SSSA 2008). Generally, soils with a surface organic layer >40 cm thick have been classified as Histosols in the U.S. soil classification system—Soil Taxonomy (Soil Survey Staff 2014). Permafrost-affected organic soils are classified as the Histels suborder in the Gelisols order (Soil Survey Staff 2014). Based on current calculations of earth's land surface of 148,940,000 km^2 and our estimate of peatland area (or the combined area of Histosols and Histels) (Table 10.1), peatlands occupy about 2.7% of the earth's surface.

Peatlands have historically been classified based on a number of criteria, such as topography, ontogeny (i.e., landscape developmental sequence), hydrology, soil and/or water chemistry, plant community composition, and degree of soil organic matter decomposition (Moore and Bellamy 1974; Cowardin et al. 1979; Gore 1983; Bridgham et al. 1996; National Wetlands Working Group 1997; Inisheva 2006; Vitt 2006). Given the confusion in peatland terminology and the emphasis of this chapter on soils, we will discuss here only the dominant ecological paradigm in peatlands—the ombrogenous–minerogenous gradient. Although the fundamental definition of this gradient is based on hydrology, it is often

TABLE 10.1

Current and Historical Global Peatland Area (in 10^3 km^2)

Regions[a]	Current	Historical
Alaska[b]	132	132
Canada[b]	1136	1150
Mexico[b]	10	–
US[c,b]	93	111
North America[b]	1372	1407
Northern	3728[d]	4045[e]
Tropical	285[f]	441[g]
Global	4013	4486

[a] Includes both permafrost and non-permafrost peatlands.
[b] Bridgham et al. (2006).
[c] Not including Alaska.
[d] Historical area—loss of 316,000 km^2 reported in Joosten (2009).
[e] Includes all non-tropical peatlands in Northern and Southern Hemispheres (Yu et al. 2010).
[f] Historical area—loss of 156,000 km^2 reported in Joosten (2009).
[g] Page et al. (2011).

thought to be coincident with (and a primary control over) plant community composition and the biogeochemistry of peatland soils (Bridgham et al. 1996).

Minerogenous peatlands have significant inputs of groundwater and/or upland runoff, generally imparting higher basic cation content and pH to their soils (Heinselman 1963; Moore and Bellamy 1974). These peatlands are generally called fens, whereas treed minerogenous peatlands are often termed swamp forests in North America, although this latter term is also used to describe forested wetlands on mineral soils (National Wetlands Working Group 1997). In contrast, ombrogenous peatlands, through deep accumulation of peat, have achieved a landscape topographic position where they are isolated from all but atmospheric inputs of water, alkalinity-generating cations, and nutrients. As a result, they have low ash and basic cation content and low pH in their soils, and are commonly termed bogs. Fens exhibit a wide range of minerotrophy due to complicated interactions between hydrology, topographic landscape position, and chemistry of surrounding and/or underlying mineral soils and groundwater (Bridgham and Richardson 1993; Bridgham et al. 1996; Verry 1997, 2006). For example, a region where mineral soils are dominated by sand with very low exchangeable cations can have fens with significant groundwater input but soil chemistry and plant communities more characteristic of bogs.

Fens with more minerogenous characteristics (i.e., higher soil pH and basic cation content) are generally described as "rich," whereas those more similar to bogs in soil chemistry and plant community composition are called "poor." Bridgham et al. (1996) objected to terms such as rich and poor fens, because they essentially describe a gradient of pH and basic cation concentration, while most studies have pointed to nitrogen and/or phosphorus as the limiting nutrients for plant growth in peatlands. They suggested that nutrient availability gradients may not be coincident with the ombrogenous–minerogenous gradient; experimental results have demonstrated that nitrogen availability is greater in more minerogenous peatlands, whereas phosphorus availability is higher in more ombrogenous peatlands (Bridgham et al. 1998; Chapin 1998), although recent research using enzymes as indicators of nutrient availability indicated that phosphorus was more limited than nitrogen across a ombrogenous–minerogenous gradient in northern Minnesota (Hill et al. 2014).

The effect of permafrost on peatlands is dramatic, lending support to defining the soil suborder Histels for permafrost-affected organic soils. The formation and development of several major peatland types are the direct result of permafrost action (Zoltai and Tarnocai 1971; Moore and Bellamy 1974; National Wetlands Working Group 1988; Botch et al. 1995; Ahrens et al. 2004). Additionally, soil carbon pool sizes, distribution, and bioavailability are strongly affected by (1) cryoturbation, which is the soil-mixing action of freeze/thaw processes, and (2) by the presence of permafrost itself, which has strong controls over soil temperature and moisture and runoff (Michaelson et al. 1996). Overall, permafrost-affected soils represent 16% of all soils on the globe, and contain up to 50% of the global belowground soil carbon pool (Tarnocai et al. 2009).

The literature on peatlands is vast, and we focus here only on the soils, particularly within the context of the ombrogenous–minerogenous gradient and the effects of permafrost. The objectives of this chapter are to: (1) summarize the geographic distribution of the world's peatlands, (2) describe Gelisols as defined in Soil Taxonomy and compare it to classifications of other countries and organizations, (3) examine the effects of the physical structure and botanical composition of various peats on their hydrologic properties, and (4) compare the physical and chemical characteristics of peats in U.S. wetlands from Florida to Alaska, with an emphasis on the ombrogenous–minerogenous gradient for Histosols and the defining characteristics due to permafrost in Gelisols.

Geographic Distribution

Global Peatlands

Ground-based estimates, remote sensing, and hydrological modeling have all been used to estimate the regional distribution and global area of wetlands (reviewed in Lehner and Döll 2004; Bridgham et al. 2006; Melton et al. 2013), but it is likely that ground-based estimates most effectively delineate peatlands from other wetland types (cf. Lehner and Döll 2004). There are two distinct peaks of wetland area in the tropical and boreal zones, with tropical wetlands being primarily mineral-soil based and boreal wetlands being primarily peatlands (Figure 10.1). It is interesting that, while northern climates are clearly conducive to peat formation, large areas of tropical peatlands do exist (Table 10.1)—for example, very deep peat deposits occur in Indonesia and the Amazon (Page et al. 2011). Remote sensing techniques suggest that the area of tropical wetlands may have been formerly underestimated (Gumbricht 2012).

Table 10.2 gives the distribution of organic soils within the U.S. There are two related databases maintained by the USDA that provide the best available estimates of organic soil area in the U.S. (Soil Survey Staff 1998). MUIR (Map Unit Interpretation Record) contains digitized soil maps at a scale of 1:12,000–1:31,680, but large areas of certain states have not had soil surveys completed. This includes states such as Michigan and Minnesota that have large expanses of organic soils. In the STATSGO (State Soil Geographic) data base, other sources of information are used to estimate soil information in unmapped areas, but the scale is at 1:250,000, except Alaska, which is at 1:1,000,000. In states that are poorly mapped, STATSGO data are necessary to obtain realistic estimates of peatland area. However, because of the coarse scale, STATSGO fails to recognize many small pockets of organic soils. Consequently, it was deemed most accurate to take the highest estimate of

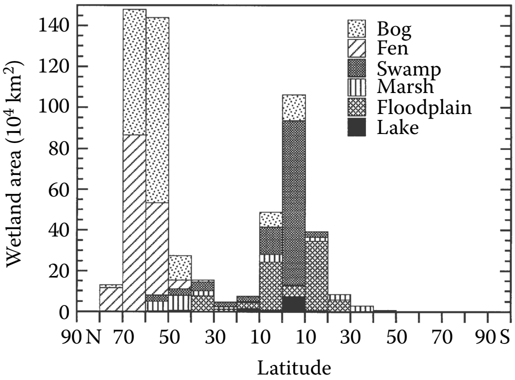

FIGURE 10.1
Global wetland area in 10° latitudinal belts for various wetland types. (Modified from Aselmann, I. and P. J. Crutzen. 1989. *J. Atmos. Chem.* 8: 307–359. With permission from Kluwer Academic Publishers.)

STATSGO or MUIR for each state (Soil Survey Staff 1998). Total organic soil area in the U.S. is 234,006 km^2 (Table 10.2), with Alaska alone accounting for 56% of all peatlands. Excluding Alaska, the two regions with the most organic soils are the Midwest and South. In particular, large areas of peatlands occur in Michigan, Minnesota, Wisconsin, Florida, Louisiana, and North Carolina.

The distribution of Alaskan peatlands into Histosols and Gelisols demonstrates that 67% of its peatlands are affected by permafrost. Tarnocai (1998) estimated that 36% of Canadian peatlands had permafrost features (Organic Cryosols). In particular, significant areas of peatlands occur in the zone of discontinuous permafrost (Gorham 1991). Mosses and black spruce tend to enhance permafrost formation in this discontinuous zone (Van Cleve et al. 1991; Camill and Clark 1998).

Global Carbon Storage in Peatlands

Although peatlands only occupy approximately 2.7% of the terrestrial land surface, they represent a globally significant carbon pool because of the deep organic soil deposits that have accumulated over thousands of years. Gorham (1991) estimated that boreal and subarctic peatlands contain 455 Pg C (1 Pg = 10^{15} g). This is very similar to the global peatland carbon pool of 462 Pg estimated by Bridgham et al. (2006). In comparison, Yu et al. (2010) estimated that Northern Hemisphere boreal and subarctic peatlands contain 547 Pg C, tropical peatlands contain 50 Pg C, and Patagonia peatlands contain 15 Pg C, for a total of 612 Pg C. Histels alone are estimated to contain 184 Pg C (Tarnocai et al. 2009), and thus contain a substantial fraction of world's peatland carbon.

Peat deposits of the boreal region tend to be deeper than those of the subarctic, and the boreal region has higher long-term net carbon accumulation rates (Ovenden 1990; Gorham 1991; Botch et al. 1995; Ping et al. 1997a; Bridgham et al. 2006; Kolka et al. 2011). On average, long-term accumulation rates in subarctic and boreal peatlands were estimated to be 7–11 and 23–41 g m^{-2} yr^{-1}, respectively (Ovenden 1990). Carbon accumulation rates ranged from 12 g m^{-2} yr^{-1} in Arctic peatlands to 80 g m^{-2} yr^{-1} in more minerotrophic mires in the boreal and temperate zones of the former Soviet Union, with an average of 30 g m^{-2} yr^{-1} (Botch et al. 1995). Bridgham et al. (2006) estimated the mean carbon accumulation rate to

TABLE 10.2

Area of Organic Soils (km^2) in the United States

State	Histosol	Data[a]	Histel	State	Histosol	Data	Histel
Midwest				**South**			
Illinois	356	M	–	Alabama	809	S	–
Indiana	1490	S	–	Arkansas	–	M	–
Iowa	301	M	–	Florida	15,943	S	–
Kansas	–	M	–	Georgia	1879	S	–
Michigan	16,511	S	–	Kentucky	–	M	–
Minnesota	24,345	S	–	Louisiana	9537	M	–
Missouri	51	M	–	Mississippi	908	S	–
Nebraska	44	M	–	North Carolina	6339	S	–
North Dakota	26	M	–	Puerto Rico	28	M	–
Oklahoma	–	M	–	South Carolina	650	S	–
South Dakota	–	M	–	Tennessee	–	M	–
Wisconsin	13,476	S	–	Texas	52	M	–
Total	56,601			Virginia	549	S	–
				Total	36,693		
Northeast				**West**			
Connecticut	434	S	–	Alaska	43,201	S	88,994
Delaware	356	S	–	Arizona	–	M	–
Maine	3965	S	–	California	617	S	–
Maryland	949	M	–	Colorado	335	S	–
Massachusetts	1364	M	–	Hawaii	1920	M	–
New Hampshire	899	M	–	Idaho	236	S	–
New Jersey	732	M	–	Montana	260	S	–
New York	3131	S	–	Nevada	74	S	–
Ohio	309	S	–	New Mexico	1	M	–
Pennsylvania	163	M	–	Oregon	329	S	–
Rhode Island	119	S	–	Utah	28	S	–
Vermont	270	M	–	Washington	790	M	–
West Virginia	–	M	–	Wyoming	30	M	–
Total	12,692			Total	47,821		88,994

Source: Adapted from Soil Survey Staff. 1998. *Query for Histosol Soil Components in the National MUIR and STATSGO Data Sets 8/98*. Natural Resource Conservation Service, USDA, Lincoln, NE and Statistical Laboratory, Iowa State University, Ames, IA.

Note:
Total Peatlands = 234,006.
Total Histosols = 153,807.
Total Wetland Histosols = 145,012.
Total Folists = 8795 km^2.

[a] S = STATSGO, M = MUIR. The highest Histosol area was taken from either STATSGO (State Soil Geographic database) or MUIR (Map Unit Interpretation Record database). Folist and Histel area were taken from STATSGO.

be 7.1 g m^{-2} yr^{-1} for the conterminous U.S. while Kolka et al. (2011) synthesized the literature and reported a range from 0.7 to 42 g m^{-2} yr^{-1} across all Histosols with rates generally increasing with decreasing latitude.

Although peatlands are generally sinks for atmospheric carbon, they are also important sources of greenhouse gases. Wetlands are an important land use that is tracked by countries for Intergovernmental Panel on Climate Change (IPCC) reporting (IPCC 2006). Recently a Wetlands Supplement was produced by the IPCC to better account for greenhouse gas fluxes and changes in carbon pools for managed peatlands (IPCC 2014). Kolka et al. (2011) completed a synthesis of the literature for carbon dioxide and methane fluxes from peatlands across the globe. For natural or unmanaged peatlands, the mean flux of carbon dioxide was 79.5 mmol m^{-2} d^{-1} (range 12–152 mmol m^{-2} d^{-1}), while for methane it was 5.4 mmol m^{-2} d^{-1} (range 0.03–18 mmol m^{-2} d^{-1}). A number of peatland drainage experiments were also included in the synthesis and drainage tends to increase carbon dioxide fluxes by about a factor of three while decreasing methane fluxes by about a factor of three (Moore and Knowles 1989; Nykanen et al. 1995; Strack et al. 2004; Kolka et al. 2011).

Gelisols

Histosol soil classification was discussed in Chapter 6. In this section we will briefly discuss the classification of organic soils in three widely used soil classification systems. In Soil Taxonomy, the U.S. soil classification, organic soils not affected by permafrost are placed in the Histosol order and those affected by permafrost are keyed out in the Histels suborder under the Gelisol order. Great groups of Histels are defined by fiber contents, period of saturation (differentiation of histic vs. folic) and presence of ground ice. In the Canadian system (Soil Classification Working Group 1998), organic soils are recognized at the Organic order, and the ones affected by permafrost are keyed out in the Organic Cryosol great group of the Cryosolic order. Subgroups then are defined by fiber content of the control section or by the depth of peat over mineral soil or ice. In the World Reference Base system (IUSS Working Group WRB 2006), organic soils are recognized at the Reference Soil Group (RSG) as Histosol and those affected by permafrost are placed at the second level with a qualifier as Cryic Histosol. In all three systems, the requirements for Histosols and permafrost-affected Histosols (Histels) are comparable.

Comparison of Four Classification Schemes

By way of comparison, we examine four alternative methods for classifying organic soils from Florida to Minnesota and two histic epipedons from a beaver meadow (Table 10.4 and see *Peat Biogeochemistry—A Comparative Approach* below). The first method is the USDA protocol (Soil Survey Staff 2014), as described in Chapter 6. The second is the ASTM protocol (ASTM 2013), with sapric, hemic, and fibric peats having 0%–32%, 33%–67%, and >67% dry-mass unrubbed fiber, respectively. The third method is the Canadian protocol (Soil Classification Working Group 1998), with sapric peat having a rubbed fiber content of <10% by volume and a pyrophosphate index (determined on the Munsell color chart after inserting white chromatographic paper into a paste composed of peat and a sodium-pyrophosphate solution) of ≤3, fibric peat having ≥75% rubbed fiber content by volume *or* ≥40% rubbed fiber by volume and a pyrophosphate index of ≥5, and hemic peat failing to meet the requirements of fibric or sapric peat. The fourth method is the von Post scale (Mathur and Farnham 1985; Parent and Caron 1993; ASTM 2013), where sapric, hemic, and fibric peats have von Post ratings of 7–10, 4–6, and 1–3, respectively.

None of the samples had ≥75% average rubbed fiber content by volume, but most of the bog and acidic fen soils would be classified as fibric in the USDA and Canadian systems based on their pyrophosphate color. Visually these samples were composed predominantly of moderately to undecomposed *Sphagnum* fibers. Similar results were obtained with the ASTM classification system. The von Post scale gave a greater variety of classification values for bogs and acidic fens.

The intermediate fens, tamarack swamps, and cedar swamps had hemic peat according to most of the classification systems, whereas the histic epipedon in the beaver meadows, the ash swamp, and the southern peats had sapric material according to one or more of the classification systems. Correlations between the classification systems ranged from an r^2 of 0.54 (between von Post and ASTM) and 0.88 (between Canadian and ASTM). Thus, quite different classifications can be given by the different systems, even though peats are only divided into three decompositional categories. Overall, the Canadian system tended to give highest values (i.e., the fewest Saprists and Hemists), and the USDA and von Post systems the lowest values (Table 10.4).

There are 279 Histosol soil series in the U.S. (excluding Folists) (Kolka et al. 2011). Of those series, 9.3% are Fibrists, 29.4% Hemists, and 61.3% Saprists. In comparison, Canadian Histosols (their Organic order) are 36.8% Fibrists (their Fibrisol), 61.8% Hemists (their Mesisol), and only 1.4% Saprists (their Humisol; Tarnocai 1998). The differences between the two countries probably reflect greater decomposition of peats at lower latitudes (see *Peat Biogeochemistry—A Comparative Approach* below), and the tendency of the Canadian soil classification system to place similar peats into less decomposed categories than the U.S. system, as discussed above.

Malterer et al. (1992) reviewed methods of assessing fiber content and decomposition in northern peats. They compared the von Post method, the centrifugation method of the former Soviet Union (Parent and Caron 1993), the USDA pyrophosphate color test and fiber-volume methods, and the ASTM fiber-weight method. Their analyses indicate that the centrifugation method of the former Soviet Union and the von Post humification field method separate more classes of peat with greater precision than the USDA and the ASTM methods. Stanek and Silc (1977) similarly found the von Post method differentiated more classes of well-humified peat than the rubbed and unrubbed fiber volume methods and the pyrophosphate color test of the USDA.

The pyrophosphate method is not particularly effective at extracting peat humic substances (Mathur and Farnham 1985). Additionally, the use of pyrophosphate color is limited because it is a qualitative variable, although spectrophotometric alternatives exist (Day et al. 1979). Mathur and Farnham (1985) state, “There is little theoretical basis for assuming that the color intensity of a [pyrophosphate] peat extract should be closely related to the extent of humification or that the extraction would be even semiquantitative in the presence of significant amounts of mineral matter.” However, the pyrophosphate color index is reasonably well correlated with other measures of humification in Table 10.5.

Hydrology

Hydrology and Peatland Development

Hydrology is the central factor, by definition, in the formation of all hydric soils, but peatlands are unique in the degree of autogenic (i.e., biotically driven) feedbacks between plant production and community composition, microbial decomposition, soil biogeochemistry, and hydrology (Heinselman 1963, 1970; Moore and Bellamy 1974; Siegel 1992; Belyea and Baird 2006). Under waterlogged conditions, especially in northern latitudes as noted above, net primary production generally exceeds decomposition, resulting in peat formation. The peat's botanical source, state of decomposition, bulk density, and depth interact to determine its hydraulic conductivity (Boelter 1969; Päivänen 1973; Silins and Rothwell 1998; Weiss et al. 1998). At some point, accumulation of deep, highly decomposed peat may impede vertical groundwater exchange with the surface layers. Additionally, the formation of peat itself increases water retention. As water retention increases, the peatland expands above the regional water table, and often above the surrounding landscape. At this point, an ombrogenous system has developed, with its characteristic soil chemistry and plant communities. Thus, we see a succession over time in many peatlands from fens to bogs, with an increasing state of ombrotrophy as a result of increasing biotic control over hydrology.

There are climatic limitations on this process: fens can occur in any climate because of their dependence on outside sources of water, whereas bogs can only occur in regions where precipitation exceeds evapotranspiration. The preponderance of peatlands in northern latitudes is at least partially due to lower temperatures limiting evapotranspiration, so that peatland formation is favored in areas of even moderate precipitation. However, substrate permeability, artesian pressure heads, landform, and other groundwater factors can override macroclimate in the formation of large peatland complexes (Heinselman 1970; Siegel and Glaser 1987). In permafrost regions, drainage is further slowed by the seasonal freeze–thaw cycle, underlying permafrost, and low evapotranspiration rates, especially on north-facing slopes (Rieger 1983) where "hanging bogs" were described. Permafrost may also act as a confining aquatard, creating artesian conditions for groundwater discharge and spring-fed wetlands (Racine and Walters 1994).

Hydrology and Peat Characteristics

As noted above, an important attribute of peats is their ability to hold and retain water. Undecomposed fibric peats are predominantly composed of air- or water-filled pore spaces of large diameter (>600 μm, Boelter 1964; Päivänen 1973; Silins and Rothwell 1998). This, in combination with low-density organic matter, results in a saturated water content often exceeding 1000% of oven-dry mass and 90% of total peat volume (Boelter 1964, 1969; Päivänen 1973; Damman and French 1987) (see Figure 10.2). More decomposed, higher bulk density peats and herbaceous peats have smaller pore spaces and correspondingly lower water-storage capacity under saturated conditions, although they still maintain >80% saturated water content by volume (Boelter 1964, 1969; Päivänen 1973; Silins and Rothwell 1998) (see Figure 10.2). However, water is held in the large pore spaces of fibric peat primarily by detention storage (i.e., easily drainable porosity), and even moderate soil tensions result in large losses of the stored water (Figure 10.2). Similar to mineral soils, more decomposed, higher bulk density peats, with correspondingly smaller diameter pore spaces, have greater water retention under unsaturated conditions, and this difference increases at higher soil tension (Figure 10.2). The different botanical compositions of peats also have an important effect on water-holding capacity and retention (Boelter 1968; Weiss et al. 1998).

Surface peats have horizontal conductivities that are orders of magnitude greater than downward hydraulic conductivities in deeper peats (Päivänen 1973; Ingram 1982, 1983; Gafni and Brooks 1990). An important cause of this anisotropy is that deeper, more decomposed peat layers tend to have lower saturated hydraulic conductivity (Figure 10.3). In peatland terminology, water flow occurs predominantly in the upper, seasonally aerobic layer of the peat, or acrotelm, with very low flow through the deeper, permanently anaerobic layer,

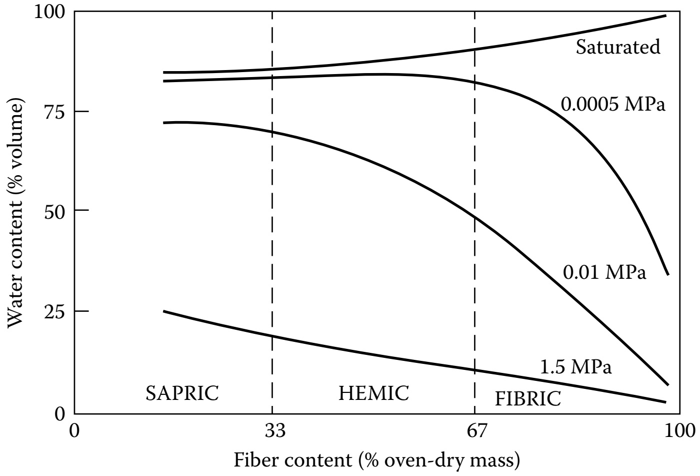

FIGURE 10.2
Relationship between fiber content of peat, water content, and soil water potential. Note that the definition for sapric, hemic, and fibric peats is somewhat different than used today in the U.S. (Modified from Boelter, D. H. 1969. *Soil Sci. Soc. Am. Proc.* 33: 606–609. With permission.)

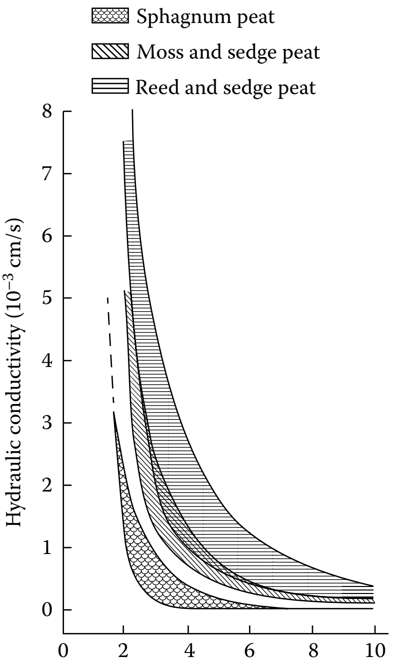

FIGURE 10.3
Effect of the botanical composition of peat and degree of humification on saturated hydraulic conductivity of peats. Humification is given in the qualitative von Post scale, where 1 is undecomposed and 10 is extremely decomposed. (Modified from Baden, W. and R. Eggelsmann. 1963. *Zulturtech. Flurber.* 4: 226–254.)

or catotelm (Damman 1986). Interestingly, unsaturated hydraulic conductivity is greater in more decomposed peats with smaller-diameter pore spaces (Silins and Rothwell 1998), similar to mineral soils (Brady and Weil 2008). Additionally, the plant composition from which the peat was derived has a dramatic effect on saturated hydraulic conductivity, with reed–sedge peat having the highest conductivity, and *Sphagnum* peats the lowest within any particular humification class (Figure 10.3). Undecayed *Sphagnum* moss has very high saturated conductivities, but conductivity decreases rapidly upon humification. Despite the high surface saturated conductivity of peats, horizontal water movement is very slow due to the low slope gradient (Brooks 1992, Chapter 3). A review of the literature indicates peat soil hydraulic conductivities range from greater than 200×10^{-3} cm s^{-1} in upper bog layers in Minnesota (Gafni and Brooks 1990) to 0.00011×10^{-3} cm s^{-1} in basal blanket peat in England (Holden and Burt 2003, Kolka et al. 2011). Bulk density varied from 0.8 g cm^{-3} in older lower layers of a Norwegian bog (Ohlson and Okland 1998) to 0.02 g cm^{-3} in the surface layer of a raised bog in New Brunswick (Korpijaako and Radforth 1972; Kolka et al. 2011).

These properties of peats have important ecological and economic consequences. The water table is often far below the surface in many peatlands, particularly in bogs, during the growing season (Boelter and Verry 1977; Bridgham and Richardson 1993; Verry 1997), and desiccation is an important constraint on the growth of *Sphagnum* mosses (Titus and Wagner 1984; Rydin 1985; Weltzin et al. 2001). Under drought conditions with a water table far below the surface, more decomposed peats would maintain higher plant-available water and faster transport of water to the roots (Päivänen 1973; Silins and Rothwell 1998).

Water retention and hydraulic conductivity are also important considerations in runoff from peatlands, drainage operations, and in commercial forestry in peatlands (Boelter 1964; Boelter and Verry 1977; Silins and Rothwell 1998). Drainage of highly decomposed, subsurface peats is quite difficult. Often effective drainage only occurs within 10 m or less of ditches (Bradof 1992a). As an example, failed attempts at draining the large Red Lake peatland complex in northwestern Minnesota from 1907 through the 1930s resulted in virtual bankruptcy of several counties and were only resolved when the state took over large areas of tax-delinquent lands (Bradof 1992b).

We have presented the traditional view of peatland hydrology. However, the work of Siegel and colleagues (Chason and Siegel 1986; Siegel 1988, 1992; Siegel and Glaser 1987; Glaser et al. 2004) has questioned the assumption that vertical flow is negligible in peatlands, and particularly in bogs because of very low conductivities in deep peat. With both field work and hydrologic modeling studies, they have demonstrated that the hydraulic head in raised bogs is sufficient to drive downward water flowpaths, making bogs recharge zones and adjacent fens discharge zones (see Chapter 3 for a discussion of these concepts). Even more interestingly, they have shown some bogs and fens to vary seasonally between being recharge and discharge zones. Chason and Siegel (1986) found much higher hydraulic conductivities in deep, decomposed peats than previous studies, which they attribute to discontinuous zones of buried wood, roots, and other structural features in peat that form "pipes" with extremely high conductivities. Working with the same group of scientists, Reeve et al. (2000) modeled vertical flow in peatlands. They found that vertical flow is negligible in raised bogs. Also, they determined that the amount of vertical flow depends on the differences in hydraulic conductivity with depth, especially at the catotelm/mineral soil boundary. Vertical flow can be more important when the mineral layer below the bog is permeable. If underlying sediment is impermeable, horizontal flow dominates. Further modelings work by Reeve et al. (2006) indicate that seasonal changes in water storage can influence the amount of vertical flow with high water tables with more head leading to higher vertical flows such as found during spring following snowmelt.

Runoff from peatlands outside permafrost areas is low, although it is higher in fens than bogs because of relatively constant groundwater inputs into fens and the potential for fens to also be present on gentle slopes (Boelter and Verry 1977; Verry 1997). However if permafrost is present, the infiltration and surface storage is low, and runoff occurs (Kane and Hinzman 1988). Free water mainly drains laterally above the permafrost following the slope. According to a study conducted in the interior of northeastern Russia, the ratio of water drained laterally to vertically is 8:1 (Alfimov and Ping 1994).

Peat Biogeochemistry: A Comparative Approach

Conterminous U.S. Peats: The Ombrogenous–Minerogenous Gradient

We examined 39 physical and chemical properties of soils from 20 different wetlands (Tables 10.3 and 10.4), 17 in northern Minnesota, 2 in North Carolina, and 1 in Florida. The Minnesota sites were part of a larger study in carbon and nutrient dynamics in wetlands and were placed along an ombrogenous–minerogenous gradient according to dominant vegetation and soil pH (Bridgham et al. 1998). While this gradient is strictly defined based on hydrology, field data generally show a close correspondence between hydrologic status, vegetation, and soil chemistry (Sjörs 1950; Heinselman 1963, 1970; Glaser 1987; Grootjans et al. 1988; Vitt and Chee 1990; Gorham and Janssens 1992; Vitt 2006). All sites were classified as Histosols, except for two of the Minnesota sites, Upper and Lower Shoepack, which were beaver meadows in Voyageurs National Park with a surface histic epipedon of from 8 to 21 cm thickness over a mineral layer.

The short pocosin (an ombrotrophic bog dominated by stunted ericaceous shrubs) and gum swamp (minerogenous forested swamp dominated by *Nyssa sylvatica*, *Liquidambar styraciflua*, *Acer rubrum*, and *Taxodium distichum*) sites in the Coastal Plain of North Carolina are described in Bridgham and Richardson (1993). The Florida Everglades site is dominated by sawgrass, *Cladium jamaicensis*. It is part of Water Conservation Area 2A and has not been impacted by agricultural runoff (C. Richardson, Duke University, personal communication). Five replicate cores from 0 to 25 cm depth were taken from hollows in each site, when significant microtopography was present.

We put the 39 variables from all 20 wetlands in Tables 10.3 and 10.4 into a principal component analysis (PCA; Wilkinson et al. 1992). PCA is a multivariate technique that combines the physical and chemical factors into master variables called components that explain the most variation in the data set. The correlation of all 39 variables with the three most important principal components is presented in Figure 10.4. The first principal component had high positive weightings from lignin, the lignin:cellulose ratio, bulk density, and the von Post index. In contrast, variables with high negative principal component 1 weightings were pyrophosphate color, rubbed and unrubbed fiber, water and acid soluble components, soluble phenolics, and extractable potassium. These variables suggest that principal component 1 describes a decomposition axis, with peat that has high positive values being highly decomposed.

The second principal component describes an alkalinity/pH axis, with high weightings from extractable Ca and Mg, the Ca:Mg ratio, cation-exchange capacity, total exchangeable bases, %base saturation, and pH (Figure 10.4). Interestingly, %humin, total soil nitrogen, and calcium-chloride extractable N clumped with these alkalinity variables, which suggest

TABLE 10.3

Chemical Characteristics of the Average of Five 0 to 25 cm Depth Cores from 20 Sites

									%AFDM		
Site	**Type**	**Lat. N**	**Total Org. C%**	**Total N%**	**Total P%**	**C/N**	**C/P**	**N/P**	**Nonpolar Extr.**	**Water Soluble**	**Acid Soluble**
Arlberg	Bog	46° 55′	41.7	1.26	0.044	33.2	971	29.0	7.00	11.60	45.9
Ash River	Bog	48° 24′	44.2	1.13	0.054	39.7	826	20.9	8.41	8.80	53.7
Pine Island	Bog	48° 17′	43.5	1.14	0.055	38.4	849	21.7	8.70	11.42	50.2
Red Lake	Bog	48° 22′	42.7	1.05	0.063	41.2	692	16.8	8.59	10.83	55.4
Toivola	Bog	47° 4′	42.2	1.12	0.039	37.8	1228	31.7	7.01	8.05	55.1
Marcell	Acidic fen	47° 31′	41.6	1.63	0.048	25.6	876	34.4	8.73	10.38	49.5
McGregor	Acidic fen	47° 39′	42.7	1.39	0.077	31.0	583	18.6	8.20	7.14	65.3
Alborn	Int. fen	47° 00′	38.9	2.61	0.082	14.9	479	32.1	4.75	7.31	48.3
Red Lake	Int. fen	48° 22′	43.3	2.43	0.076	17.9	573	32.0	7.66	7.13	28.8
Ash River	Tamar. sw.	48° 24′	42.9	1.98	0.078	21.8	558	25.6	8.56	6.83	28.3
Meadowlands	Tamar. sw.	47° 4′	42.6	2.57	0.114	16.6	380	22.9	5.32	5.52	39.1
Ash River	Cedar sw.	48° 24′	42.4	1.88	0.077	22.8	791	34.9	7.56	7.42	34.3
Isabella	Cedar sw.	47° 36′	42.6	1.85	0.076	23.3	584	25.0	6.20	8.92	30.5
Meadowlands	Cedar sw.	47° 3′	44.0	2.04	0.079	21.8	574	26.1	7.25	5.64	36.2
Gnesen	Ash sw.	46° 59′	34.7	2.58	0.266	13.5	131	9.7	6.16	8.27	37.0
Voyageurs	Meadow	48° 28′	21.1	1.53	0.127	13.7	166	12.0	6.83	7.22	35.6
Voyageurs	Meadow	48° 28′	23.8	1.59	0.115	15.0	212	13.9	6.57	9.05	30.8
North Carolina	Short pocosin	34° 55′	53.3	1.74	0.029	30.7	1838	59.8	7.25	4.97	25.1
North Carolina	Gum sw.	34° 55′	28.1	1.37	0.126	20.6	232	11.1	7.48	5.49	18.0
Florida	Everglades	26° 30′	45.0	2.99	0.034	15.1	1318	87.7	7.58	5.68	19.6

(*Continued*)

TABLE 10.3 (*Continued*)

Chemical Characteristics of the Average of Five 0 to 25 cm Depth Cores from 20 Sites

		%AFDM								
Site	**Type**	**Wat. Sol. Carbo.**	**Acid Sol. Carbo.**	**Soluble Phenolics**	**Lignin**	**Lignin/N**	**Lignin/ Cellulose**	**Mineral Content (%)**	**Bulk Density (mg m^{-3})**	**pH Water**
Arlberg	Bog	7.67	31.8	0.515	33.3	26.4	0.420	12.1	0.036	3.74
Ash River	Bog	7.89	39.4	0.568	29.8	26.7	0.356	5.2	0.050	3.75
Pine Island	Bog	7.38	35.7	0.649	28.4	24.8	0.361	6.3	0.054	3.80
Red Lake	Bog	7.30	41.7	0.687	24.1	22.9	0.304	6.0	0.052	3.72
Toivola	Bog	7.73	47.8	0.584	28.6	25.6	0.341	8.4	0.030	3.81
Marcell	Acidic fen	4.95	25.0	0.338	29.3	18.1	0.373	11.2	0.020	4.22
McGregor	Acidic fen	4.13	62.6	0.480	18.6	13.3	0.222	5.0	0.018	3.95
Alborn	Int. fen	3.84	14.5	0.203	38.2	14.6	0.441	22.7	0.100	4.84
Red Lake	Int. fen	6.64	24.3	0.215	53.3	22.0	0.650	12.5	0.076	5.57
Ash River	Tamar. sw.	5.66	15.5	0.291	54.3	27.6	0.658	13.4	0.102	5.91
Meadowlands	Tamar. sw.	2.58	17.6	0.247	48.7	19.1	0.555	13.4	0.104	5.63
Ash River	Cedar sw.	9.57	19.1	0.354	48.7	26.2	0.586	13.3	0.095	4.35
Isabella	Cedar sw.	2.15	7.7	0.155	52.2	28.5	0.632	14.7	0.147	6.61
Meadowlands	Cedar sw.	1.53	21.7	0.213	49.3	24.4	0.576	13.0	0.110	5.76
Gnesen	Ash sw.	3.42	8.7	0.096	44.5	17.3	0.546	29.3	0.150	6.13
Voyageurs	Meadow	3.05	5.5	0.070	43.0	28.9	0.548	55.4	0.213	5.75
Voyageurs	Meadow	5.06	4.1	0.070	45.9	28.9	0.598	52.3	0.236	6.16
North Carolina	Short pocosin	3.13	9.0	0.141	62.2	35.8	0.712	3.8	0.087	3.36
North Carolina	Gum sw.	2.43	3.6	0.019	63.2	47.0	0.778	46.1	0.206	3.97
Florida	Everglades	1.69	11.7	0.097	65.1	21.8	0.770	14.8	0.100	6.60

(*Continued*)

TABLE 10.3 (*Continued*)

Chemical Characteristics of the Average of Five 0 to 25 cm Depth Cores from 20 Sites

		cmolc/kg									
					Extractable Bases						
Site	**Type**	**Exch. Acidity**	**Exch. Bases**	**CECpH 7**	**Na**	**K**	**Mg**	**Ca**	**Ca/Mg**	**Base Sat. (%)**	**Acid-F Extr. P. (μg g^{-1})**
Arlberg	Bog	19.9	13.2	33.1	0.382	2.87	3.3	6.7	2.01	39.6	3.26
Ash River	Bog	13.9	11.8	25.7	0.433	1.55	3.5	6.3	1.88	45.1	3.08
Pine Island	Bog	15.7	19.1	34.7	0.544	3.63	4.2	10.7	2.51	56.1	2.68
Red Lake	Bog	17.2	16.5	33.7	0.430	2.57	4.7	8.8	1.89	49.8	3.00
Toivola	Bog	24.0	18.1	42.2	0.465	2.83	3.9	10.9	2.82	43.2	1.12
Marcell	Acidic fen	31.3	21.1	52.4	0.550	1.65	5.0	13.9	2.79	40.8	1.94
McGregor	Acidic fen	30.7	22.0	52.6	0.793	4.42	5.7	11.1	1.97	41.8	36.91
Alborn	Int. fen	11.3	12.3	23.6	0.500	0.90	2.6	8.3	3.29	51.4	1.85
Red Lake	Int. fen	6.4	34.8	41.2	0.465	1.25	8.0	25.1	3.15	85.2	1.45
Ash River	Tamar. sw.	15.4	84.3	99.7	0.344	1.05	21.6	61.3	2.86	84.5	1.32
Meadowlands	Tamar. sw.	14.6	60.2	74.8	0.537	1.01	17.0	41.7	2.45	80.5	13.03
Ash River	Cedar sw.	19.6	31.9	51.5	0.422	1.55	6.8	23.1	3.45	62.8	4.91
Isabella	Cedar sw.	7.8	116.9	124.7	0.524	0.78	24.0	91.6	3.84	93.7	1.58
Meadowlands	Cedar sw.	19.1	67.0	86.1	0.381	0.70	17.4	48.5	2.78	77.8	1.80
Gnesen	Ash sw.	10.6	51.3	61.8	0.679	0.69	10.6	39.3	3.70	82.8	8.49
Voyageurs	Meadow	4.4	26.3	30.7	0.263	1.34	7.5	17.3	2.38	85.5	7.23
Voyageurs	Meadow	3.5	35.2	38.7	0.267	1.13	10.1	23.7	2.45	88.4	3.85
North Carolina	Short pocosin	28.1	7.1	35.2	0.733	0.68	5.3	0.4	0.07	20.1	0.82
North Carolina	Gum sw.	19.3	1.4	20.7	0.294	0.40	0.4	0.3	0.73	6.8	6.56
Florida	Everglades	5.5	139.9	145.4	7.658	1.94	30.3	100.0	3.30	96.2	8.01

(*Continued*)

TABLE 10.3 (*Continued*)

Chemical Characteristics of the Average of Five 0 to 25 cm Depth Cores from 20 Sites

		$CaCl_2$ Ext.		Oxalate Ext.		%AFDM		
Site	**Type**	**P (μg g^{-1})**	**N (μg g^{-1})**	**Fe (mg g^{-1})**	**Al (mg g^{-1})**	**Humin**	**Fulvic Acids**	**Humic Acids**
Arlberg	Bog	5.66	24.9	2.85	1.88	72.4	20.7	12.0
Ash River	Bog	0.96	0.7	0.90	0.46	72.1	0.6	23.1
Pine Island	Bog	6.16	14.6	0.93	0.57	72.7	23.8	7.6
Red Lake	Bog	11.95	9.6	2.61	1.01	72.3	3.5	21.3
Toivola	Bog	0.43	14.2	3.35	1.08	72.2	6.5	23.4
Marcell	Acidic fen	7.87	72.1	2.95	1.99	75.7	22.9	10.2
McGregor	Acidic fen	36.16	31.6	3.29	0.61	73.8	21.2	7.5
Alborn	Int. fen	0.53	16.1	12.29	3.24	75.9	26.5	23.0
Red Lake	Int. fen	0.91	26.6	6.48	2.08	79.8	14.7	13.8
Ash River	Tamar. sw.	2.38	85.1	2.76	1.63	79.2	3.3	11.5
Meadowlands	Tamar. sw.	1.79	39.0	7.34	1.19	70.6	4.8	11.7
Ash River	Cedar sw.	6.31	41.0	2.98	2.08	80.0	24.2	13.5
Isabella	Cedar sw.	1.02	48.6	6.09	1.09	80.2	0.9	13.4
Meadowlands	Cedar sw.	1.76	54.7	7.88	1.43	79.7	6.3	11.7
Gnesen	Ash sw.	0.20	42.2	10.48	5.61	77.1	13.5	17.2
Voyageurs	Meadow	3.09	19.8	5.70	3.03	73.2	57.0	26.4
Voyageurs	Meadow	0.80	38.9	6.29	2.39	63.5	54.0	23.2
North Carolina	Short pocosin	16.25	5.3	0.62	0.99	72.0	17.6	26.8
North Carolina	Gum sw.	0.41	7.0	1.38	7.64	54.4	42.6	37.1
Florida	Everglades	11.49	35.6	1.71	0.83	77.3	22.5	8.9

Note: All sites are in Minnesota except where noted. Int.: intermediate, Tamar.: tamarack, sw.: swamp, Lat.: latitude, Org.: organic, Extr.: extractable, AFDM: ash-free dry mass, Wat.: water, Sol.: soluble, Carbo.: carbohydrates, Exch.: exchangeable, CEC: cation exchange capacity, Sat.: saturation, Acid-F: acid fluoride.

TABLE 10.4

Physical Characteristics and Various Classification Schemes for the Average of Five 0 to 25 cm Depth Cores from 20 Sites

		Unrubbed Fiber		Rubbed Fiber		10YR				Classifications[a]			
Site	**Type**	**% Dry-mass**	**% Volume**	**% Dry-mass**	**% Volume**	**Value Color**	**Chroma Color**	**Composite[b] Color**	**von Post Index**	**U.S.**	**Canadian**	**ASTM**	**von Post**
Arlberg	Bog	78	73	68	53	7.2	2.2	5	3	2.4	2.6	2.8	2.8
Ash River	Bog	92	82	80	62	8	1.4	6.6	2.6	3	3	3	3
Pine Island	Bog	81	75	68	53	7.8	1.8	6	2.4	2.8	2.8	2.8	3
Red Lake	Bog	86	78	78	60	8	1.6	6.4	3.6	3	3	2.8	2.4
Toivola	Bog	78	73	74	57	7.8	1.8	6	2.8	2.8	2.8	2.8	3
Marcell	Acidic fen	76	72	60	48	8	1.4	6.6	4.6	3	3	3	2
McGregor	Acidic fen	85	78	77	60	8	1	7	2.8	3	3	3	3
Alborn	Int. fen	33	46	26	26	6.2	3.4	2.8	4.6	1.2	2	1.8	2
Red Lake	Int. fen	52	56	41	34	8	2	6	4	2	2	2	2
Ash River	Tamar. sw.	63	63	51	41	7.8	2.2	5.6	4.2	2.4	2.4	2.4	2
Meadowlands	Tamar. sw.	48	53	30	26	7	3.2	3.8	6.8	1.8	2	2	1.2
Ash River	Cedar sw.	53	57	44	36	7.6	2.4	5.2	6.2	2.4	2.4	2	1.6
Isabella	Cedar sw.	47	52	30	26	7	2.8	4.2	8	1.8	2	2	1
Meadowlands	Cedar sw.	58	60	43	35	6.8	2.8	4	6	2	2.2	2.2	1.6
Gnesen	Ash sw.	45	51	11	13	5.2	3	2.2	9.4	1	2	2	1
Voyageurs	Meadow	31	42	20	19	6.8	3.2	3.6	6	1.6	2	1.4	2
Voyageurs	Meadow	35	45	17	17	5.6	3	2.6	6.4	1	2	1.6	1.4
North Carolina	Short pocosin	48	53	16	16	5	3	2	10	1	2	2	1
North Carolina	Gum sw.	28	40	8	10	3	2	1	10	1	1.4	1.2	1
Florida	Everglades	63	63	20	19	5.8	3	2.8	9	1	2	2.2	1

Note: All sites are in Minnesota except where noted. See text for description of classification schemes. Int.: intermediate, Tamar.: tamarack, sw.: swamp.

[a] Average classification for the five cores. 1 = sapric, 2 = hemic, 3 = fibric.

[b] 10YR Value—10YR Color (Parent and Caron 1993).

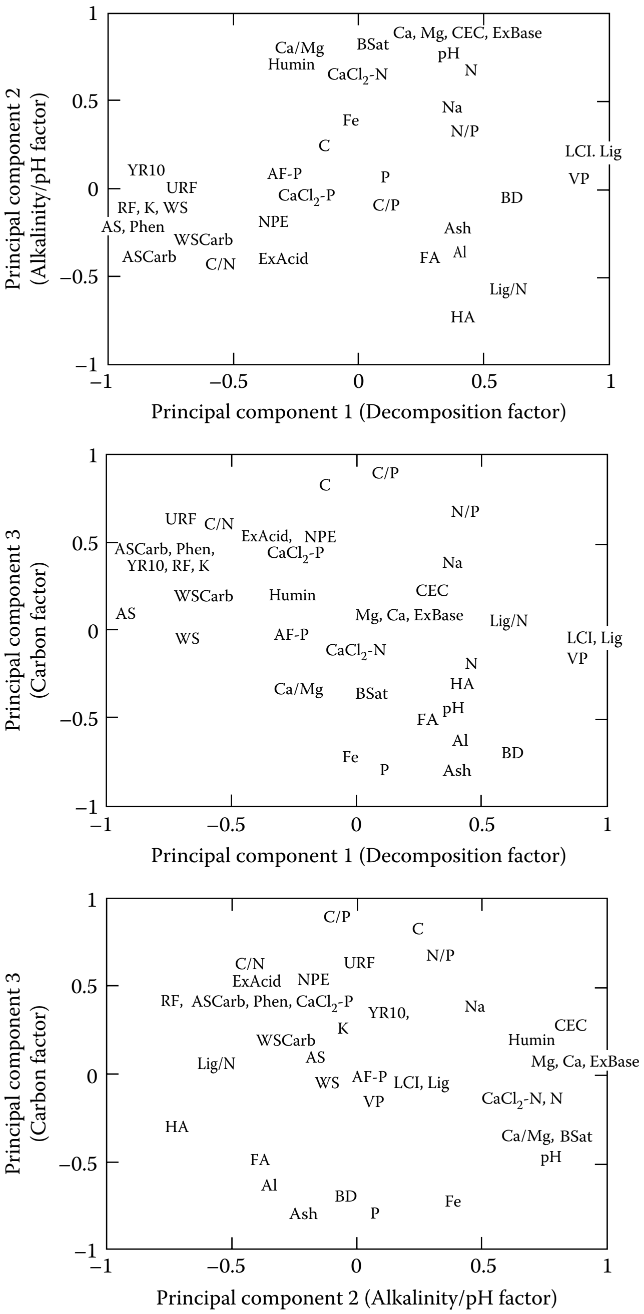

FIGURE 10.4
The loadings of 39 soil variables from 15 peatlands in northern Minnesota, 2 beaver meadows with histic epipedons in northern Minnesota, 2 peatlands in North Carolina, and 1 peatland in Florida on the first 3 axes of a principal components analysis. The loading is comparable to the correlation coefficient (*r*) for each variable against each axis. Abbreviations are as in Table 10.5.

a positive relationship between alkalinity/pH, humin formation, and nitrogen pools and fluxes. In contrast, humic acid content had a high negative weighting on this axis, which suggests it has a negative relationship with alkalinity/pH.

The third principal component axis was related to soil carbon and mineral content (Figure 10.4). It had positive weighting from total soil carbon, and high negative weightings from %mineral content, oxalate-extractable Fe and Al, bulk density, and total soil phosphorus. Phosphorus is strongly sorbed by iron and aluminum hydroxyoxides, so it is not surprising that greater mineral content is related to higher total soil phosphorus levels, although this does not necessarily translate into higher available phosphorus (Bridgham et al. 1998). Additionally, more minerogenous peats may receive greater inputs of apatite–phosphorus from weathering.

There is a large cost in labor, time, and expense in doing many of these chemical analyses, and it is promising that a simple set of physical and chemical variables often measured in peats is closely correlated with many of the more difficult chemical analyses. In particular, mineral content, bulk density, pH, fiber content, and the von Post index are correlated with many other chemical variables (Table 10.5). They are also as effective as the chemical variables in predicting nutrient and carbon mineralization in peats (Lévesque and Mathur 1979; Bridgham et al. 1998).

PCA also allows one to determine "factor scores" for each of the 20 wetlands along these three principal component axes. We used our multivariate data set to discriminate natural groupings of peatlands according to their soil characteristics (Figure 10.5). The first, second, and third factors explained 28.8%, 22.5% and 21.1%, respectively, of the variance among sites, or 72.4% of the total variance. The first factor (Decomposition Factor) effectively separated three groups of wetlands: acidic fens and bogs, more minerotrophic northern wetlands, and southern peatlands. The second factor (Alkalinity/pH Factor) separated bogs from acidic fens, beaver meadows from minerotrophic northern peatlands, and the alkaline Everglades site from the acidic North Carolina peatlands. The third factor (Carbon Factor) separated minerotrophic northern cedar and tamarack swamps from intermediate fens, the ash swamp site, and the two beaver meadows. The nutrient-deficient short pocosin and Everglades sites were separated from the relatively nutrient-rich North Carolina gum swamp.

The difficulty of applying the ombrogenous–minerogenous gradient to southern peatlands is evident from our data. One sees the expected decrease in rubbed fiber content and increase in mineral ash, lignin, pH, %base saturation, and related variables expressing increasing alkalinity from bogs to ash swamps and beaver meadows in the northern sites, related to increasing minerogenous water inputs and their impact on water chemistry (Table 10.3, Figure 10.6). However, both short pocosins and the Everglades are profoundly phosphorus limited, whereas the gum swamp is relatively fertile (Walbridge 1991; Koch and Reddy 1992; Bridgham and Richardson 1993; Craft and Richardson 1997). Hydrologically, the Everglades site would be considered a "poor" fen, despite its alkaline soil conditions, and the gum swamp is a highly minerogenous "rich" swamp forest, despite its very acidic soil (Table 10.3, Figure 10.6). The sands of the North Carolina Coastal Plain have very low exchangeable basic cation concentrations, so contribute little alkalinity despite being highly minerogenous (Bridgham and Richardson 1993). Additionally, all of the southern peats are highly decomposed hemic or sapric peats with very low fiber and cellulose content, but high lignin content (Tables 10.3 and 10.4; Figures 10.4 through 10.6).

Our data support the traditional concept of an ombrogenous–minerogenous gradient in northern peatlands in terms of alkalinity and degree of decomposition of peats; however, soil nutrient availability is more problematic. We found in these same Minnesota

TABLE 10.5

Pearson Correlations (r) when $P < 0.05$ for Variables in Tables 10.3 and 10.4

	C	N	P	C/N	C/P	N/P	NPE	WS	AS	WSCarb
C										
N										
P	−0.57									
C/N	0.48	−0.78	−0.55							
C/P	0.74		−0.74	0.51						
N/P	0.56	0.44	−0.55		0.77					
NPE		−0.52		0.58						
WS		−0.54		0.51						
AS		−0.49		0.63				0.55		
WSCarb		−0.51		0.59				0.59	0.46	
ASCarb		−0.51		0.75			0.47		0.85	0.52
Phen	0.44	−0.62	−0.46	0.88			0.50	0.63	0.80	0.73
Lig		0.58		−0.62				−0.69	−0.97	−0.52
Lig/N									−0.58	
LCI		0.54		−0.64				−0.63	−0.99	−0.49
Ash	−0.95		0.57	−0.64	−0.65					
BD	−0.77		0.58	−0.69	−0.58		−0.44		−0.66	−0.48
pH		0.69		−0.78	−0.45				−0.53	−0.54
ExAcid	0.47			0.55	0.46				0.44	
ExBase		0.60							−0.46	−0.47
CEC		0.55				0.48				−0.46
Na		0.50				0.80				
K		−0.49		0.62			0.45	0.50	0.71	0.47
Mg		0.60		−0.44					−0.48	−0.50
Ca		0.60		−0.44					−0.47	−0.47
Ca/Mg		0.51								
BSat		0.57		−0.56						
AF-P										
$CaCl_2$-P										
$CaCl_2$-N										
Fe		0.58	0.59	−0.63	−0.58		−0.77			
Al	−0.62		0.69	−0.49	−0.55					
Humin	0.51									
FA	−0.78									
HA	−0.47									
URF	0.56	−0.48	−0.51	0.82	0.45		0.68	0.52	0.69	0.55
RF		−0.60	−0.51	0.83			0.59	0.57	0.81	0.67
YR10		−0.45	−0.45	0.63			0.62	0.52	0.70	0.65
VP		0.49		−0.59				−0.58	−0.78	−0.68

(*Continued*)

TABLE 10.5 (*Continued*)

Pearson Correlations (r) when $P < 0.05$ for Variables in Tables 10.3 and 10.4

	ASCarb	Phen	Lig	Lig/N	LCI	Ash	BD	pH	ExAcid	ExBase
C										
N										
P										
C/N										
C/P										
N/P										
NPE										
WS										
AS										
WSCarb										
ASCarb										
Phen	0.87									
Lig	−0.81	−0.80								
Lig/N			0.52							
LCI	−0.84	−0.81	0.99	0.55						
Ash	−0.64	−0.66								
BD	−0.81	−0.78	0.58	0.49	0.64	0.90				
pH	−0.59	−0.65	0.51		0.53		0.57			
ExAcid	0.53					−0.53	−0.63	−0.73		
ExBase			0.49		0.47			0.81	−0.45	
CEC			0.44					0.70		0.98
Na										0.63
K	0.84	0.76	−0.74		−0.73		−0.64	−0.48		
Mg			0.52		0.50			0.81		0.98
Ca			0.50		0.48			0.82	−0.47	1.00
Ca/Mg				−0.58				0.64	−0.45	0.57
BSat								0.90	−0.74	0.76
AF-P										
$CaCl_2$-P	0.53						−0.44		0.54	
$CaCl_2$-N								0.56		0.56
Fe				−0.48				0.55		
Al	−0.53	−0.56				0.68	0.60			
Humin				−0.60		−0.51				0.48
FA		−0.46				0.81	0.61			
HA				0.66		0.54	0.51			−0.49
URF	0.86	0.88	−0.68		−0.70	−0.75	−0.85	−0.51	0.48	
RF	0.91	0.95	−0.80		−0.81	−0.66	−0.81	−0.57	0.47	
YR10	0.81	0.81	−0.71		−0.71	−0.61	−0.75			
VP	−0.79	−0.82	0.80		0.80		0.63			

(*Continued*)

TABLE 10.5 (*Continued*)

Pearson Correlations (*r*) when $P < 0.05$ for Variables in Tables 10.3 and 10.4

	CEC	Na	K	Mg	Ca	Ca/Mg	BSat	AF-P	CaCl$_2$-P	CaCl$_2$-N
C										
N										
P										
C/N										
C/P										
N/P										
NPE										
WS										
AS										
WSCarb										
ASCarb										
Phen										
Lig										
Lig/N										
LCI										
Ash										
BD										
pH										
ExAcid										
ExBase										
CEC										
Na	0.62									
K										
Mg	0.96	0.59								
Ca	0.97	0.59		0.97						
Ca/Mg	0.51			0.48	0.60					
BSat	0.64			0.76	0.76	0.74				
AF-P			0.49							
CaCl$_2$-P			0.63					0.75		
CaCl$_2$-N	0.61			0.59	0.57	0.53	0.51			
Fe						0.55	0.46			
Al			−0.49							
Humin	0.50			0.45	0.48	0.67	0.53			0.47
FA										
HA	−0.55			−0.47	−0.47	−0.53	−0.45			−0.58
URF			0.74							−0.49
RF			0.75							−0.49
YR10			0.66							
VP			−0.68							

(*Continued*)

TABLE 10.5 (*Continued*)

Pearson Correlations (r) when $P < 0.05$ for Variables in Tables 10.3 and 10.4

	Fe	Al	Humin	FA	HA	URF	RF	YR10
C								
N								
P								
C/N								
C/P								
N/P								
NPE								
WS								
AS								
WSCarb								
ASCarb								
Phen								
Lig								
Lig/N								
LCI								
Ash								
BD								
pH								
ExAcid								
ExBase								
CEC								
Na								
K								
Mg								
Ca								
Ca/Mg								
BSat								
AF-P								
$CaCl_2$-P								
$CaCl_2$-N								
Fe								
Al								
Humin		−0.49						
FA		0.47	−0.51					
HA		0.57	−0.67					
URF	−0.53	−0.64		−0.54	−0.47			
RF		−0.60		−0.47		0.92		
YR10		−0.63		−0.44	−0.52	0.83	0.92	
VP		0.52				−0.70	−0.88	−0.85

Note: C: %organic C, N: %total N, P: %total P, NPE: nonpolar extractable organic matter, WS: water soluble organic matter, AS: acid soluble organic matter, WSCarb: water soluble carbohydrates, ASCarb: acid soluble carbohydrates, Phen: soluble phenolics, Lig: lignin, LCI: lignin/cellulose, BD: bulk density, ExAcid: exchangeable acidity, ExBase: exchangeable bases, CEC: cation-exchange capacity, BSat: %base saturation, AF-P: acid fluoride extractable P, $CaCl_2$-N and $CaCl_2$-P: calcium chloride extractable N and P, FA: fulvic acid, HA: humic acid, URF: %unrubbed fiber, RF: %rubbed fiber, YR10: composite pyrophosphate color (10YR Value—10YR Color), VP: von Post index.

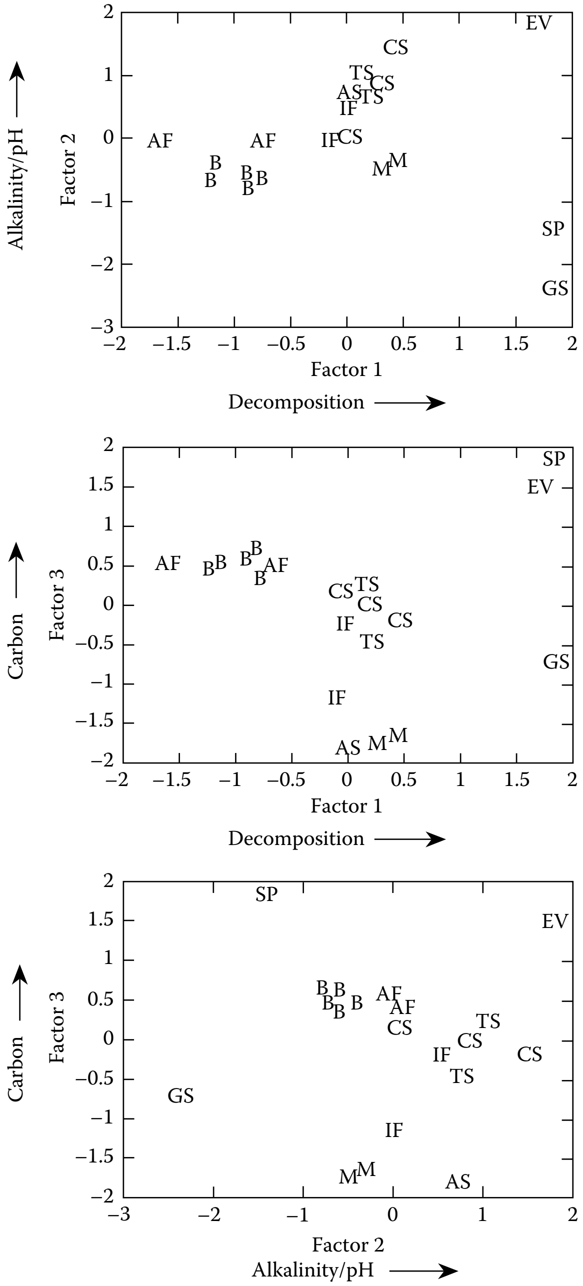

FIGURE 10.5
Factor scores for the first three axes of a principal components analysis of 39 soil variables from 15 peatlands in northern Minnesota, 2 beaver meadows with histic epipedons in northern Minnesota, 2 peatlands in North Carolina, and 1 peatland in Florida. B: bog, AF: acidic (poor) fen, IF: intermediate fen, TS: tamarack swamp, CS: cedar swamp, AS: black ash swamp, M: beaver meadow, SP: short pocosin (NC), GS: gum swamp (NC), and EV: Everglades (FL). The northern wetlands occur across an ombrogenous–minerogenous gradient in the order listed above, whereas hydrologically SP is an ombrogenous bog, GS is a minerogenous swamp forest, and EV is a "poor" fen.

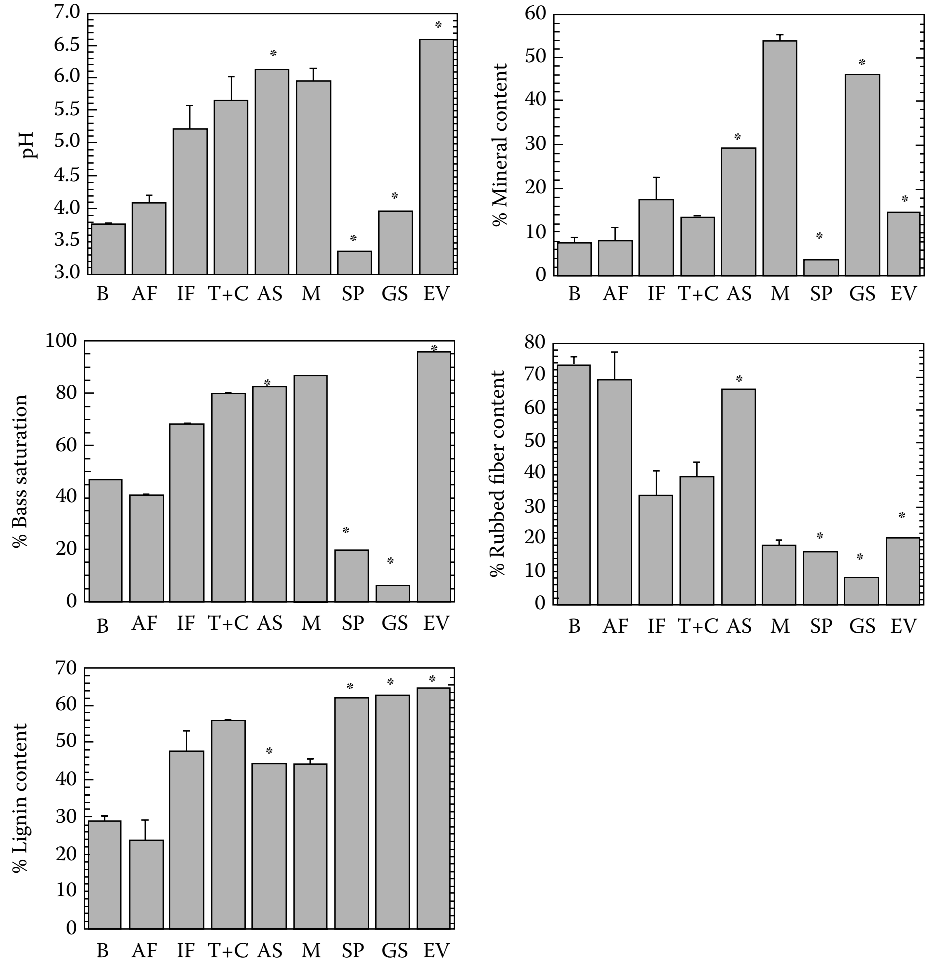

FIGURE 10.6
Relationship between pH, mineral content, base saturation, rubbed fiber content, and lignin to the ombrogenous–minerogenous gradient in the northern wetlands (going from left to right on the *x*-axis) and the three southern peatlands (SP, GS, and EV). The northern wetlands occur across an ombrogenous–minerogenous gradient in the order listed above, whereas hydrologically SP is an ombrogenous bog, GS is a minerogenous swamp forest, and EV is a "poor" fen. Average ± 1 standard error, except * indicates $N = 1$ site so standard errors could not be obtained.

wetlands that more minerogenous wetlands have larger total soil nitrogen and phosphorus pools, but those pools turn over more slowly in minerogenous sites (Bridgham et al. 1998). A phosphorus isotope addition experiment across the ombrogenous–minerogenous gradient resulted in no differences in available phosphorus, microbial phosphorus, and the root phosphorus at 10–20 cm, although total soil phosphorus and aboveground vegetation phosphorus content increased from bog to rich fen (Kellogg and Bridgham 2003). It appears that although bogs and intermediate fens have a small total phosphorus pool, they have similar phosphorus availability to rich fens because of rapid cycling and efficient retention of phosphorus. The large increase in bulk density in more minerogenous sites also has important consequences, because plant roots and microbes exploit a volume and not a mass of soil. The net result of all these factors was that nitrogen availability was higher in more minerogenous Minnesota wetlands (Bridgham et al. 1998). Chapin (1998) conducted a detailed fertilization experiment in an intermediate fen and bog in northern Minnesota and found similar results. Interestingly, she found that bog vegetation was not nutrient limited, except for a delayed response in ericaceous shrubs, and *Sphagnum* mosses were actually inhibited at moderate rates of nitrogen addition. The fen vegetation was phosphorus limited. Similar results have been found for both soil nutrient availability (Waughman 1980; Verhoeven et al. 1990; Koerselman et al. 1993; Updegraff et al. 1995) and plant-nutrient response (Clymo 1987; Lee et al. 1987; Boyer and Wheeler 1989; Bridgham et al. 1996) in other northern peatlands. More recent research using enzymes to determine nutrient limitations found phosphorus to be more limiting than nitrogen across a gradient of ombrogenous to minerogenous peatlands in northern Minnesota (Hill et al. 2014).

We suggest that the ombrogenous–minerogenous paradigm is an important and useful concept in northern peatlands, although its relation to a nutrient availability gradient appears to be complicated and worthy of further research. We conclude that the ombrogenous–minerogenous gradient does not appear to be directly translatable into an oligotrophic–eutrophic gradient. Furthermore, traditional concepts of how the ombrogenous-minerogenous gradient affects peat chemistry and physical properties in northern peatlands do not appear to be useful in southern peatlands.

Alaskan Peatlands: Histosols and Gelisols

We also examined a more limited set of soil variables in peats collected in the five pedons from Alaska (Table 10.6). Pedons 1 and 2 are intermediate fens, whereas pedons 3 through 5 are bogs. Pedons 3 and 5 are Histosols, whereas pedons 1, 2, and 4 are Histels within the order Gelisols.

The bulk density and mineral content of the horizons from the five pedons from Alaska are much higher than those from the Minnesota and southern peats (Table 10.3). Eolian and volcanic deposits (loess and tephra) have been active in many parts of Alaska and northwest Canada since the Late Pleistocene (Péwé 1975; Riehle 1985). Because of this frequent or intermittent input of mineral deposits, the organic soils in these regions have a higher bulk density compared with those developed in the humid maritime zones of southeastern Alaska and British Columbia. The additions of these materials appear in bands and layers in the peat, and thus they can serve as time-stratigraphic markers. In peat developed in bottom lands, mineral layers exist in lamella or bands due to the erosion or washing from surrounding slopes (Pedon 2).

In northern Alaska, as in the Minnesota sites, vegetation and land cover class show a strong correlation with the base status and pH of the soil (Ping et al. 1998). The pH of Alaskan peatlands decreases from 5.5 to 7.7 in the Arctic coast to 4.0 to 4.5 in the boreal forest in the interior, to 3.0 to 3.5 in south central and southeastern Alaska. Most bogs in south central Alaska are extremely acidic and have low base status. Some of the bogs have hydraulic conductivity less than 10 cm h^{-1} (Clark and Kautz 1997). Péwé (1975) pointed out that there is continuous deposition of carbonate-rich loess in the Arctic Coastal Plain and in interior Alaska if streams are transporting glacial debris. In these soils, extractable Ca and Mg dominate the soluble salts and the exchange sites in the soils (Pedons 1 and 2). Pedon 3 is a raised bog with *Sphagnum* moss as the dominant vegetation making the pH very acidic. Even though the area has relatively low loess deposition, the added carbonates from the loess are reflected in the Ca-dominance of the exchange sites and the slightly higher base saturation in the surface layer. Although Pedon 4 formed in humid

TABLE 10.6

Characteristics of Selected Histosols from Alaska

								cmolc/kg									
										Extractable Bases					Fiber Content		
Pedon #Lat. N	**Horizon**	**Depth (cm)**	**Total Org. C (%)**	**C/N**	**Mineral Content (%)**	**Bulk Density (mg m^{-3})**	**pH $CaCl_2$**	**Exch. Acidity**	**CEC**	**Na**	**K**	**Mg**	**Ca**	**Base Sat. (%)**	**Unrub. (%)**	**Rubbed (%)**	**Pyrophosphate Color**
1	Oa1	0–18	23	35	62	0.39	6.9	17	79	1	tr	4	85	100	52	16	10YR 5/3
70° 17′	Oa2	18–39	15	13	77	0.49	5.9	13	29	1	tr	1	16	61	26	12	10YR 4/3
	Oe	39–50	22	14	65	0.38	6.3	18	49	1	tr	4	43	99	58	24	10YR 4/3
	Oef	50–100	25	19	61	n.d.	7.1	12	63	2	tr	6	115	100	80	26	10YR 4/3
	Cf	39–80	tr	11	n.d.	1.8	7.7	n.d.	2	0	tr	1	n.d.	100	n.d.	n.d.	n.d.
2	Oi	0–17	51	25	15		7.7	21	168	tr	3	20	183	100	92	64	10YR 7/3
67° 26′	Oe1	17–35	49	17	20	0.12	6.7	38	197	tr	tr	15	186	100	64	36	10YR 6/3
	Oe2	35–48	52	29	n.d.		5.8	49	160	tr	tr	11	146	98	n.d.	n.d.	n.d.
	C/Oa	48–54	24	n.d.	n.d.		5.1	47	89	tr	tr	6	81	99	n.d.	n.d.	n.d.
	Oef1	54–85	42	21	32		5.4	66	139	tr	tr	6	113	86	n.d.	n.d.	n.d.
	Oaf	85–95	29	20	54		n.d.	58	109	tr	tr	5	90	87	52	16	10YR 3/3
	Oef2	95–108	n.d.	n.d.	87		5.6	18	25	tr	tr	1	22	94	20	12	10YR 5/3
3	Oe	0–31	39	19	15	0.13	4.3		136	1	1	15	40	42	70	40	7.5YR7/5
64° 52′	Oi	31–61	38	31	9	0.1	3.9		116	tr	tr	5	12	16	88	75	10YR 8/2
	Oif	61–127	38	26	7	n.d.	4.4		81	tr	tr	5	12	22	90	80	10YR 8/1
4	Oi	0–29	53	68		n.d.	4.1	79	129	1	1	13	63	60			
61° 25′	Oe	29–47	53	32		0.15	4.3	83	106	1	tr	6	49	52			
	Oa	47–79	49	27		0.4	4.3	82	96	1	tr	4	42	49			
	O′e1	79–97	22	30		0.57	4.5	61	49	1	tr	2	18	40			
	O′e2	97–148	55	28		0.2	4.5	78	106	1	tr	4	48	50			
	O′I	148–165	60	32		n.d.	4.5	85	132	1	tr	6	68	57			
5	Oi	0–3			17		3.3	94	99	1	2	7	13	23	76	56	10YR 8/3
56° 30′	Oe	3–18			7		3	130	132	1	1	10	13	19	62	42	7.5YR 8/2
	Oa	18–94			54		3.5	72	76	1	1	2	4	9	48	30	5YR 3/4

south central Alaska, the base saturation is higher than that of Pedon 3 because it is on a broad flood plain which collects seasonal input of minerals. Pedon 5 is a well-drained Folist in perudic southeastern Alaska. Its soil is strongly acidic (pH at 3.3) and has very low base saturation.

Ping et al. (1997b) found that organic matter in fens of the arctic coast was dominated by cellulose (approximately 50%), whereas the humin fraction was <20%. Humic acids dominated the soluble fractions, and the C/N ratio ranged from 6 to 17. In comparison, the Minnesota peats had generally <40% cellulose (i.e., acid-soluble carbohydrates), >70% humin, a variable humic acid:fulvic acid ratio, and a C/N ratio which ranged from 14 to 41 (Table 10.3). All these data point to a lesser degree of humification of peats as the climate gets colder. This generalization is borne out by a similar comparison of the Minnesota peats to those in North Carolina and Florida in Table 10.3.

Peat formed in the zone of continuous permafrost, such as arctic Alaska and northwest Canada, contains cryogenic features such as ice lenses, ice wedges, and other types of ground ice, generally at a depth of 40–60 cm (Tarnocai et al. 1993; Ping et al. 1997a, b, 1998). The upper permafrost layer of these soils often contains up to 80% ice by volume. Cryoturbation causes mixing of soil horizons and redistribution of carbon, resulting in significant carbon stores in the permafrost (Michaelson et al. 1996; Tarnocai et al. 2009). Thawing as a result of climate change is predicted to have important positive feedbacks to the global carbon cycle thereby increasing warming potential (Schurr et al. 2008; Kovan et al. 2011).

Our emphasis in this comparative biogeochemical approach has been on the peatlands of the U.S. A multivariate analysis of numerous soil properties of Canadian bogs was performed by Brown et al. (1990), but their emphasis was not on the ombrogenous–minerogenous gradient, and the study was done within a more limited geographical setting. Additionally, a wealth of information on Canadian peats is found in National Wetlands Working Group (1988). The review by Clymo (1983) emphasizes European peatlands and has long been a classic in this field. Bohlin et al. (1989) examined a wide range of peat properties in a diverse group of Swedish peats and used principal components analysis to examine their results. They found that the peats were differentiated by botanical composition and degree of decomposition, and particularly emphasized the differences between *Sphagnum* (bog) and *Carex* (fen)-derived peats. *Carex* peats were more humified due to microbial decomposition than *Sphagnum* peats. A thorough review of humic substances in peats is provided by Mathur and Farnham (1985). Vitt (2006) used a five-factor approach integrating hydrology, climate, chemistry, substrate, and vegetation into a practical model to classify peatlands and natural gradients among peatland types. He developed functional levels of organization based on the five factors and used this framework to construct chronological "grades" that begin at wetland initiation followed by peatland development and then ultimately differentiate peatlands between bogs and fens (Vitt 2006).

Conclusions

We have presented here a framework for understanding the physical and biogeochemical properties of peat based upon the ombrogenous–minerogenous gradient, and examined how the properties of this gradient differ among different climatic zones. It is clear from the work presented here and elsewhere that peatlands are a critical ecosystem for many reasons. Peatlands harbor key flora and fauna, contribute to clean water, mitigate flooding, and store vast amounts of carbon. As a result of centuries of carbon accumulation, peatlands have mitigated rising concentrations of carbon dioxide in the atmosphere. Warming of Histosols and Gelisols will lead to positive feedbacks to the atmosphere, possibly accelerating climate change. Management approaches and research aimed at mitigating or adapting to climate change should be a priority for these globally important ecosystems.

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