Soils of the Northern Lake States Forest and Forage Region: LRR K

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Randall J. Schaetzl

10.1 Introduction and Overview

Within the Northern Lake States Forest and Forage Region (NLSFFR) are 17 Major Land Resource Areas (MLRAs), each of which is fairly internally homogeneous with respect to soils, landforms and land use (Fig. 10.1). The focus of this chapter is on the characteristics, distribution, classification, and genesis of soils within the NLSFFR, as well as on issues related to management and land use.

In this chapter, soils of MLRA 95B (Southern Wisconsin and Northern Illinois Drift Plain) in southeastern Wisconsin (Fig. 10.1) are not specifically discussed; discussion of the soils there will be in Chap. 11. Additionally, MLRA 96 (Western Michigan Fruit Belt) of northwestern Lower Michigan is included in this chapter even though it is technically not part of the NLSFFR, because its soils are similar to many of the other soils in northern Michigan, especially those within MLRA 94A. Thus, coverage of the NLSFFR, as slightly modified in extent in this chapter, spans northern Lower Michigan, all of Michigan's Upper Peninsula (UP), northern Wisconsin, and northeastern Minnesota and includes 17 MLRAs (Fig. 10.1).

The recently glaciated landscapes of the NLSFFR generally have gentle to moderately sloping topography (USDA-NRCS 2006). Most of the landscape has its origins in the last major glaciation. Nonetheless, two MLRAs in the NLSFFR occur south of the Late Wisconsin glacial border—one (94B) on areas of older drift in central Wisconsin (Attig et al. 2011a) and one that is dominated by the sandy, wet, former lake bed of Glacial Lake Wisconsin (Clayton and Attig 1989; Fig. 10.1). All other areas bear the conspicuous marks of recent (Late Pleistocene) glaciation, and most of the soils therein are formed in glacigenic sediments.

This LRR is dominated by Histosols, Alfisols, Spodosols, Inceptisols, and Entisols (Fig. 10.2). Histosols are common in lowland areas, such as in glacial kettles and on former glacial lake basins. Thus, with the exception of a few lake plains, most areas of Histosols are small in areal extent. Alfisols dominate large parts of the landscape where the parent materials are loamy or finer-textured, typical of tills or lacustrine sediment. Spodosols are more prevalent on sandier parent materials, and in the north. Young, sandy landscapes, e.g., sand dunes and recently exposed beaches, steeply sloping areas, and regions of shallow bedrock, are dominated by Entisols. Inceptisols are also found, commonly on wet, loamy lake plains and in areas of moderate slope where slope processes facilitate erosion and, thus, maintain soils in a minimally developed state. Much of northern Minnesota has a cover of Inceptisols and Entisols. A few areas of Vertisols and upland Mollisols are also mapped in parts of Minnesota, near the western and southwestern margins of the region. Small areas of lowland Mollisols are found in isolated areas across the region.

10.2 Geomorphology, Physiography, and Relief

The geologic and geomorphic history of this region involves repeated coverage by continental glaciers during the Pleistocene Epoch (Mickelson et al. 1983). Hence, most landscapes and soils are geologically young, i.e., less than about 18,000 years old, and many areas have deranged and poorly integrated drainage patterns. Kettle lakes and wetlands—many of them quite large—are common, having originated as buried ice blocks subsequently melted. Small, isolated hills and uplands, and hummocky moraines, are also common. Soils formed in bedrock residuum are found in only a few regions; most bedrock is either deeply buried by glacial drift or was scraped clean by the ice, leaving behind only hard bedrock that has not had enough time to weather into thick residuum. Therefore, most landforms have direct glacial origins, e.g., moraines, till plains, outwash plains,

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R.J. Schaetzl (✉)
Michigan State University, East Lansing, MI 48823, USA
e-mail: soils@msu.edu

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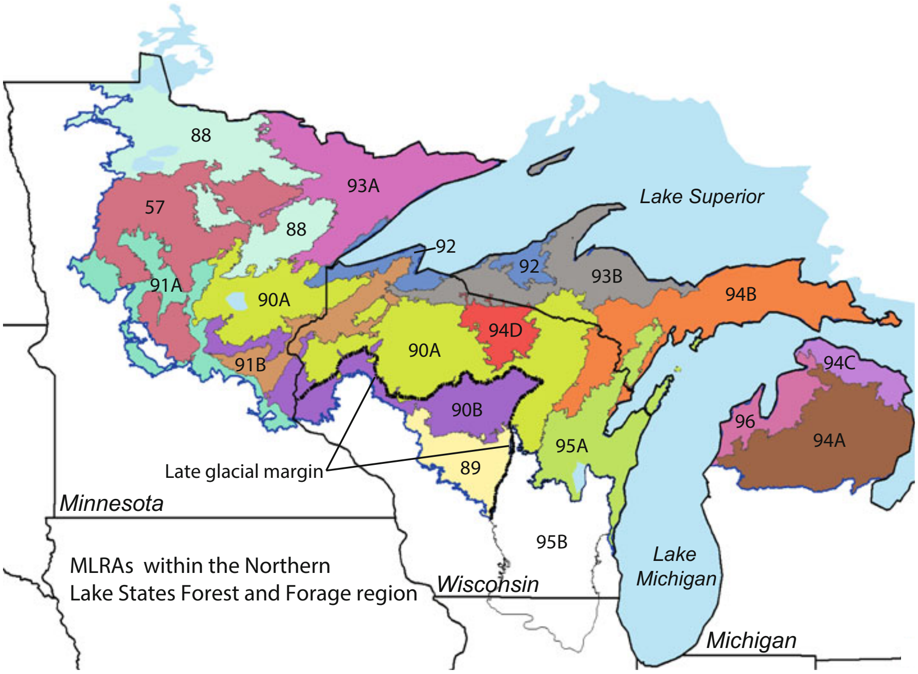

Fig. 10.1 Map showing the Major Land Resource Areas within the Northern Lake States Forest and Forage Region. Note that the soils of MLRA 95B, which is within the Northern Lake States Forest and Forage Region, is discussed in Chap. 11. Similarly, MLRA 96, which is included in a different LRR (Lake States Fruit, Truck Crop, and Dairy Region) IS included in this chapter, because its soils are fairly similar to the other soils in northern Michigan. Also shown in this figure is the limit of the last glaciation (Wisconsin stage) in the state of Wisconsin (*bold black line*). MLRA numbers and names: *57* Northern Minnesota Gray Drift, *88* Northern Minnesota Glacial Lake Basins, *89* Central Wisconsin Sands, *90A* Wisconsin and Minnesota Thin Loess and Till, Northern Part, *90B* Wisconsin and Minnesota Thin Loess and Till, Southern Part, *91A* Central Minnesota Sandy Outwash, *91B* Wisconsin and Minnesota Sandy Outwash, *92* Lake Superior Plain, *93A* Superior Stony and Rocky Loamy Plains and Hills, Western Part, *93B* Superior Stony and Rocky Loamy Plains and Hills, Eastern Part, *94A* Northern Michigan and Wisconsin Sandy Drift, *94B* Michigan Eastern Upper Peninsula Sandy Drift, *94C* Michigan Northern Lower Peninsula Sandy Drift, *94D* Northern Highland Sandy Drift, *95A* Northeastern Wisconsin Drift Plain, *95B* Southern Wisconsin and Northern Illinois Drift Plain, and *96* Western Michigan Fruit Belt

lacustrine plains, and including such common glacial landforms as eskers, kames and drumlins. Most soils are formed in recent and minimally weathered glacigenic sediments, whether the sediments are meters thick or exist as only a few cm of overburden above hard and glacially scoured bedrock. Areas of late Pleistocene- and Holocene-aged sand dunes also dominate some areas, especially near the current shores of the Great Lakes, and on inland, sandy surfaces that were formerly associated with proglacial lakes or outwash plains (Rawling et al. 2008; Arbogast 2009; Blumer et al. 2012; Loope et al. 2012).

Surface topography is, in many places, rolling, hummocky and irregular, due to its glacial origins and geologic youth. Most landscapes are low or moderate in slope. Most of the lowest relief areas are former lake plains and outwash plains. The highest relief areas are the hummocky end moraines, particularly in central Wisconsin and the western Upper Peninsula of Michigan, and the bedrock terrain of MLRA 93B, also in the western Upper Peninsula. Hummocky areas associated with formerly buried ice are, in some areas, impressive and extensive (Attig and Clayton 1993).

10.3 Climate

Upland soils in the NLSFFR have udic soil moisture regimes, typical of humid climates. Aquic soils with wet, reducing regimes, are mainly found in lowlands and on flat uplands with low permeability and minimal runoff. Large areas of wetlands, and hence, aquic soil moisture regimes, occur in the eastern UP of Michigan and in northern Minnesota. Although most of the region is in the frigid soil temperature regime, the southern parts of the more southerly MLRAs, e.g., 89, 91A, and 95A, are mesic. In northwestern Lower Michigan, MLRA 96, where the lake effect snowpacks insulate the soil and minimize wintertime

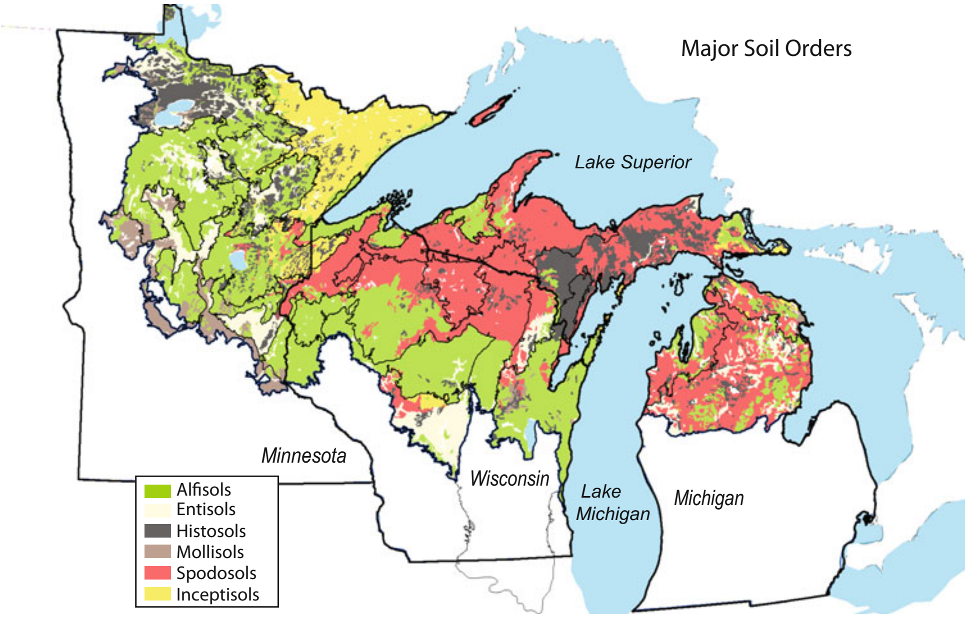

Fig. 10.2 Map of the major soil orders (excluding Vertisols, which are minor in extent) in the NLSFFR

freezing, is also within the mesic soil temperature regime (Schaetzl et al. 2005).

The NLSFFR has a strongly seasonal climate, with cold, often snowy, winters and warm, humid summers. Annual precipitation values are relatively uniform across the region, averaging between $\approx$750 mm in the eastern and northeastern sections of Michigan, to $\approx$850 mm in parts of central Wisconsin (Fig. 10.3). Precipitation totals fall off markedly in northwestern Minnesota; the extreme northwestern parts of the NLSFFR receive an average of only 500–550 mm of precipitation annually. These western areas mark the transition to the drier, prairie parklands of the Great Plains. Precipitation across the NLSFFR is fairly evenly partitioned throughout the growing season; there is no pronounced dry season, although February is commonly the driest month. Soils usually reach their driest point in late August and early September, before the start of predictable fall rains and then, winter snows (Schaetzl et al. 2015).

The frost-free period ranges from <90 days in the uplands of northern Lower Michigan, the western Upper Peninsula of Michigan, and the arrowhead region of Minnesota, to 170 days in central Wisconsin. Longer growing seasons also occur nearer the Great Lakes; these areas also have noticeably cooler summers and warmer winters, because of the slower response of the large water bodies to changes in air temperature and inputs of solar energy (Schaetzl and Isard 2002). As a result, many vegetation communities and soil types common to northerly sections of the NLSFFR have extended ranges to the south along the Great Lakes' shores. Additionally, soils typical of cooler regions, e.g., Spodosols and Histosols, tend to be better developed near the shores of Lakes Superior and Michigan. Land use patterns follow the lakes, as fruit (and some vegetable) production is typically better expressed on uplands near the Great Lakes, other things being equal (Hull and Hanson 2009).

Snowfall is common across the region in winter. Most sites in the region develop and maintain a persistent snowpack throughout at least part of the winter. Snowfall is particularly heavy, and snowpacks are thick and long-lasting, in areas immediately east and south of the Great Lakes (Muller 1966; Norton and Bolsenga 1993; Burnett et al. 2003). The importance of heavy lake effect snow to pedogenesis is discussed below. Climate data suggest that, in recent decades, snowfall is decreasing and snowpacks are thinning (Isard et al. 2007). In general, this trend will lead to colder soils in winter, because the snowpack tends to insulate the soil from frost and freezing (Isard and Schaetzl 1995).

In general, the udic soils of the NLSFFR receive adequate precipitation and snowmelt to allow for deep percolation (through the profile) at least once per year, and usually much more often. Commonly, this period of deep percolation is associated with spring snowmelt, and secondarily, with heavy, extended, fall or winter rains (Schaetzl et al. 2015). The latter types of events vary greatly both temporally and spatially. Most soils receive enough precipitation to flush salts and many types of soluble materials, e.g., carbonates, from the upper profile, in the few thousand years that have elapsed since $\text{time}_{\text{zero}}$. Most soils in the region, therefore, are leached of carbonates to a meter or more, depending on local hydrology and carbonate content of the parent material, i.e., if carbonates even exist in the parent material—see below.

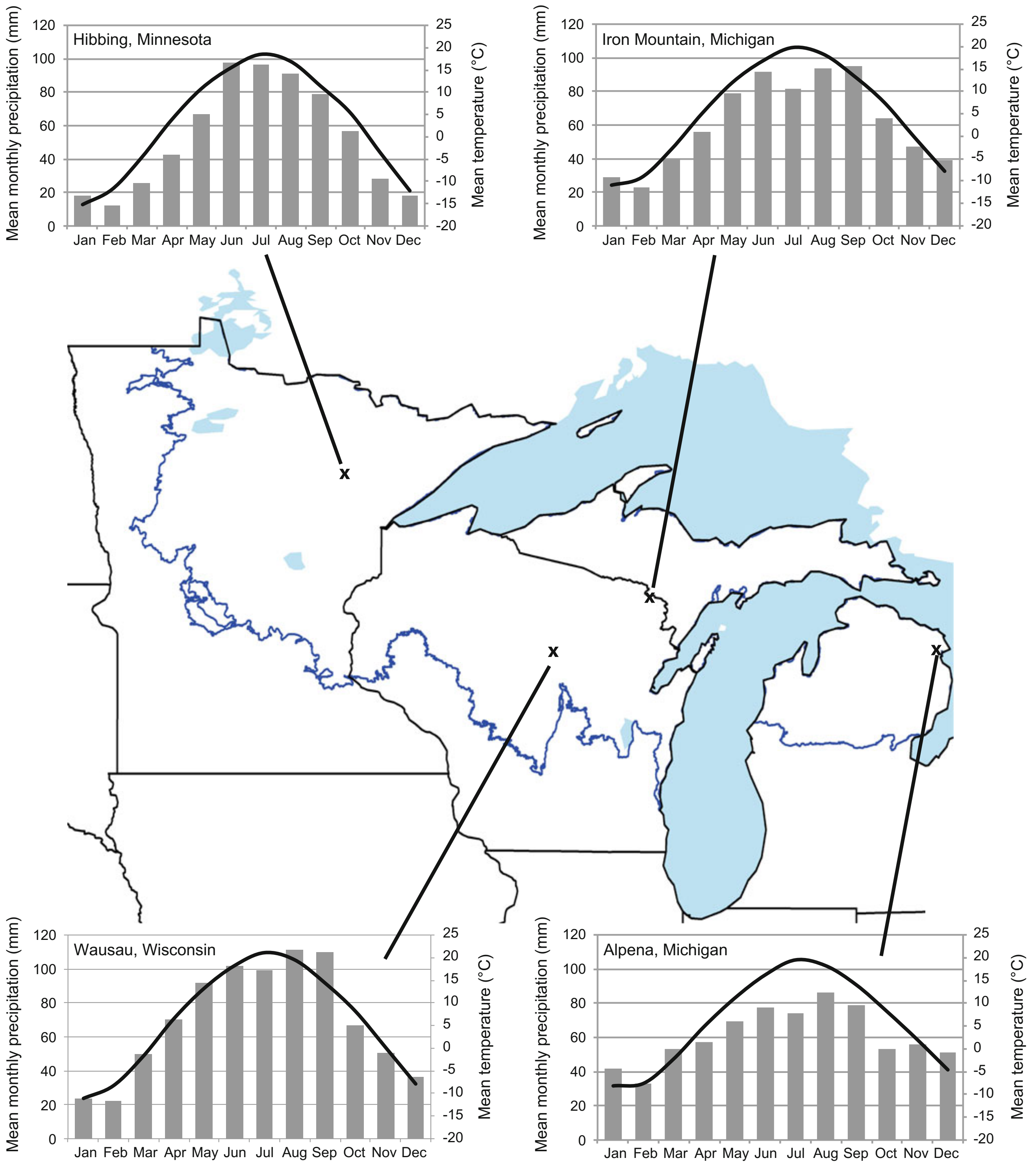

Fig. 10.3 Climographs for four representative sites within the NLSFFR. Most have been constructed using 1961–1990 data from the US National Weather Service

10.4 Vegetation and Fauna

Because of the humid, seasonal climate, and relatively fertile soils, most of the landscape was forested prior to European settlement. And much of it remains forested today (McNab and Avers 1994). Most of the forest was a mixture of coniferous species such as pine (*Pinus* spp.), hemlock (*Tsuga canadensis*), spruce (*Picea* spp.), and fir (*Abies* spp.), with broadleaf deciduous species such as maple (*Acer* spp.), basswood (*Tilia americana*), birch (*Betula* spp.), oak

(*Quercus* spp.), aspen (*Populus* spp.), and beech (*Fagus grandifolia*) (Nichols 1935; Curtis 1959). Many refer to this forest assemblage as the Laurentian Mixed Forest type, or simply as northern hardwoods (Nichols 1935; Stearns 1949). Wet soils in lowland areas tended to support more conifers, as did the driest upland sites, where pine species dominated on deep, infertile sands. In general, conifers tended to out-compete broadleaf trees on the end-members of the wetness and fertility spectrum—on the wettest and on the driest (sandy or shallow to bedrock) sites. In the far north, especially the arrowhead region of Minnesota, relatively pure boreal forest stands occur, but even here they are best developed in wet sites (McNab and Avers 1994). In northwestern Minnesota, drier climatic conditions led to a more discontinuous, parkland-type of forest community, as the region transitions to the western grasslands (Davis 1977).

Although fire is a dominant, natural disturbance factor in the forests of this region, it only indirectly affects the soils. Therefore, because of the near-continuous forest cover, tree uprooting is a common disturbance agent. Trees tear up soil as they uproot, often forming a pit at the former location of the roots, and an adjacent mound, located where the soil slumps off the roots (Fig. 10.4). Soil materials within the mound can be thoroughly mixed as they slump off the root plate, although in some cases, they are simply overturned in a more-or-less intact manner (Schaetzl 1986). Recent work on the longevity of the pit-and-mound topography formed by uprooting suggests that it can persist for millennia (Schaetzl and Follmer 1990; Šamonil et al. 2013), implying that the results of uprooting, i.e., the microtopography, may in many areas be a semipermanent part of the soil landscape. Pits and mounds affect pedogenesis by diverting water into the depressions and off the mounds, leading to enhanced leaching and soil formation in the pits and slower pedogenesis in the comparatively drier mounds (Schaetzl 1990). This type of disturbance leads to high spatial variability in the soil landscapes, especially at small scales (Meyers and McSweeney 1995; Kabrick et al. 1997; Šamonil et al. 2015).

Unforested areas in the NLSFFR generally are of three types: (1) bedrock outcrops, (2) recent and active sand dunes, and (3) very poorly drained sites with a water table at or above the surface. The wetter sites are typically covered in marsh or bog vegetation. Areas of open water—of all sizes—are extremely common in this region, and indeed, help define its character. And although it is not a dominant land use, many areas of agriculture do exist in the region, and as such, create unforested patches on the landscape.

Soil fauna play important roles in the soil system, particularly with respect to nutrient cycling and bioturbation (Salem and Hole 1968; Green et al. 1998). Invasive species are always a threat, and with respect to soils a particularly notable invasive is the common earthworm. Resner et al. (2011) reported on invasive earthworms in the forests of northern Minnesota. Here, bioturbation by earthworms has changed the soils by blurring horizon boundaries in the upper profile and dramatically affecting P and C distributions with depth.

10.5 Parent Materials

In this complex glacial landscape, determining the spatial variation in parent materials is perhaps the best way to understand and explain the composition and pattern of the soil landscape. Parent materials set the stage for soil genesis. And perhaps nowhere is parent material a more important soil forming factor than in young landscapes like this. Because of repeated Pleistocene glaciations, most soils in the NLSFFR have formed in sediments derived directly from the ice (till), indirectly from meltwater (outwash or lacustrine sediment), or due to later, secondary transport of glacial sediment by wind (dune sand or loess) or running water (alluvium) (Fig. 10.5). In many places, especially in northern Lower Michigan, the glacial sediments are many tens of meters thick (Rieck and Winters 1993).

An important, major division in parent material types across the region involves contents of $CaCO_3$ (carbonates)

Fig. 10.4 Photos showing the effects of uprooting on soils and soil landscapes. **a** An uprooted red pine tree, showing the root plate and the adjacent pit. Photo by RJS. **b** Pit-and-mound topography in northern Wisconsin, formed by millennia of tree uprooting. Photo by RJS. **c** Sequence of horizons across a 3600-year-old pit–mound pair in a northern Michigan Spodosol, showing the intact but buried horizons below the mound (*left*), and the spatially focused soil development in the pit (*far right*), as exemplified by deep E and B horizon tongues. Photo by Šamonil et al. (2013)

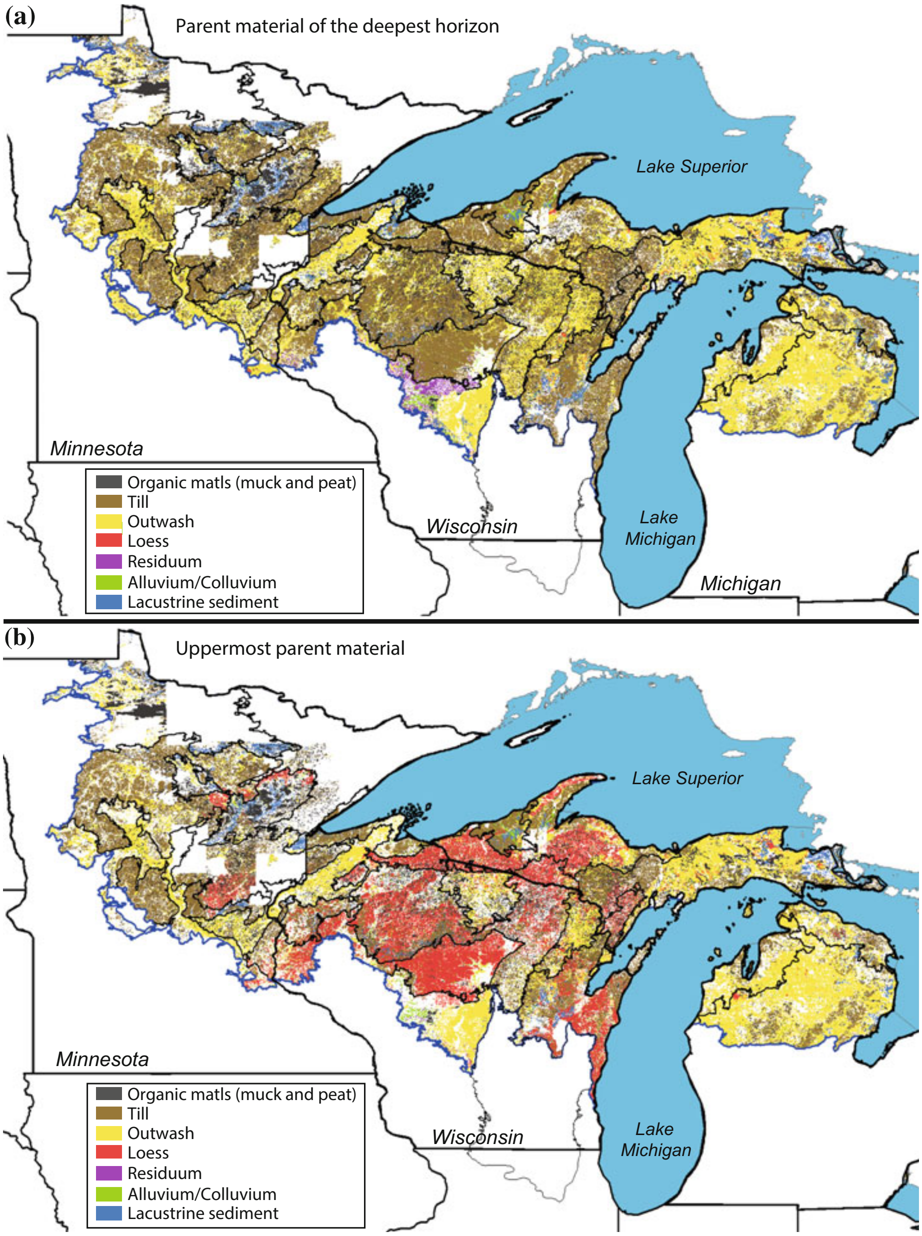

Fig. 10.5 Map of the major soil parent materials in the NLSFFR, as indicated by the Soil Survey Geographic Database (SSURGO) and the official soil series descriptions (OSDs). Areas of organic parent materials are very common, but because they normally occur in isolated, small pockets, they are not readily depicted on a map of this scale. **a** The parent material described at depth, i.e., in the lowermost horizon, in the OSD. **b** Shown here is the same map, but for the uppermost parent material. Note the common occurrence of loess (*red colors*) in this landscape, especially in Wisconsin and the western Upper Peninsula of Michigan. Because the loess here is seldom thicker than 100 cm, only rarely does it occur as the lowermost parent material in the OSD

(Fig. 10.6). In soils formed on calcareous parent materials, the bottom of the solum is usually determined by the depth of carbonate leaching. Soils that form in calcareous parent materials tend to be more fertile, but they also must be acidified and leached of carbonates before important processes like clay translocation and podzolization can begin, before fragipans can form, and before intense weathering of primary minerals can begin. Thus, soils forming in acidic (or at least noncalcareous) parent materials tend to have thicker sola; they have had a "pedogenic head start" of sorts. Parent materials across the north-central parts of the region have been derived from the acidic, igneous and metamorphic rocks of the Canadian Shield, which is centered in south-central Canada and extends into the western Upper Peninsula of Michigan, and into northern Wisconsin and Minnesota. As the glaciers moved across this landscape, they eroded mainly crystalline rocks, producing coarse-textured, acidic drift. In contrast, as the ice traversed the eastern Upper Peninsula of Michigan and parts of western Wisconsin and eastern Minnesota, it also eroded the overlying carbonate rocks like limestone and dolomite, along with shales (some of which are also calcareous) and acidic sandstones. Thus, parent materials in these regions tend to be strongly calcareous and (usually) finer-textured. An area of limestone

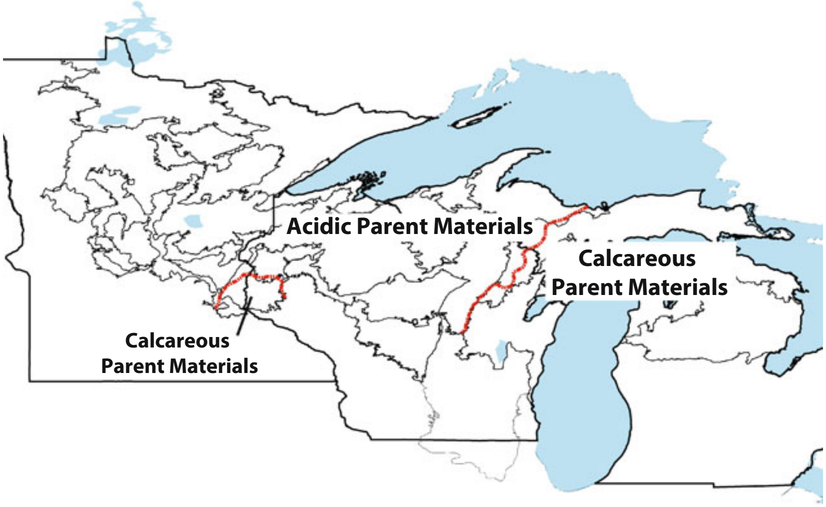

Fig. 10.6 Generalized boundary between acidic and calcareous parent materials in the region

Fig. 10.7 Examples of soil parent materials that are commonly found in the NLSFFR. **a** Sandy glacial till—a particularly rocky example. **b** Stratified sandy/gravelly outwash. **c** Lacustrine sediment—with strata of fine sand and silt. **d** Silty/flaggy colluvium at the base of a slope. Rocks from upslope have been incorporated into the colluvium. Photos by RJS

bedrock in western Wisconsin and eastern Minnesota has also led to calcareous parent materials there (Fig. 10.6).

Till parent materials are widespread; most are sandy-to-loamy in texture (Fig. 10.7). Most tills contain at least some coarse fragments, and some are extremely rocky. Upland soils in the region, particularly those in areas of morainic topography, are usually formed in till parent materials, which can vary markedly in texture and coarse fragment content across even short distances. Thus, soil landscapes formed in till often exhibit great spatial variability in texture, slope, and depth to water table, largely because of their direct glacial origins. These characteristics, combined with complex vertical stratification and frequent lithologic discontinuities (Schaetzl 1998), make mapping such soil landscapes extremely difficult. As a result, the soil maps in this region often have great complexity, with many small mapping units and untold numbers of map unit inclusions (Asady and Whiteside 1982; Miller and Schaetzl 2015). Indeed, this region may contain some of the most difficult and complex terrain in the US, from a soil mapping perspective (Khakural et al. 1993; Fig. 10.8).

As shown in Fig. 10.5, wide expanses of the region are comprised of sandy materials on outwash plains or lacustrine plains. These areas may range in wetness, depending on local depth to the water table, but the spatial variation in soils across them is generally lower than on other landscapes in the region. Many of the sandy lake plains, e.g., the Glacial Lake Algonquin plain in MLRA 94B or the Glacial Lake Wisconsin plain in MLRA 89, are wet. Conversely, many outwash plains, e.g., the Vilas outwash plains in MLRA 94D, are dominated by excessively drained, sandy soils. Some of these landscapes are spotted with small sand dunes which postdate the deposition of the outwash or lacustrine sediment by millennia (Loope et al. 2012).

Soils formed in residuum are not extensive in the NLSFFR, because most bedrock is covered by thick glacial

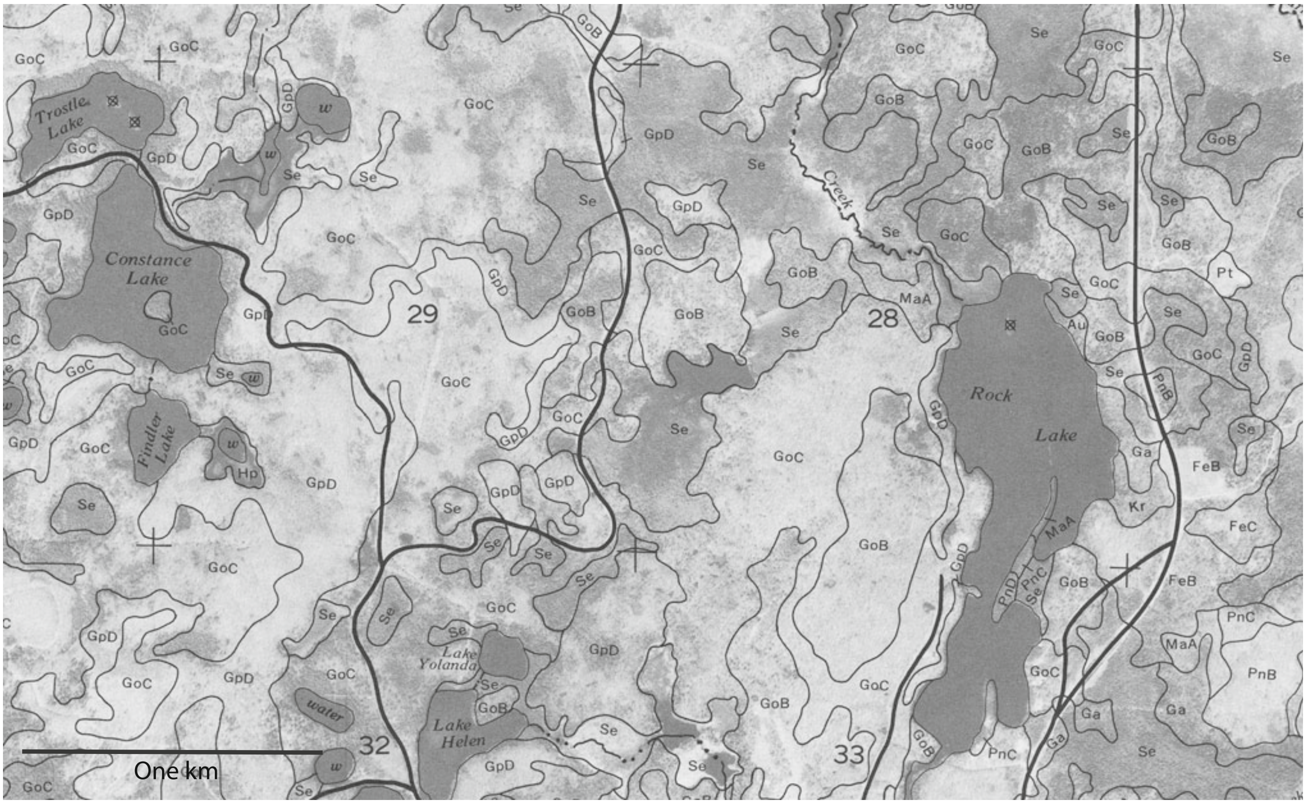

Fig. 10.8 Portion of the NRCS soil map for Vilas County, Wisconsin (Natzke and Hvizdak 1988), within the hummocky Winegar Moraine. Note the many lakes, the contorted outlines of many of the mapping units, and the many small, isolated mapping units within depressions. These characteristics are typical of glacial landscapes formed in till

deposits or has been scraped clean by the ice and has not had ample time to develop a weathered mantle. Similarly, soils formed in colluvium are not widespread, because in most areas slopes are not steep enough to initiate mass movement. Nonetheless, an area with considerable amounts of residual and colluvial soils does occur in the western part of MLRA 89 (but not on the lake plain proper), which lies outside of the last glacial border. The residual soils occur on sandy bedrock uplands, where soft Cambrian sandstones have weathered into sandy Entisols and Inceptisols. Colluvial parent materials here mainly occupy footslopes and lowland areas; often the colluvium is mixed with loess that had formerly accumulated on hilltops.

Other soils in the NLSFFR have developed in materials that postdate the recession of the ice, e.g., dune sand, alluvium, and loess. After ice recession, perhaps for a millennium or more, the landscape was unstable, winds were strong, and sediment was readily available for eolian transport (Schaetzl and Attig 2013; Schaetzl et al. 2014). Thus, many soils in the region are capped with several tens of cm of loess, which is usually silty but in places is loamy (Kabrick et al. 1997; Schaetzl 2008; Scull and Schaetzl 2011; Schaetzl et al. 2014; Fig. 10.5b). Most of the loess was locally derived from outwash plains, meltwater valleys, and abandoned lacustrine surfaces (Schaetzl and Loope 2008; Luehmann et al. 2013). The loess cover is particularly thick in parts of MLRA 90A, especially in Wisconsin. Only recently has the extent and the widespread nature of the loess "mantle" on soils in the NLSFFR been understood and appreciated. Many soils with a thin cap of silty loess exhibit loamy, rather than silty, textures in their upper profiles, sometimes because the silty loess has been mixed into the (normally) coarse-textured sediment below, resulting in a loamy mantle that was (previously) not recognized as loess. These types of loamy soils are particularly widespread in the western Upper Peninsula of Michigan (Luehmann et al. 2013). The loamy cap, even if thin and especially if it overlies sandy sediment, is important for sustaining productive forests. Without this cap, forest productivity on these landscapes would be considerably lower.

While the glaciers were present in the region, permafrost covered many parts of the landscape, south of the ice margin (Clayton et al. 2001). As the ice melted and the climate warmed, this permafrost thawed, leading to long periods of slope instability and erosion. This episode exposed many new parent materials, as soils above were stripped from slopes by solifluction (Attig and Muldoon 1989). Then, before vegetation colonized the landscape, erosion (assisted by the thawing permafrost) by running water contributed large amounts of sediment to local rivers, filling their valleys with alluvium. Other rivers were filled with alluvium derived directly from the melting ice, i.e., by sandy outwash. Today, wide expanses of alluvial soils occur in the major river valleys, many of which have one or more alluvial terraces. For these reasons, outwash is one of the main parent materials in the region, attesting to the vast amounts of meltwater that traversed the post-glacial landscape.

A second, more pronounced and temporally focused wave of erosion and valley alluviation occurred as settlers opened up the landscape to farming in the 1800s. Erosion of upland soils at this time led to valley filling and burial of preexisting soils in valley bottoms; this new sediment is called post-settlement alluvium (Faulkner 1998; Knox 2006).

In perhaps, no other Land Resource Region are Histosols such a dominant component of the soil landscape. Histosols are organic soils that have formed in decaying organic materials. They occur mainly in wet sites where organic matter decomposition is slowed by cold and anaerobic conditions (Kolka et al. 2011). This situation is typical of swamps, marshes, bogs, and fens, which are very common in the isolated depressions (kettles) and broad lake plains of these glacial landscapes (Fig. 10.9).

10.6 Time or Soil Age

All areas within the glacial limit are younger than approximately 18,000 years old, representing the approximate time when the ice started its retreat from its maximum position (Attig et al. 2011b; Schaetzl et al. 2014; Fig. 10.1). The ice was largely gone from the region by 11,000 years ago, implying that most soils in the NLSFFR are between 18,000 and 11,000 years old—quite young by worldwide pedogenic standards.

Soils south of the Late Wisconsin border in central Wisconsin are much older, having been formed in pre-Wisconsin aged deposits that may be a million years old or older. A few of these soils have weathered to such an extent that they classify as Ultisols (Mason et al. 1994), although most have been geologically rejuvenated by additions of loess generated during the late Wisconsin glaciation,

Fig. 10.9 The wet, very poorly drained plain of Glacial Lake Algonquin in the central Upper Peninsula of Michigan, in MLRA 94B. Histosols are widespread here. The wet conditions facilitate the continued formation of thick accumulations of peat. The upland in the background is a small sand dune. Photo by RJS

ca. 18,000–14,000 years ago (Stanley and Schaetzl 2011). Still others exist on old landscapes but have formed in less weathered parent materials, brought to the surface by slope instability and mass movements initiated as late Wisconsin permafrost thawed and solifluction was active (Mason and Knox 1997; Clayton et al. 2001). Indeed, most of the soils in the NLSFFR that are beyond the glacial border retain few, if any, characteristics of older, highly weathered soils that they probably exhibited prior to the last glacial advance.

Soils formed in sand dunes and alluvium can significantly postdate the last glaciations; many of these soils are Holocene in age. Additionally, along the shores of the Great Lakes are several terraces associated with former high water levels. Soils on these terraces and exposed lake beds generally date to 11,000 years ago or earlier (Barrett 2001; Schaetzl et al. 2002; Drzyzga et al. 2012). Lastly, along many bays and inlets of the Great Lakes are beach ridges formed by small-scale oscillations in lake level; soils here can be very young (Lichter 1998). Characteristics of soils on these beach ridges (and dunes that cap them) have been very useful in identifying the extent and ages of lake level fluctuations in the late Holocene (Thompson and Baedke 1997).

10.7 Pedogenesis

Pedogenesis can occur only after the landscape and its parent materials have stabilized. The immediate post-glacial landscape of the NLSFFR was probably a wet, unstable mess, with many areas of localized instability caused primarily by processes of thawing, slumping, washing, and blowing. Although there is at present no way to be certain, it may have taken hundreds to thousands of years before the glacial landscape stabilized and soils could begin forming, largely because of thawing permafrost and the melting of millions of buried (partially or wholly) ice blocks. The legacy of the latter is told today in the thousands of kettle lakes, swamps, and isolated depressions that so aptly characterize this landscape. Next, vegetation colonized the landscape, stabilizing the surface, trapping any loess that may have still been blowing around, and adding organic matter to the soil surface, forming O and eventually A horizons. Slowly, soils began to form.

On the acidic parent materials of the region (Fig. 10.6), pedogenic processes such as clay translocation (lessivage), weathering of primary minerals, and podzolization could proceed almost immediately. On the high-pH (≈8.0–8.3), carbonate-rich materials, these processes were delayed until the carbonates could be leached from the upper profile, and the pH values lowered to at least 6.0. The decarbonation-leaching process probably took thousands of years. Carbonates leached more rapidly on coarser-textured parent materials like sands, while on many of the fine-textured parent materials, carbonates are today only leached to about a meter or less. Any clay that does get translocated in the latter types of soils stops at the upper carbonate boundary, forming a Bt (clay-enriched) horizon. In soils that are more deeply leached of carbonates, the depth of clay translocation is mainly due to depth of wetting fronts and the location of any textural discontinuities.

Soil formation across the region has led to different kinds of soil profiles, which the Soil Survey Staff (1999) has classified into several different orders. The discussion below focuses on soils by order. Occasionally, taxonomic suborders are also singled out.

10.7.1 Entisols

Entisols have minimal horizonation and/or thin profiles (Fig. 10.10). Many Entisols lack a B horizon, or have developed only a very weak B horizon. Many different types of soil landscapes contain small numbers of Entisols, for the reasons discussed above, even though the landscape itself may be dominated by soils of other orders. Several different reasons exist to explain why soils of this kind occur in the NLSFFR, not the least of which is that most soils here are less than a few thousand years old.

Some Entisols (Orthents) occur on clayey parent materials, where carbonates have only been leached to less than ca. 50 cm due to very low permeabilities and high runoff potentials. Water that runs off does not fully function in pedogenesis. Other Entisols (Orthents) occur on steep slopes, where high proportions of runoff again leave little water to percolate vertically and promote horizonation. Additionally, any water that runs off may erode the soil, keeping the profile thin and bringing unaltered parent material ever-closer to the surface. Many Entisols of this kind can be found in the clayey landscapes of MLRA 92. Some Entisols (Lithic Orthents) form in thin regolith (in this case, glacial sediments) over hard bedrock. Here, the overlying sediment, i.e., the soil's parent material, is so thin that a thick, well-developed soil profile cannot form in the accommodation space that remains. These types of soils are common in MLRA 93B, in the western UP of Michigan, and on the rolling bedrock hills of the Arrowhead region of Minnesota (MLRA 93A). Other Entisols (Psamments) are found on sand dunes and on dry, sandy outwash plains, where water tables are very deep. Many of these soils, especially on the dunes, are young and have not had ample time to form a well-horizonated profile. However, many areas of sandy Entisols occur on outwash plains and moraines that are >16,000 years old, e.g., those in MLRAs 94A and 91B. These soils are weakly developed because the sands are so coarse-textured that the soils remain dry throughout much of the summer. Vegetation is poor, often scrubby jack pine (*Pinus banksiana*) or pin oak (*Quercus palustris*) forest that burns frequently (Simard and Blank 1982). This type of

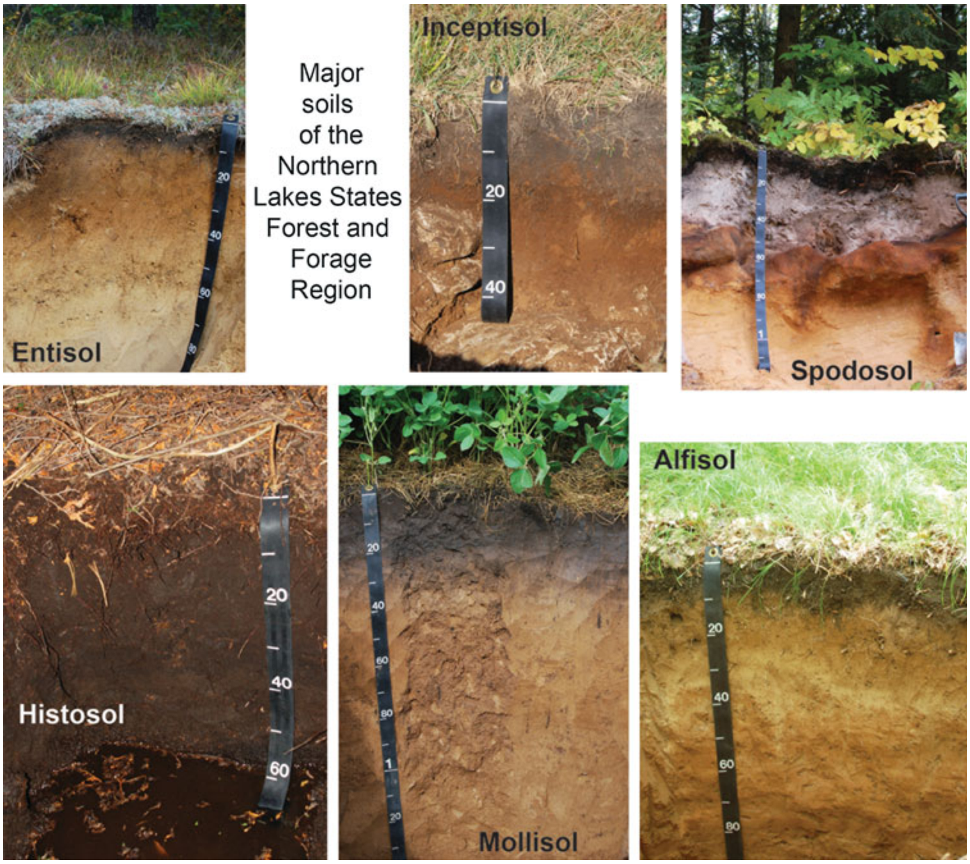

Fig. 10.10 Collage of photos of the typical soils found in the Northern Lake States Forest and Forage Region. Tape increments in cm. Photos by RJS

vegetation produces little litter to enhance pedogenesis (podzolization mainly, see below), and frequent fires burn up what litter is present (Mokma and Vance 1989; Schaetzl 2002). Soils formed in the recent alluvium of river valleys, especially those valley floors that flood commonly, are in the Fluvent suborder. These soils are prevented from developing thick profiles because of frequent additions of sediment from floods, or from high water tables (Aquents). On floodplains and elsewhere, Aquents have weakly developed profiles because of high water tables, which inhibit weathering and translocation. Aquents are common on the plain of Glacial Lake Wisconsin, for example, in MLRA 89.

Entisols are used for a variety of low-intensity purposes in the region. Many, if not most, remain in forest. Some, however, are cropped to hay or forage, and others are left in permanent pasture. The natural fertility of these soils is largely a function of the parent material, but in most cases the parent materials are too sandy, dry, wet, or clayey to be managed for agriculture, unless intensively fertilized, drained, or irrigated.

10.7.2 Inceptisols

Inceptisols are similar to Entisols in many ways, but have a slightly better developed profile (Fig. 10.10). Inceptisols are widely distributed in the NLSFFR and occur across a wide range of ecological settings, except for the sandiest landscapes. Soil Taxonomy (Soil Survey Staff 1999) does not allow most extremely sandy soils to be classified as Inceptisols. Two main Inceptisol suborders are recognized in the NLSFFR—Aquepts (Inceptisols with high water tables) and Udepts (all others). Upland Udepts in the region fall into two great groups—Eutrudepts and Dystrudepts. The former have higher contents of base cations (K, Ca, Mg, and Na) and nutrients, and tend to be found on carbonate-rich parent materials. Dystrudepts are more acidic and tend to be infertile; they are common on acidic parent materials (Figs. 10.2, 10.6). Udepts are especially common in the Arrowhead region of Minnesota (MLRA 93A). Many of the loamy soils on moraines and other, steeply sloping landscapes are also Inceptisols.

Considerable expanses of wet Inceptisols with high water tables (Aquepts) occur on the clayey lake plains of the eastern Upper Peninsula of Michigan (Fig. 10.11). Here, the high water table has inhibited pedogenesis, and thus, these soils have gleyed (gray, reduced, and waterlogged) Bg and Cg horizons.

Inceptisols, like Entisols, are often not intensively managed for agriculture, and most remain in forest. Aquepts on the clayey lake plains of the eastern UP are, however,

Fig. 10.11 The Chippewa Clay Plains region, part of MLRA 94B—the former floor of Glacial Lake Algonquin. The clay-rich Aquepts on this landscape are wet and calcareous at depths of less than a meter. Too wet and muddy to cultivate and re-plant each spring for grain crops, the soils are left in forage and cut annually for hay. The long summer days and cool temperatures combine to make hay production profitable in this otherwise wet, clayey landscape. Photo by RJS

successfully managed for hay production (Fig. 10.11). In other areas of Aquepts, subsurface drains are used to lower the water table and make agriculture possible. Many Udept landscapes are steeply sloping or erosion-prone, and hence, remain in forest or are used for pasture.

10.7.3 Alfisols

Alfisols have a strongly developed Bt horizon, which by definition is enriched in illuvial clay (Fig. 10.10). The clay is translocated from the upper profile by percolating water, but only if the pH is acidic (Schaetzl and Thompson 2015). Thus, soils on calcareous parent materials must first be leached of carbonates before clay translocation (termed *lessivage*) can begin. In most soils, ample decarbonation would have occurred after about 3000 to 5000 years. As the boundary between the (lower) calcareous zone and the (upper) leached zone deepens with time, the Bt horizon grows downward too, and often gets thicker. In many soils of this region, the boundary between the upper (eluvial) zone and the Bt horizon is not smooth, but undulating and wavy. Soil scientists refer to this type of morphology as interfingering or tonguing. Horizons that contain tongues or fingers of the E (eluvial) horizon in the Bt are called glossic horizons. Many soils in the NLSFFR are Glossudalfs—Alfisols with glossic features (Ranney and Beatty 1969; Bullock et al. 1974).

Alfisols can develop on a wide variety of parent materials, as long as the material contains some clay, which most parent materials in the NLSFFR do. Even sands can show signs of clay translocation, manifested as thin, often wavy, clay bands called lamellae (Schaetzl 1992; Rawling 2000). Bt horizons are very important ecologically, as they provide natural filters for percolating water, but more importantly, they enhance the soil's ability to retain nutrients and water. On many sandy landscapes, for example, forest type and productivity change when the sands have lamellae; even a few lamellae greatly enhance the productivity of the forest ecosystem (Host et al. 1988).

Everywhere across the NLSFFR ample precipitation exists to drive the process of lessivage, i.e., to produce at least some deep percolation events each year. Free drainage is also necessary for efficient clay translocation. For this reason, Bt horizons are often only weakly developed in some settings with high water tables; wet Inceptisols (Aquepts) then develop. If Bt horizons are weakly developed because the parent material is fine-textured and has low permeabilities, soil development will again be slowed, and Udepts (Inceptisols) will form.

Wide expanses of the NLSFFR have a mantle of Alfisols. In these landscapes, Histosols dot the lowlands and Entisols or Inceptisols may occur on areas of steep slope. But the matrix is an Alfisol landscape dominated by till parent materials that have undergone clay translocation—enough to produce (in places) what the locals may call a "clay pan." Alfisols have not only this "clay pan" but, as a consequence, they also have an upper profile that has lost clay, and some can even be quite sandy. Farming Alfisols for corn, hay, potatoes, and small grains is a common occurrence across the region. The upper part of the profile—the tilled part—can be loose and easy to till, whereas the subsoil is more clay-rich and thus, is effective at retaining water for deeply rooted crops (Fig. 10.12). This situation works well for the local farmers; agricultural production on Alfisols here is hampered more by climate than by soil. Indeed, many areas of Alfisols in Michigan's western Upper Peninsula and northern Minnesota could be brought into production if the growing season were only a little longer, or warmer. As it is, these areas support very productive forest ecosystems, especially valued for quality hardwood lumber and veneer products.

Wet Alfisols with high water tables classify as Aqualfs, whereas upland Alfisols are in the suborder Udalfs. Several different great groups of Udalfs also occur here, e.g., Hapludalfs, the "simple" ones, Glossudalfs with a glossic horizon, Fragiudalfs with a fragipan, and Fraglossudalfs with the combination. A fragipan is a hard, brittle, and dense pan that forms in the lower profile. Many Alfisols and Spodosols in the NLSFFR have fragipans. Fragipans are almost entirely found in the acidic parent material parts of the region (Fig. 10.6). Although fragipans inhibit deep rooting, many areas with these types of pans are still successfully managed for forest products and even crops.

10.7.4 Spodosols

On coarse-textured parent materials, and especially in the northern parts of the NLSFFR, Spodosols are the dominant soil order (Fig. 10.2). Spodosols form via a process called *podzolization*, which involves the translocation of organic materials, Fe and Al compounds in percolating water (Schaetzl and Harris 2011). Unlike clay translocation in Alfisols, the Fe and Al move in solution, as dissolved compounds. Soluble organic compounds also move in such soils, as a key part of the podzolization process. The result is a B horizon enriched in Fe, humus (decomposed and soluble compounds of organic matter) and Al. These compounds give the B horizon—the spodic horizon—its characteristic red, reddish brown, or black colors (Fig. 10.10). The more of these "spodic materials" in the B horizon, the darker and redder it becomes (Schaetzl and Mokma 1988). Eventually, the content of the spodic materials reaches a point where

Fig. 10.12 Irrigated potato production on the Antigo Flats—an outwash plain in northeastern Wisconsin that is covered by 60–100 cm of loess. The soils here are Alfisols and Inceptisols. The Antigo area is one of the region's main potato producing areas. Photo by RJS

they may cement the horizon into a substance called ortstein. Spodosols with ortstein represent the pinnacle of development for soils undergoing podzolization.

Upland Spodosols form best under a cool-cold, humid climate, where ample precipitation exists to drive soluble materials into the lower profile. (By necessity, this section does not discuss the wet Spodosols that are common in warm climates such as Florida.) Also necessary is a forest cover that produces acidic litter; the best trees for this purpose are many of the conifers, as well as beech (*Fagus* spp.), oak (*Quercus* spp.), hemlock (*T. canadensis*), and even some maples (*Acer* spp.). The litter produced by these trees accumulates on the soil surface, decomposing only slowly in the cool climate. As it decomposes, the soluble organic materials released are washed into the soil, complexing with Fe and Al compounds released by weathering of primary minerals. Once complexed, such compounds are readily translocated to the lower profile in percolating water. Thus, in locations farther south in the LRR that lack this type of forest cover, and areas to the west where grasslands are more common, Spodosols are absent.

Within the "Spodosol province" of the NLSFFR, Spodosols of varying degrees of development can be found. Strongly developed Spodosols also occur here; nowhere in the continental US are there better developed Spodosols (Schaetzl et al. 2015). On the margins of the Spodosol province, weakly developed Spodosols transition into sandy Entisols (Psamments).

The POD Index, developed by Schaetzl and Mokma (1988) to quantify the degree of development of spodic-like soils, shows the distribution of Spodosol development across the region—reaching its maximal expression in the eastern Upper Peninsula of Michigan (Fig. 10.13). Spodic development and the intensity of podzolization across the region appears to vary mainly as a function of climatic factors (Schaetzl and Isard 1991, 1996), or of climatic factors as they have (directly or indirectly) influenced vegetative cover and forest type (Mokma and Vance 1989; Schaetzl 2002). In particular, strong Spodosols usually coincide with areas of heavy snowfall and thick snowpacks. These snowbelt areas tend to occur about 20 to 70 km inland, west and/or south of the Great Lakes (Fig. 10.14). In these areas, thick, early snowpacks inhibit soil freezing and keep the soil and litter layers relatively warmer than at areas farther inland, which receive less snow (Isard and Schaetzl 1995, 1998). As a result, soils in snowbelt areas stay unfrozen and permeable throughout the winter. Then, in spring, large pulses of snowmelt water can freely infiltrate into and percolate through these soils (Schaetzl et al. 2015). The deep, reliable, and continuous snowpacks in snowbelt areas also insulate the fresh litter in the O horizon, facilitating its steady breakdown throughout the winter, thereby promoting the production of soluble organic acids. Wetting events that occur during snowmelt (and those associated with prolonged fall rain events) can readily translocate these soluble organic acids from the litter layer, deep into the mineral soil below. In sandy areas where podzolization is weak, less water is available for springtime percolation because of thinner snowpacks and the more frequently frozen soil, or the fall season is much drier. Much of the little snowmelt that exists in such areas runs off the still frozen surface and does not participate in pedogenesis.

Spodosols are mainly used for forest production and grazing. Some Spodosols that have formed in sandy materials that have 5–25 % silt + clay contents can develop a clay-rich horizon at depth, and these soils are more likely to be cropped because of their higher water- and nutrient-holding capacities. Potatoes and hay are common crops on such soils.

10.7.5 Mollisols

Mollisols have a thick, dark A horizon, rich in organic matter (Fig. 10.10). They are typical of drier climates and grassland ecosystems. Nonetheless, they can and do form in the NLSFFR, primarily where conditions permit the long-term accumulation of soil organic matter within the mineral soil (not on *top* of it—that is Histosols).

Soils accumulate organic matter when its production rate exceeds its rate of decay. This situation can occur in wet sites, where a high water table inhibits decomposition. These soils are called Aquolls, and their distribution is spotty and localized, often occurring immediately upslope from Histosols. Soils can even accumulate organic matter beneath forest, where large amounts of carbonate rocks are intermixed in the parent material (Schaetzl 1991). The carbonate minerals form strong bonds with the organic matter, slowing its decay. Lastly and most commonly, soils accumulate organic matter under grassland ecosystems, because grass roots form and die so rapidly that the processes of decay cannot keep pace. Eventually, an equilibrium state develops, where inputs of soil organic matter (mainly from root decay) nearly balance losses from decomposition. This "break-even point" typically occurs at about the depth of most grass roots, and in many Mollisols the soil organic carbon content at this depth is about 1.0–2.0 %. Because, the roots of grasses in these environments grow deep, the A horizon is much thicker than that of Alfisols formed under forests of more humid environments. Grasslands, or grassland-forest

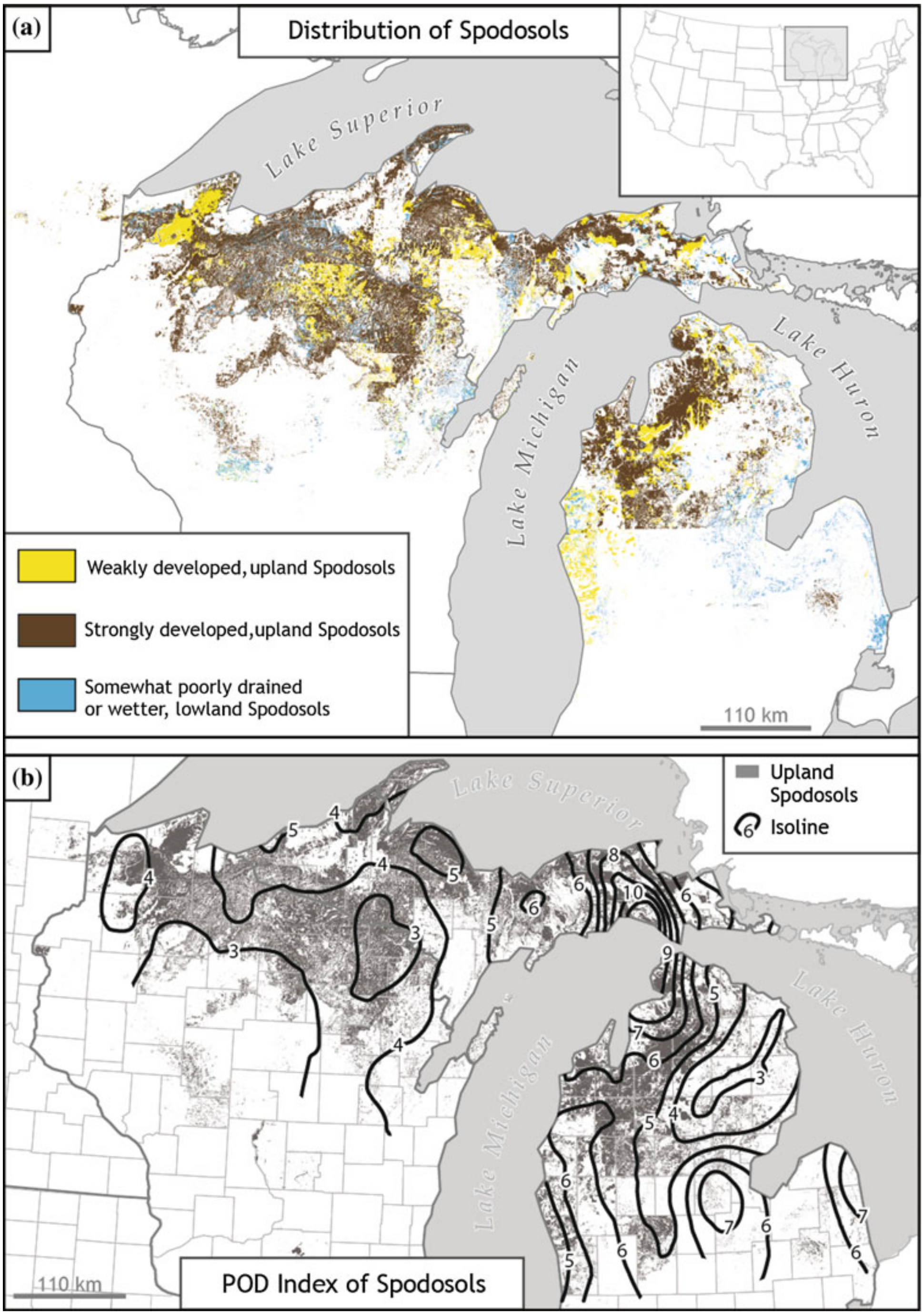

Fig. 10.13 Distribution of Spodosols in the Great Lakes region. **a** Spodosols, as grouped into three general categories based on taxonomic subgroup. Data source: NRCS SSURGO. **b** Isolines of interpolated POD Indices for upland Spodosols. Higher values indicate stronger soil development. So few upland Spodosols occur in Minnesota that the isolines were not interpolated for that area. After Schaetzl et al. (2015)

savanna ecosystems, occur in the far western parts of the NLSFFR, specifically in MLRA 91A, explaining why Mollisols occur here (Fig. 10.2).

Because of their high organic matter contents, Mollisols are highly productive soils. Aquolls are often drained and brought into agricultural production. If drainage is not required, as in Udolls, they are readily cultivated for many types of crops, with cereals and legumes being the most common types in this region. In most instances, Mollisols are the most productive soils of not only this region, but of most regions within the US (Schaetzl et al. 2012).

10.7.6 Histosols

Histosols are organic soils whose parent material is predominantly organic matter, e.g., leaves, grasses, roots, and wood, rather than mineral material, as in the other soil orders

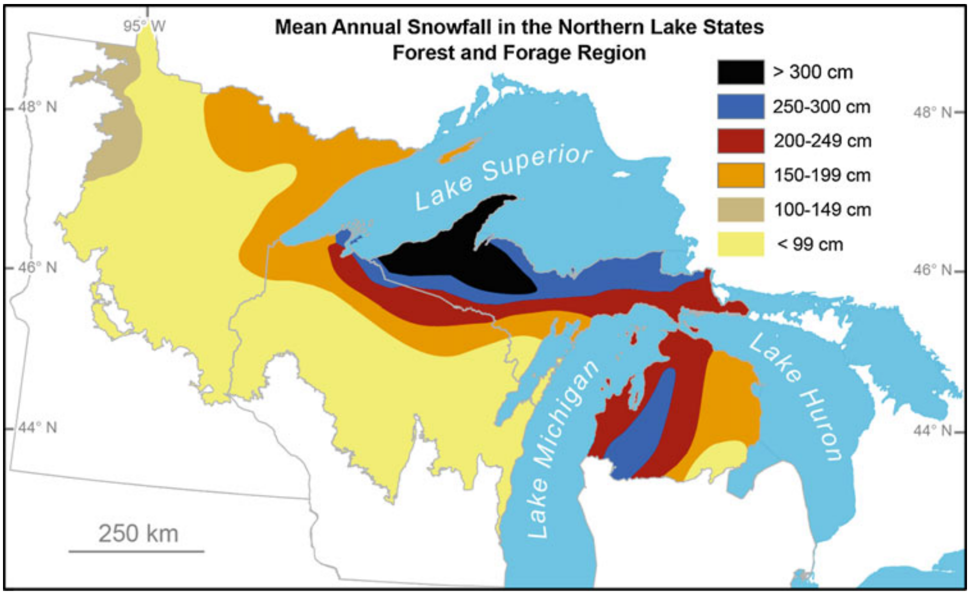

Fig. 10.14 Mean annual snowfall in the NLSFFR. Compiled from various sources

(Kolka et al. 2011; Kroetsch et al. 2011; Fig. 10.10). Although most soils, in their natural state, have an organic (O) horizon at the surface of the mineral soil, for a soil to classify as a Histosol, this organic layer must be at least 40 cm thick. This situation typically occurs in two types of settings. First, they can form on top of rock, where the decaying organic matter cannot be mixed into any mineral soil below, and hence, it simply accumulates (Fox and Tarnocai 2011). These soils are called Folists, and they are fairly rare. Much more commonly, Histosols form in lowlands where the long-term water table is at or above the surface (Gates 1942; Heinselman 1970; Fig. 10.9). Litter that falls into the cool water decays very slowly due to the (often) anoxic conditions within, and hence, partially decayed organic matter accumulates, sometimes to many meters in thickness. Although both of these situations occur commonly outside of the NLSFFR, across the entire US one normally would not find Histosols because the warmer climatic conditions lead to more rapid decomposition. That is, the cool conditions of the NLSFFR are vital for the development of Histosols. Because of the many isolated depressions left behind by the melting of buried ice in this young, glacial landscape, small-to-large bodies of Histosols are a part of almost every soil landscape. The consistent presence of small-to-medium pockets of Histosols adds great ecological diversity to the landscape. Areas of large expanses of Histosols also occur in the NLSFFR, mainly on Pleistocene lake plains.

Histosols are important as wetland habitat and play a key role in the Earth's carbon cycle. Obviously, they are also vital to the local and regional hydrologic cycles. Some Histosols have been drained for production of turfgrass or cranberries, and some are mined for peat and muck. Nonetheless, the vast majority of these soils remain essentially untouched. Most Histosols in the NLSFFR are naturally forested, unless too wet, where they transition to bog or marsh vegetation, and then (often) to open water.

10.8 Conclusions

The soil landscapes of the Northern Lakes States Forest and Forage Region are diverse and pedologically–geologically young. Many soils are just beginning to develop. Poorly integrated drainage networks and myriad of isolated depressions have led to an abundance of wet soils, and some of the greatest densities of Histosols anywhere in the US. Upland soils are mainly a product of their parent materials, as many soils have not had adequate time to overprint pedogenic characteristics onto the inherited sediments. Thus, the landscape's complexity is more geologic than pedologic. And it IS complex; perhaps some of the most complex and variable soil landscapes in the US are within this region. On top of this pedogenic diversity are a plethora of lakes and marshes; this is the land of far more than 10,000 lakes!

Most soils here have formed due to pedogenic processes associated with a cool, humid climate, under the influence of forest vegetation. Podzolization dominates on coarse-textured parent materials, leading to some of the strongest and best developed Spodosols in the US. On loamy and finer-textured materials, Bt horizons form readily, and if well-developed, these soils classify as Alfisols. Histosols are common in wetlands and lowlands, providing pedologic diversity to an already diverse soil landscape.

Most soils are minimally weathered, rich in nutrients and fertile, although many are too wet, or too dry and sandy to economically cultivate for agriculture. Still others are too far north and hence, too cold, for the production of most cash grains. For this reason, most of this landscape remains forested even today.

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