THE NATURAL SOIL DRAINAGE INDEX: AN ORDINAL ESTIMATE OF LONG-TERM SOIL WETNESS

Randall J. Schaetzl
Department of Geography
128 Geography Building
Michigan State University
East Lansing, Michigan 48824-1117

Frank J. Krist, Jr.
GIS and Spatial Analysis, Forest Health Technology Enterprise Team
USDA Forest Service
2150 Centre Avenue
Bldg. A, Suite 331
Fort Collins, Colorado 80525-1891

Kristine Stanley
Department of Geography
University of Wisconsin
Madison, Wisconsin 53706-1491

Christina M. Hupy
Department of Geography and Anthropology
University of Wisconsin
Eau Claire, Wisconsin 54702-4004

Abstract: Many important geomorphic and ecological attributes center on soil water content, especially over long timescales. In this paper we present an ordinally based index, intended to generally reflect the amount of water that a soil supplies to plants under natural conditions, over long timescales. The Natural Soil Drainage Index (DI) ranges from 0 for the driest soils (e.g., those shallow to bedrock in a desert) to 99 (open water). The DI is primarily derived from a soil's taxonomic subgroup classification, which is a reflection of its long-term wetness. Because the DI assumes that soils in drier climates and with deeper water tables have less plant-useable water, taxonomic indicators such as soil moisture regime and natural drainage class figure prominently in the "base" DI formulation. Additional factors that can impact soil water content, quality, and/or availability (e.g., texture), when also reflected in taxonomy, are quantified and added to or subtracted from the base DI to arrive at a final DI value. In GIS applications, map unit slope gradient can be added as an additional variable. The index has myriad applications in forestry, ecology, geomorphology, and environmental modeling, especially when examined spatially; we provide some examples in this paper. The DI has great potential for many landscape-scale modeling and GIS applications where soil water content is an important variable. DI values for all soils currently classified by the NRCS can be accessed from pull-down menus on the DI web site: http://www.drainageindex.msu.edu/ [Key words: soil wetness, modeling, GIS, landscape scale, forest ecology.]

Physical Geography, 2009, **30**, 5, pp. 383-409.
 DOI: 10.2747/0272-3646.30.5.383

INTRODUCTION

Soil data are vital components of many geomorphic, forest, ecological, and landscape models (Post et al., 1982; Wosten et al., 1985, Ung et al., 2001; Willgoose and Perera, 2001). Nonetheless, many spatial modelers often experience difficulty and frustration in working with soils data, often because they exist as imprecisely defined and poorly understood, nominal scale variables. And although taxonomic terms often convey large amounts of useful information about soils, they are, for many users, difficult to unravel and fully utilize. Consider, for example, the major soil drainage classes (well-drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained), which are general indicators of soil wetness and long-term water availability. Because these classes are nominal variables, utilizing them in quantitative applications is often problematic. Similar statements could be made for several other soils variables, e.g., texture class, structure, erodibility, mineralogy, nutrient potential, and color. Nonetheless, for many environmental and forestry applications, one of the most important ecologic attributes (variables) is soil water content and availability (White, 1958; Zahner, 1958; Elliott and Swank, 1994; Davidson, 1995; Stephenson, 1998; O'Connell et al., 2000). Additionally, in many forestry and modeling applications, data on *long-term* soil water content are more important than comparable data for recent periods or for short time intervals (Iverson et al., 1997; Lookingbill et al., 2004). Therefore, in this study, we present a rationale and methodology for quantifying *long-term soil wetness* into an ordinal variable, thereby enabling modelers and environmental managers to more fully incorporate soil wetness and water content into their work.

The Value and Use of Indices in Environmental Analysis

Indices serve to take the complexity (and nominal-scale attribute tendencies) inherent within soil classification systems and reduce it to a single number or a set of numbers. Thus, "indexing" is common in soils research; certain aspects of the soil are entered into a formulation designed around a specific goal, the end result of which is a single number (index) that can then be applied in various quantitative, spatial, and modeling applications. Examples of a few of the more commonly applied soil indices are mentioned here. The Profile Development Index (Harden, 1982) is perhaps the most popular soil development index (Vidic, 1998; Dahms, 2002; Ortiz et al., 2002). The goal of this index is to quantify *soil development* using a number of morphological and chemical parameters, many of which are actually nominal- or even categorical-scale variables, e.g., argillans, texture, rubification, color. Other popular indices designed to assess soil development include the POD Index (Schaetzl and Mokma, 1988), a field-based index designed for pozdolic soils, and Martini's (1970) index of weathering in red, tropical soils. As is clear from these examples, most soil-based indices focus on soil development, and thus have mainly pedogenic and geomorphic applications (Schaetzl and Anderson, 2005). In this study, we present a new index, the Natural Soil Drainage Index (DI), whose purpose is to mimic the amount of water that a soil makes available to plants on a long-term basis. Early versions of the DI were first initiated by Hole (1978) and Hole and

Campbell (1985), and expanded upon by Schaetzl (1986). None of these studies, however, attempted to develop an index that was "universal," i.e., could be applied to all known (classified) soils, as we illustrate here.

Schaetzl's (1986) early formulation of the DI has found utility as an indicator of denitrification across soil landscapes (Groffman and Tiedje, 1989; Groffman et al., 1992; Jungkunst et al., 2004). Bragg et al. (2004) applied it in an ecological study to model soil moisture–based growth response in forests. Schaetzl's (1986) DI application was an exercise in discriminating between landform regions and local-scale changes in geomorphology; recent studies by the U.S. Forest Service, using a DI prototype, have shown it to be useful for determining forest health and risk (Krist et al., 2007). Therefore, we argue that our new and expanded application of the new DI has great utility, especially in environmental inventory and modeling (e.g., Thogmartin et al., 2006; Lookingbill and Urban, 2004).

Although indexing soil wetness to a single number appears to have great potential in many applications, its operationalization can be frustrating. Usually, long-term soil wetness data are, appropriately, derived only from soil drainage class information. Unfortunately, these data are inadequate surrogates for long-term water supplying ability (for plants) on *inter-regional* bases, because the influence of macroclimate is not directly considered in their definition. That is, a well-drained soil in a humid climate provides far more water to plants than does a well-drained soil in a semi-desert, i.e., it is generally "wetter." Thus, incorporating climate into an index of long-term soil wetness seems advantageous, even necessary.

Many modelers have used available *soil water-holding capacity* (a.k.a. "available water") as a surrogate for the long-term ability of a soil to supply water to plants, with some success (Ung et al., 2001). Available water capacity is mainly a function of soil texture, organic matter content, structure, and rooting zone depth (Ritchie, 1981; Rawls et al., 1982; Hillel, 1998). Thus, it is pedon- or site-specific, i.e., neither climate nor water table (drainage class) factors need be included in its derivation, rendering available water data useful only across small areas of similar climate and drainage class. For example, humus-rich, silty soils tend to have the highest available water-holding capacities, but if they are in a dry climate or have a deep water table, their ability to supply water to plants is far surpassed by soils in a more humid climate, or in a wetter drainage class, regardless of their other attributes.

Recognizing these issues, and perceiving the need for an index of soil wetness that has broad regional-scale applications, we developed the DI, using components derived from soil climate and drainage class data in its core formulation. The purpose of our study is, therefore, to reintroduce the DI, in its expanded form, explain and justify its formulation, and provide some examples of its utility and applicability.

Types of Soil Wetness Models

It is important to point out how the DI differs from other, perhaps more empirical, indexes of soil wetness. We view existing soil wetness indexes as falling into two main groups: (1) those that use existing soil maps and interpret/model soil wetness from them; and (2) those that develop quantitative relationships among soil wetness (however defined) and various soil, landscape, or climate variables. The DI falls into the first category; we accept existing soil maps as our current, best understanding of the distribution and character of soils across a landscape, and use our knowledge of soils in the DI formulation to place a DI value on each soil map unit. Thus, our research focuses on modeling applications *using* existing soil maps.

The second group of soil wetness modeling applications is fundamentally different in its approach. These models develop quantitative relationships between various soil, climatic, and topographic parameters, in order to either (1) better resolve, i.e., map, wetness across the landscape or (2) make predictions regarding soil wetness based on assumed or known inputs. For example, one line of research has focused on patterns of soil color as an estimate of long-term soil wetness (e.g., Evans and Franzmeier, 1988; Thompson and Bell, 1996; Blavet et al., 2000). Applications here center mainly on ascertaining the appropriate drainage class or wetness condition of a soil, which can be used to assist future mapping endeavors or to improve existing soil or wetland maps. Many of these color-based indices have restricted applicability, e.g., to one particular soil order or region (Thompson et al., 1997). Another approach relies heavily on terrain data in the determination of soil wetness, because when various soil, sedimentologic, ecologic, and climatic data are combined with terrain information, the output can be highly useful in determining the extent and degree of soil wetness on a landscape (Beven and Kirkby, 1979; O'Loughlin, 1986, 1990; Moore et al., 1988; 1993; Barling et al., 1994; Zheng et al., 1996; Thompson et al., 1997; Chaplot et al., 2000). As above, these applications center on improving our ability to visualize current, or predict future soil wetness conditions, rather than to utilize existing soil maps in various modeling endeavors. Although these indices do a good job of incorporating topography into landscape-based measures of soil wetness, and thus may have better spatial accuracy than does the DI for a given catchment, they nonetheless are often limited to intra-regional applications. That is, their use in large-scale, inter-regional applications is often severely limited, due either to model assumptions, data limitations, or computing power. Lastly, the many topographically based soil wetness models are often insensitive to permeability characteristics of the soils, i.e., soils at the base of slopes are viewed as being wetter that soils upslope, regardless of whether runoff is expected or not.

This discussion highlights the fact that analysis of soil wetness varies according to scale and whether pre-existing soil maps are the main data input (Ryan et al., 2000). Indeed, in many landscape applications, high quality, large-scale soil maps do exist, and modelers are content with using these data (e.g., Davidson and Lefebvre, 1993; Zheng et al., 1996) rather than developing a more complicated model to potentially increase detail and accuracy. Our work has, therefore, centered on developing an index to quantify long-term soil wetness *from existing NRCS soil maps*, assuming that the accuracy of these soil maps is sufficient for the given application.

The Drainage Index: Background, Theory, and Goals

The DI is formulated to mimic the quantity (and to a lesser extent, quality as it relates to salinity) of water that a soil contains and makes available to plants under normal, long-term climatic conditions, including water under saturated and unsaturated conditions. It is primarily determined from a soil's taxonomic classification (Soil Survey Staff, 1999). The DI only nominally takes soil texture into consideration, as texture can be independent of soil wetness, especially under saturated conditions. Sandy soils, if their sandiness is manifested in their taxonomic classification, are rated drier on the DI scale than are soils of other textures. Two examples are used here to illustrate this point.

1. Poorly-drained soils, with high water tables, can supply far more water to plants than do well-drained soils, regardless of texture. Texture is only minimally important in this case. For this reason, the DI formulation places a high degree of importance on soil drainage class.

2. A well-drained, sandy soil in a humid climate has more plant-available water, long-term, than does a well-drained silt loam soil in a drier climate, even though silt loam is a more favorable texture for supplying water to plants. For this reason, the DI formulation places a high degree of importance on soil climate, as expressed in soil moisture regime data (ibid.). However, within a small area, such as a first-order watershed, soils with siltier textures will probably be able to supply more water to plants than will sandy or clayey soils, other things being equal. In short, soil climate may be more important than texture, except at local scales.

Thus, the main factors affecting the DI, by way of the soil's taxonomic classification, are *mean water table depth* (as indicated by the *natural soil drainage class*) and *soil climate* (as indicated by the *soil moisture regime*). The six main soil moisture regimes (aquic, perudic, udic, ustic, torric, and xeric) and their intergrades figure prominently in the formulation of the DI (ibid.). Some other factors that can affect the DI include surface (map unit) slope gradient, organic matter content, coarse textures, and the various types of soil horizons (Fig. 1). Again, these characteristics can only be taken into account in the DI formulation if they are manifested in the soil's taxonomic classification.

The DI ranges from 0 to 99 (Schaetzl, 1986), with higher DI values for soils that can, theoretically, supply more water to plants. Sites with DI values of 99 are, essentially, open water filled with soil material (usually, saturated organic soil materials). A soil with a DI of 1 is so thin and dry (and in a desert climate) as to be almost bare bedrock. Most well-drained, mesic sites in humid climates have DI values that range from 35 to 50. Because a soil's taxonomic classification is not (initially) affected by such factors as irrigation or artificial drainage, the DI does not change as soils become irrigated or drained, unless the long-term effects of these activities result in a change in the soil's taxonomic classification.

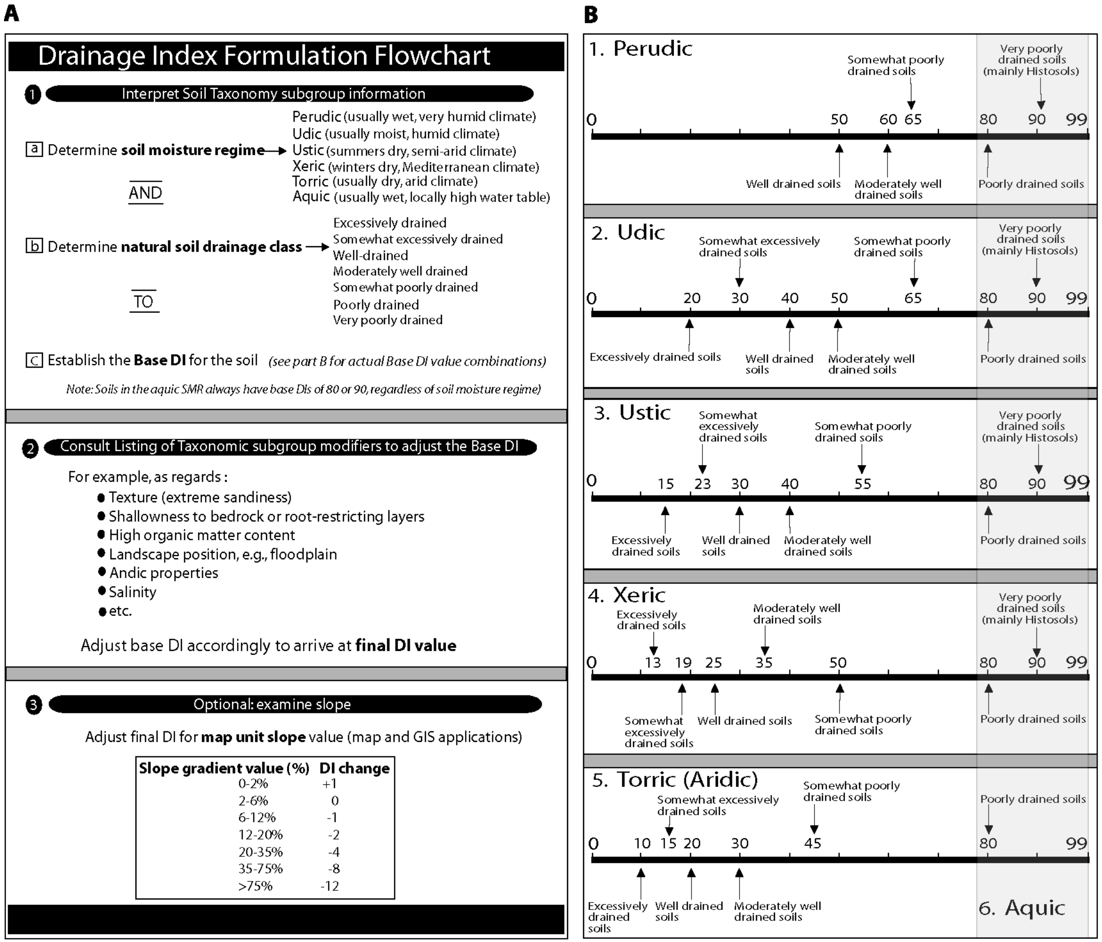

Fig. 1. Base data and formulation information for the Natural Soil Drainage Index (DI). A. Flow chart showing the basic steps associated with the formulation of the DI, and the main variables that enter into that formulation. B. Graphic representation of the base DI values for soils of different drainage classes in the six major soil moisture regimes. For the base values for soils in intergrade soil moisture regimes, e.g., udic-ustic, see Table 1.

METHODS

Formulation of the Drainage Index

The DI is largely based on the United States system of Soil Taxonomy (Soil Survey Staff, 1999). It can be determined by knowing the soil's taxonomic Great Group (e.g., Hapludalf, Torripsamment, or Dystrudept) or, preferably, subgroup (e.g., Typic Hapludalf, Vitrandic Torripsamment, or Lithic Dystrudept). Adjusting/refining the DI by incorporating data on slope gradient class (e.g., 0–2% slopes or 12–18% slopes) is optional, and often useful.

Local-scale and within-region comparisons of soil wetness do not need to take macroclimate into account, as it is usually assumed to be regionally uniform. In this case, soil wetness varies mainly as a function of water table depth, i.e., natural soil drainage class. However, it is important to realize that, across larger study areas, soil wetness is not only a function of water table location, but also of macroclimate, which is best expressed by the soil moisture regime (ibid.). For example, a well-drained soil in a udic soil moisture regime has more water, i.e., is generally wetter, than a well-drained soil in an ustic soil moisture regime. Thus, soil moisture regime is an important "axis" of base value DI variation, because the DI is designed to be useful in inter-regional studies and models.

Working on these assumptions, the DI formulation begins by assigning place-holder numbers, hereafter termed "base DI" values, to each of the seven major soil drainage classes, in each of the six soil moisture regimes (Table 1; Fig. 1). As in its prototype formulation (Schaetzl, 1986), the core placeholders of the DI scheme are udic, well-drained soils, with a DI = 40. DI base values range from wet, very poorly drained Histosols (90) to the theoretically driest soils—excessively drained soils in a torric soil moisture regime (10). As another example, a somewhat poorly drained soil in a udic soil moisture regime has a base DI value of 65, whereas ustic equivalents are assigned a base DI of 55. Assignment of these base DI values derives not only from some of the initial forays into this work by Hole (1978; Hole and Campbell, 1985) and Schaetzl (1986), but also from our understanding of soil wetness and classification.

From the base DI values (Table 1, Fig, 1B), which are unique to each soil drainage class in each soil moisture regime, the DI values of soils in the ~2450 taxonomic subgroups are subsequently derived (Fig. 1A). To do this, the taxonomic classification of the soil is examined to determine if any formative modifiers included in it indicate additional wetness or dryness, e.g., horizons that might restrict the rooting zone, textures, or organic matter contents that could affect the soil's water-holding capacity, or landform locations that might imply occasional flooding (Table 2). Numeric values are assigned to these various taxonomic modifiers, based on our knowledge of their effect on long-term soil wetness, with the focus being on relative, rather than absolute, values. By way of example, Fluvents are 2 points wetter than are Orthents (the modifier "Fluv" merits a +2; Table 2), based on the assumption that Fluvents are on floodplains and are thus prone to occasional periods of extreme wetness that Orthents might not normally experi-

Table 1. Examples of Variation in DI Values by Natural Soil Drainage Class and Soil Moisture Regime

Natural soil drainage class	Soil moisture regime (regional)	Base DI	Actual subgroup DI[a]	Representative subgroup
Very poorly drained	Aquic	90	90	Typic Sulfisaprists
Poorly drained	Aquic	80	80	Typic Alaquods
			84	Andic Endoaquods
Somewhat poorly drained	Udic	65	65	Aeric Acraquox
			69	Vitrandic Cryofluvents
	Ustic	55	53	Ustic Epiaquerts
			56	Aquic Calciustepts
	Torric	45	45	Ustic Aquicambids
			47	Fluventic Aquicambids
	Xeric	50	53	Aquic Haploxeralfs
			57	Aquandic Haploxeralfs
Moderately well-drained	Perudic	60	60	Aquic Eutroperox
	Udic	50	50	Aquertic Eutrudepts
			42	Aquic Lithic Acrudox
	Ustic	40	40	Oxyaquic Haplustepts
			36	Aquic Petroferric Haplustox
	Torric	30	30	Oxyaquic Torriorthents
			34	Aquic Gypsiargids
	Xeric	35	35	Oxyaquic Xerorthents
			42	Aquultic Argixerolls
Well-drained	Perudic	50	50	Typic Haploperox
	Udic	40	40	Typic Alorthods
			50	Lamellic Paleudalfs
	Ustic-Udic intergrade	37	37	Ustic Dystrocryepts
	Udic-Ustic intergrade	33	33	Udic Haplustepts
	Ustic	30	30	Xanthic Eutrustox
			37	Alfic Argiustolls
	Torric-Ustic intergrade	27	27	Torrertic Haplustepts
	Ustic-Torric intergrade	23	23	Ustertic Haplocambids
	Torric	20	20	Typic Anthracambids
			12	Petrogypsic Haplosalids
	Xeric-Torric intergrade	22	22	Xerertic Haplocambids
	Torric-Xeric intergrade	23	23	Aridic Haploxererts
	Xeric	25	25	Typic Haploxerepts
			19	Durinodic Xeropsamments
	Udic-Xeric Intergrade	30	30	Udic Haploxererts
	Xeric-Udic intergrade	35	35	Xeric Eutrocryepts
Somewhat excessively drained	Udic	30	29	Psammentic Paleudults
	Ustic-Ustic intergrade	28	20	Ustic Quartzipsamments
	Udic-Ustic intergrade	25	29	Udic Argiustolls

Table continues

Table 1. *continued*

Natural soil drainage class	Soil moisture regime (regional)	Base DI	Actual subgroup DI[a]	Representative subgroup
	Ustic	23	22	Lamellic Ustipsamments
	Torric-Ustic intergrade	20	22	Aridic Calciustolls
	Ustic-Torric intergrade	17	12	Lithic Ustic Haplargids
	Torric	15	1	Lithic Torripsamments
	Xeric-Torric intergrade	17	11	Xeric Torripsamments
	Torric-Xeric intergrade	17	12	Torripsammentic Haploxerolls
	Xeric	19	16	Psammentic Haploxerults
Excessively drained	Udic	20	14	Typic Udipsamments
	Ustic-Udic intergrade	19	11	Ustic Quartzipsamments
	Udic-Ustic intergrade	17	17	Udic Haplustepts
	Ustic	15	14	Psammentic Paleustalfs
	Torric-Ustic intergrade	14	14	Aridic Ustipsamments
	Ustic-Torric intergrade	12	13	Ustic Haplocalcids
	Torric	10	4	Typic Torripsamments
	Xeric	13	10	Argic Xeropsamments

[a]Actual DI of the soils listed may vary from the base value, due to modifiers within the subgroup that indicate wetness or dryness beyond that of the base DI (see Table 2).

ence. The Great Group modifier "Petr," which indicates a cemented B horizon, merits a –3 DI change, because soils with a cemented B horizon have less rooting volume than do soils whose B horizons are not cemented. Although some may quibble with the actual values that we have assigned to the DI modifiers (Table 2), we argue that (1) the direction of DI change (addition vs subtraction from the base DI) is accurate, and (2) subtle changes to the DI modifiers would not markedly increase the overall utility of the DI scheme.

Qualifiers and Unique Situations

Soils in some taxonomic subgroups span more than one drainage class. In order to address this taxonomic inconsistency, we downloaded all the known subgroups and soil series from the NRCS National Soils database in Lincoln, Nebraska and matched them via a query operation, enabling us to determine which subgroups currently contain soil series with multiple drainage classes. We then calculated a DI for each drainage class combination for the subgroups indicated. Using the MUKEY variable in the soils database, which is unique down to the soil series level, we were then able to assign a DI to each taxonomic subgroup, even in those cases where the subgroup spanned more than one drainage class. Likewise, in cases where some soil map units are complexes of more than one taxonomic subgroup or soil series, the DI derives from the *dominant* soil in the map unit. Users could determine the DI for all soils in the map unit complex and develop a weighted median DI value for these situations.

Table 2. Examples of Taxonomic Formative Elements that Change the Base DI[a]

Modifier	DI change	Rationale
		Order
Andisols	+4	Andic soil materials have high water retention properties
Alfisols, Ultisols	+3	Argillic horizon enhances water retention
Mollisols	+1	Large amounts of organic matter enhances water retention
Gelisols	−5	Frozen for much of the year, making soil water less accessible
		Suborder
Fluv	+2	Floodplain soils may have more incidents of extreme wetness/ponding
Fol	−2	Thin to bedrock, Folists do not retain large amounts of water
Sal	−3	Salty soil water is not always readily available to plants
Psamm	−6	Sandiness causes soils to drain freely and dry quickly
		Great Group
Fluv	+2	Floodplain soils may have more incidents of extreme wetness/ponding
Calci, Calc	+1	Calcic horizon facilitates water retention
Natr, Na	−2	Sodium negatively influences soil water uptake by its influence on structure and water chemistry
Plinth	−2	Plinthite reduces rooting volume
Quartz	−2	Typically sandy, with little opportunity to retain water or neoform clay minerals, which retain water
Petr	−3	Indurated horizon reduces rooting volume
Sal	−3	Salty soil water is not always readily available to plants
Anhy	−5	Anhydrous conditions typical of similar to cold, dry soils
		Subgroup
Lamellic	+5	Lamellae enhance water holding capacity of otherwise xeric, sandy soils
Cumulic	+2	Overthickened A horizon facilitates water retention
Kandiudalfic, Kandiustalfic	+1	Bt horizon enhances water retention, but low activity clays limit this effect
Fragic, Fragiaquic	−1	Fragipan reduces deep percolation and commonly perches water
Duric, Duridic	−2	Duripan (or ortstein) reduces rooting volume
Arenic	−4	Sandiness reduces water retention capacity and facilitates surface dryness
Grossarenic	−6	Thick, sandy surface horizons reduces water retention capacity and facilitates surface dryness
Lithic	−8	Shallow bedrock contact greatly reduces rooting volume

[a]Modifiers that merit no DI change are not included here. For a complete listing of all DI modifiers, please go to http://www.drainageindex.msu.edu

In order to calculate the DI for a soil map unit, as in a GIS application, slope gradient information can also be added to the DI formulation. In most NRCS soil attribute tables (in a GIS), typical slope gradient data are provided for each map unit in whole percentage values, e.g., 6% slopes. Because we do not have detailed data on the effects of slope on soil wetness (that can be applied in a "universal" context), we chose to place all slope class values into one of seven groups, assuming that soils on progressively steeper slopes are incrementally drier on a long-term basis (Zaslavsky and Sinai, 1981). Soils on steeper slopes, therefore, acquire a more negative DI modifier (Fig. 1A).

In actuality, although two taxonomic subgroups (out of ~2450) have DI values that are negative, none are larger than 99. For some soils with DI values that are positive but near zero, inclusion of the slope modifier to the DI formulation will also drive their final DI values into negative numbers. We do not view this as a problem; in most applications these slightly negative DI values can be rounded up to zero. Details of the various DI calculations, such as the specific DI values for the >2000 existing soil suborders, other non-soil units (e.g., dumps, pits, open water, mine spoils areas) cannot be presented here but are available on the DI website (http://www.drainageindex.msu.edu/), which is updated regularly.

Applications

In order to examine the applicability and utility of the DI in soil landscapes, we first applied it to county-level, NRCS soil survey data (SSURGO format), downloaded from the NRCS's Soil Data Mart (http://soildatamart.nrcs.usda.gov/). In a GIS, these data were then joined, using the MUKEY variable in the attribute table, to our internal table of DI values that also included data on map unit slope. This "join table" can also be downloaded from the DI website. After this join operation, DI values for the soil map units in each county are accessible in the attribute table. We then developed a spectral color scheme to represent soil wetness in GIS applications, ranging from light orange (the driest soils) through yellow, green, blue, and finally purple (the wettest soils) (Fig. 2).

RESULTS AND DISCUSSION

Soil Wetness across Landscapes

DI values were joined to NRCS SSURGO (county-level soils) data within a GIS in order to develop landscape maps of soil wetness. These types of applications may have great utility in land use and modeling applications. Draping the DI over a hillshaded DEM, as shown in some of the following figures and discussed below, provides an excellent graphical display and portrayal of soil wetness across the landscape, for both research and educational purposes.

Dodge County, Wisconsin contains a large, well-known drumlin field (Borowiecki and Erickson, 1985; Colgan and Mickelson, 1997) (Fig. 3). The area shown in Figure 3, in southwestern Dodge County, illustrates the variation in DI value/color across the short catenas that comprise this drumlinized landscape. From the drumlin crests

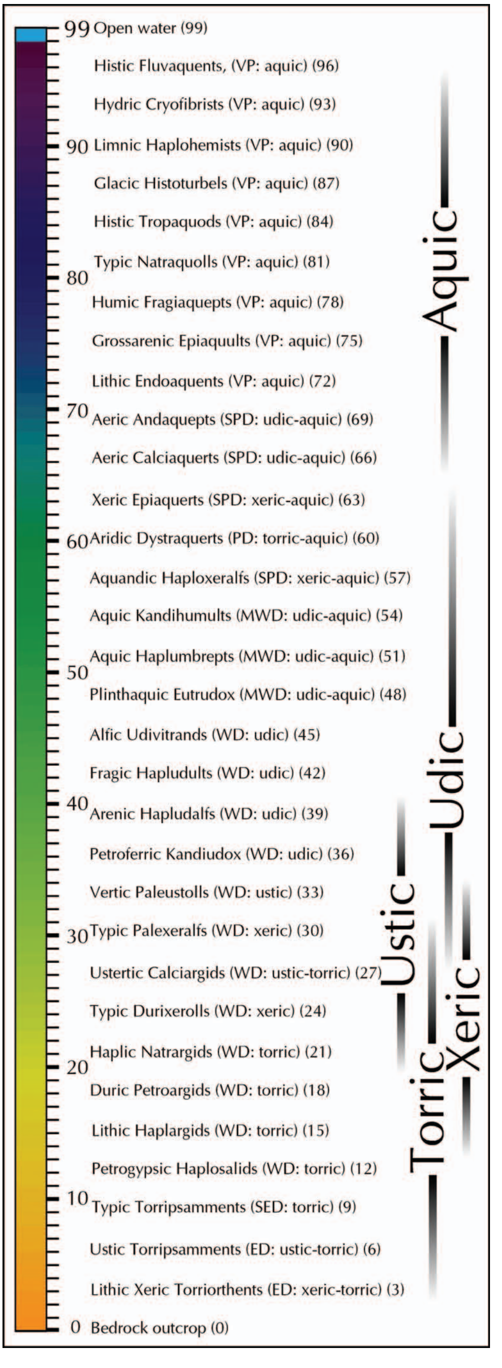

Fig. 2. Examples of DI values for some representative soil subgroups in various soil moisture regimes, assuming a 0% slope gradient. Our suggested color ramp (style file) for GIS applications is also shown.

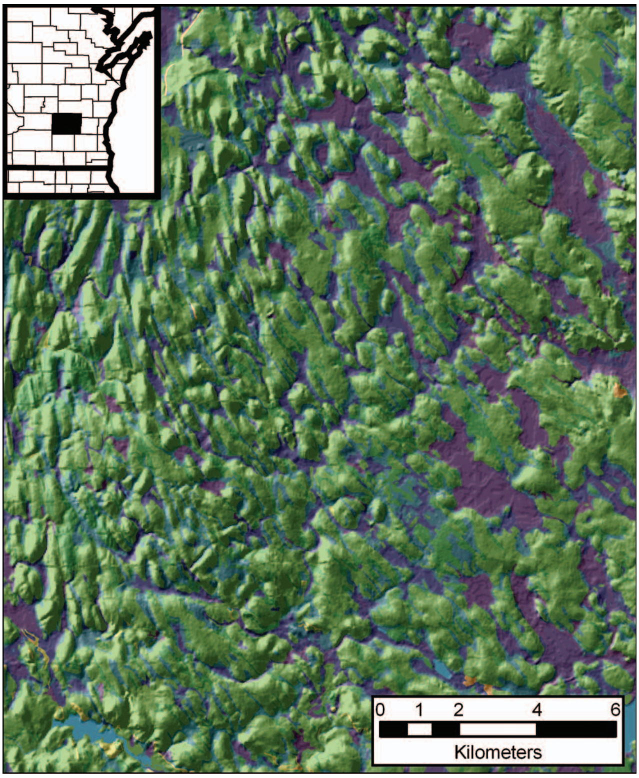

Fig. 3. Drainage Index map of a part of Dodge and Washington counties, Wisconsin. This example shows how the DI values reflect soil wetness in an area of rolling drumlinized topography, in a udic soil moisture regime. Upland soils here (green hues) have DIs that generally range from 38 to 44, whereas lowland areas have DIs of ~80 to 92. In this and subsequent figures, areas mapped as open water have been colored medium blue and the DI values for the soil map units have been made 30% transparent and then draped over a hillshaded digital elevation model, to illustrate the close correspondence between DI and topography.

to the interdrumlin lows, the soils are typically in the St. Charles (Typic Hapludalfs; DI = 43), Miami (Oxyaquic Hapludalfs; DI = 53), and Elburn (Aquic Argiudolls; DI = 69) series (Fox and Lee, 1980). Long, narrow drumlins (Fig. 4) capped with well-drained soils (greens) and inter-drumlin swales with poorly drained soils (blues) are clearly apparent. Pella soils (Typic Endoaquolls; DI = 81) have formed in the wettest sites (dark blue), in poorly drained alluvial sediments. A broad, lowland area of Histosols (DI = 91) is also shown in purple. The DI map captures the topography and its effect on soil wetness exceptionally well in this young, udic-aquic (humid-climate) landscape.

Knox and Whitley counties, Kentucky epitomize the deeply dissected, bedrock-controlled Cumberland Plateau of southeastern Kentucky (Love, 1988) (Fig. 5). Upland soils here have formed mainly in residuum from shale, siltstone, and sandstone bedrock (Fig. 6). Colluvial sediments occur at the bases of the steep slopes,

Fig. 4. The St. Charles–Miami–Elburn soil landscape shown in Figure 3 is illustrated here. Note the roadcut through a large drumlin. Photo by R. J. Schaetzl.

and alluvial deposits are found in valley bottoms. Latham soils (Aquic Hapludalfs; DI = 45), formed largely in shale residuum, occupy the ridgetops. Shelocta soils (Typic Hapludults) on sideslopes are drier (DI = 35), due mainly to their locations on steep slopes. Various soils are found in the valley bottoms, depending on local conditions (Stendal: Fluventic Endoaquepts; DI = 68 or Bonnie: Typic Fluvaquents; DI = 93). DI data from the central parts of these counties illustrate how the index is capable of mimicking the topography and its wetness, and how steep slopes act to lower the DI of soils that otherwise have similar taxonomic classifications.

Hildago County, in extreme southwestern New Mexico, is in the torric soil moisture regime of the Basin and Range geomorphic province (Cox, 1973; Fig. 7). Isolated mountain ranges, composed largely of acidic igneous rock, stand >500 m above broad alluvial basins that comprise almost two-thirds of the county. Large areas described as "rough broken land" and "rock land" in the Soil Survey—the core of the various mountain ranges (DI = 0)—are indicated in orange. Backslopes of the mountains are dull yellow in hue, and mapped as Lithic Haplargids (DI = 13). Farther down, into the basins, DI values increase and map units have yellow and green hues. Here, soils formed in alluvium dominate the landscape—e.g., Typic Haplargids and Natrargids (DI = 22), Ustollic Haplargids (DI = 27), and Typic Haplocalcids (DI = 21). The graphic representation of the soils in Hildago County demonstrates the utility of the DI in even the driest of landscapes, as well as its excellent inter-regional comparisons of soil wetness (cf. Figs. 5 and 7).

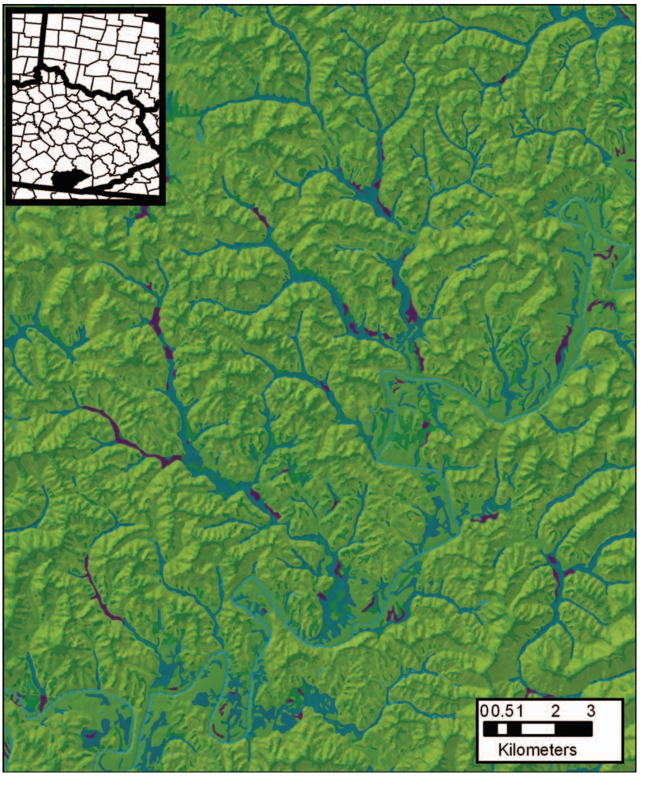

Fig. 5. Drainage Index map of a part of Knox and Whitley counties, Kentucky. The dendritic stream dissection and bedrock control typical of the Cumberland Plateau is clearly evident. Well-drained Ultisols and Inceptisols dominate the uplands and side slopes (DIs 35–45), whereas Aquents (DI = 68) are common in stream bottoms.

Forest Ecology Applications

Soils supply nutrients and water to ecosystems, and in conjunction with climate and disturbance are often the controlling factor in determining the basic distribution of forest species across the landscape (Curtis, 1959; Burns and Honkala, 1990a, 1990b; Gessel and Harrison, 1999). Establishing rigorous relationships among environmental factors (such as soil characteristics) and forest species distributions is often a complex task, because many soil attributes are not readily quantifiable, or the data do not exist at appropriate scales or over the required spatial extent. As a result, assessment of forest site potential for development and management is often difficult, especially when attempting to separate true site capability from past forest disturbance and management practices (Burger and Kotar, 2003; Pilon, 2006). When used in conjunction with a detailed soil map, the DI provides a unique opportunity to incorporate spatial data on long-term soil wetness into forest ecology and management applications. We provide two examples below.

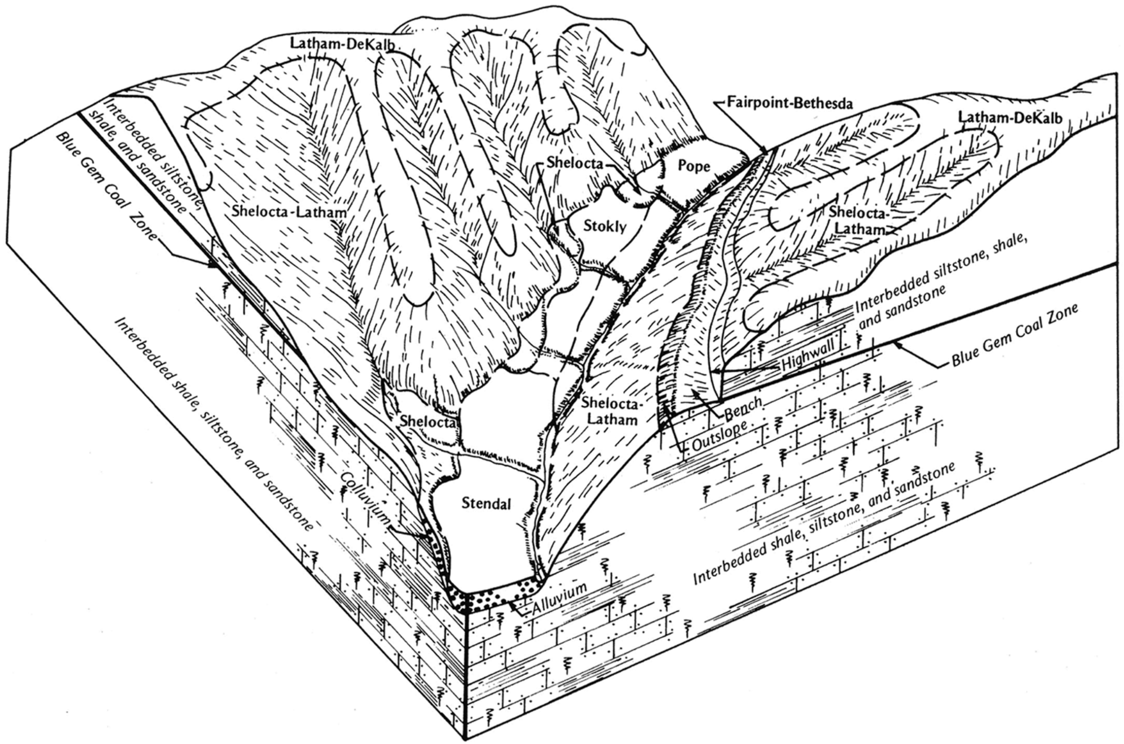

Fig. 6. Block diagram showing the typical pattern of soils and parent materials in the Shelocta–Latham–DeKalb soil association of southeastern Kentucky, a fluvially dissected plateau. Shelocta: fine-loamy, mixed, active, mesic Typic Hapludults (DI = 43). Latham: fine, mixed, semiactive, mesic Aquic Hapludults (DI = 53). DeKalb: loamy-skeletal, siliceous, active, mesic Typic Dystrudepts (DI = 40). Fairpoint: loamy-skeletal, mixed, active, nonacid, mesic Typic Udorthents (DI = 40). Bethesda: loamy-skeletal, mixed, active, acid, mesic Typic Udorthents (DI = 40). Pope: coarse-loamy, mixed, active, mesic Fluventic Dystrudepts (DI = 42). Stokly: coarse-loamy, mixed, semiactive, acid, mesic Aeric Fluvaquents (DI = 67). Stendal: fine-silty, mixed, active, acid, mesic Fluventic Endoaquepts (DI = 82). From Love (1988).

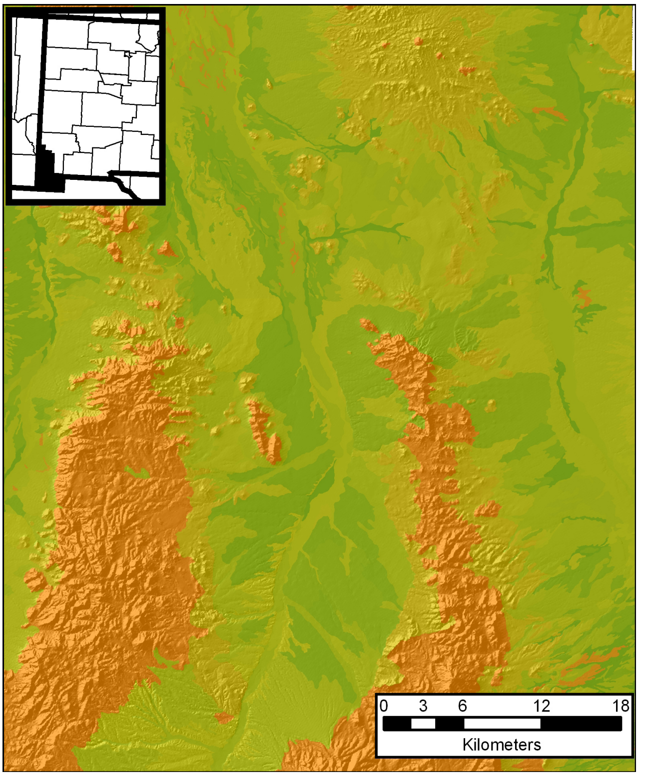

Fig. 7. Drainage Index map of a part of Hildago County, New Mexico, which has a torric soil moisture regime. This landscape, in the dry Basin and Range physiographic province, is dominated by rugged mountains and alluvial basins. Mountainous uplands have mainly "rough and broken land" (DI = 0), pediment backslopes have Haplargids (DIs = 13–28), and playa bottoms have Haplargids and Haplocambids (DIs = 20–28).

In order to demonstrate the relationships among soil wetness (DI values) and patterns in tree species frequency and site potential, we overlayed two sets of forest data within a GIS onto data layers of DI values, derived from county-level NRCS soil maps. The two forest data sets were derived from: (1) the U.S. General Land Office's original Public Land Survey (PLS) bearing and line tree data, covering over 15,000 km^2 of the west-central Lower Peninsula of Michigan; and (2) an array of National Forest Inventory and Analysis (FIA) subplots.

The first forest data set consists of bearing- and line-tree data from the General Land Office's (GLO) original PLS, conducted in Michigan between 1816 and 1856, prior to the onset of Euro-American settlement (Comer et al., 1995). As part of the PLS, surveyors divided the landscape into townships measuring 9.7 × 9.7 km (6 mi × 6 mi); each township was further divided into 36 sections, measuring 2.59 km^2 (1 mi^2). At each section corner, surveyors recorded data for two to four "bearing trees," usually one tree in each quadrant from the section corner—the species, its diameter at breast height (DBH), and the bearing (direction) and distance of each bearing tree in relation to the section corners. Bearing trees were selected based on: (1) distance from the corner survey posts; (2) species size, age, and longevity,; and (3) their conspicuousness in the stand. The surveyors also commonly recorded the location, species, and DBH of trees that were encountered along the survey lines and along the halfway point of the 1.6 km section lines; these were referred to as "line trees" (Bourdo, 1956).

GLO notes are available today for several states, many in digital form. They have been used in a wide array of ecological analysis (e.g., Hushen et al., 1966; Mladenoff and Howell, 1980; Barnes, 1989; Barrett et al., 1995; Dodge, 1997; Brown, 1998; Wang and Larsen, 2005). Although PLS tree data were collected for legal—not ecological—purposes, and some degree of bias is inherent in them (Bourdo, 1956), the data do provide an excellent record of forest communities before the onset of Euro-American settlement (hereafter, presettlement) and are extremely valuable for a wide range of applications. The PLS bearing-and line-tree data used here were collected from a compilation of the original notes generated by the Michigan Natural Features Inventory (MNFI). MNFI compiled the original PLS data onto 7.5-minute U.S. Geological Survey maps, and interpreted the tree data to produce a map of Michigan's native vegetation (Comer et. al., 1995). Our data, collected directly from these maps, were entered into a GIS database (Hupy, 2006). The bearing- and line-tree locations were then intersected in a GIS with the DI values, which were, as with the FIA data, grouped into seven ecosystem, dry-to-mesic classes. The relative frequency values of eight tree species, representing a wide range of habitat types, were then tallied for each class.

The USDA Forest Service's FIA Program conducts annual inventories of forested lands for all ownerships in each state across the United States (Bechtold and Patterson, 2005; U.S. Forest Service, 2007). Over the past 70 years, the FIA program has provided the only scientifically credible data on the distribution of forest resources in the U.S. (Van Deusen et al., 1999). FIA plot data are used by a wide range of agencies for regional and subregional assessments in support of ecologic and economic decision making. This dataset provides, therefore, a nationally consistent measurement of individual trees for determining various forest parameters within each plot, each representing about 2400 ha (Bechtold and Patterson, 2005). Because FIA data are collected as part of an annual inventory, with availability varying across states, we selected cycles that intersected a common year (2002). From these cycles, all live trees $\geq$ 2.5 cm diameter were isolated, and then, from this sample, subplots with sugar maple (*Acer saccharum* Marsh.) and longleaf pine (*Pinus palustris* Mill.) were selected. We chose these two trees because they are widespread and because their ecology is well understood, but different. Sugar maple is a well-known mesic forest dominant, whereas longleaf pine is common on xeric, fire-prone sites in the southern United States. FIA plots that lacked sugar maple or longleaf pine trees were not sampled.

The frequencies of sugar maple and longleaf pine on soils of a given DI class, across the entire range of each of these tree species, were determined by overlaying the FIA subplots with a DI layer derived from county-level NRCS soil maps. Prior to conducting this overlay, we grouped the DI values into seven commonly used ecosystem, dry-to-mesic classes (Burger and Kotar, 2003), based on field knowledge of the various types of soil-vegetation assemblages in the Midwest, and guided by Curtis (1959). Sugar maple and longleaf pine subplots that intersected with each of these seven DI classes were tallied from the results of the GIS overlay. Because there are not an equal number of FIA plots in each DI class, we calculated the relative percentage of each species by dividing the number of sugar maple and longleaf pine plots residing on every DI class by the total number of forested plots, and multiplying by 100, to arrive a relative frequencies for each of these two species, for each DI value.

Relative frequencies of the PLS tree species data, grouped into the seven DI ecosystem classes, compliment and support existing knowledge of presettlement tree species distributions and ecology in central Lower Michigan (Whitney, 1986; Comer et al., 1995; Cohen, 1996, 2000, 2002a, 2002b, 2002c; Barnes and Wagner, 2008) (Fig. 8). Jack pine (*Pinus banksiana* Lamb.), red pine (*Pinus resinosa* Aiton), white pine (*Pinus strobus* L.), and white oak (*Quercus alba* L.) are all abundant on very dry to dry sites. These species are all dominants in the most xeric forest communities, oak and pine barrens, in the Lower Peninsula of Michigan (Comer et al., 1995; Cohen, 1996, 2000; Burger and Kotar, 2003; Barnes and Wagner, 2008). Jack and white pine have the highest frequencies on very dry (DI = 0–14) and dry (DI = 15–21) sites. Red pine has the highest frequencies on dry and dry-mesic (DI = 22–33) sites (Fig. 8). The narrow niche breadth of jack pine is readily apparent, as it exhibits a high frequency (>10%) on only one ecosystem class; the relatively wider niche breadth of white pine, and its unique ability to compete well on both wet and dry sites, is also evident (Fig. 8). These frequency patterns illustrate the ability of the DI (and the GLO data) to resolve fine differences between sites where white pine is able to out-compete jack pine, i.e. the difference between very dry and dry sites. White oak is common on very dry to dry sites, where it is a canopy co-dominant species in upland oak-hickory forests on well drained sandy loam to clay loam soils in southern Lower Michigan (Barnes and Wagner, 2008), as well as in pine-oak forests and oak and pine barrens on dry sandy soils in northern Lower Michigan (Cohen, 1996, 2000). White oak also exhibits high relative frequency values on mesic (DI = 34–56) sites, where it is a subdominant species in the beech–sugar maple forests (Barnes and Wagner, 2008). In the dry-mesic to mesic classes, higher frequencies of sugar maple, hemlock (*Tsuga canadensis* L.), and to a lesser extent basswood (*Tilia americana* L.) occur, corresponding closely with Cohen's (2002a, 2002b, 2002c) descriptions of forest dominants on dry-mesic and mesic sites in northern Lower Michigan. The ability of sugar maple to compete on sites with a wide variety of soil moisture regimes in central Lower Michigan is also clearly evident in Figure 8. The DI is also effective at classifying very wet sites, where species such as Tamarack (*Larix laricina* [Du Roi] K. Koch), a wetland species, have the highest frequency (Fig. 8). Overall, the results from the DI ecosystem class analysis reinforce the ecological descriptions and successional pathways that Burger and Kotar (2003) identified as having a significant impact on forest and wildlife management in the state of Michigan (Pilon, 2006).

The results from the analysis of the FIA data are equally impressive. They show that longleaf pine, once found across a wide range of wet and dry ecosystems (Boyer, 1990; Landers et al., 1995) is currently limited to dry sandy sites which are

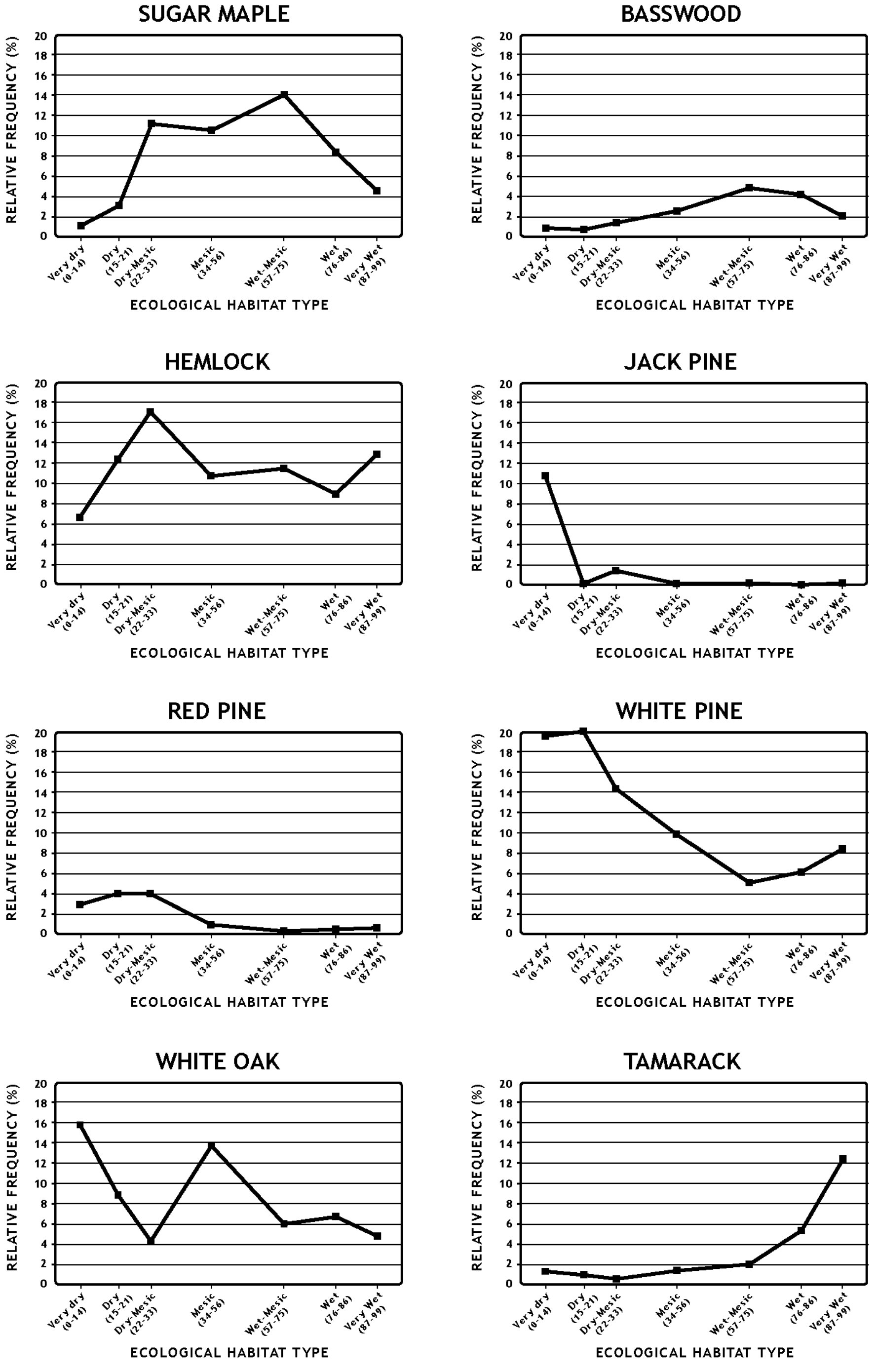

Fig. 8. Relative frequencies of eight major forest trees, across seven ecosystem, dry-to-mesic DI classes, in the presettlement forests of west-central Lower Michigan. Tree locational data were compiled from 19th century Land Surveyors' notes and overlain onto soils maps (coded by DI) in a GIS.

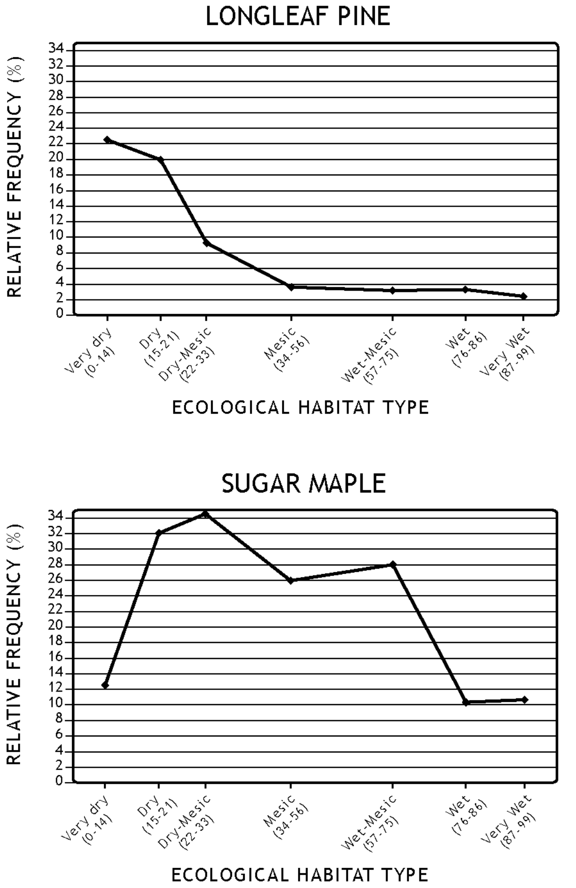

Fig. 9. Relative frequencies of sugar maple and longleaf pine, across seven ecosystem, dry-to-mesic DI classes, within their native ranges of the eastern United States, based on U.S. Forest Service FIA plot data.

suitable neither for farming nor for other pine species, e.g., Loblolly (*Pinus taeda* L.) and slash (*Pinus elliottii* Englem.) (Fig. 9). This pattern, i.e., longleaf pine's distribution across the soil landscape, is clearly captured in the FIA–DI overlay data (Fig. 9). The distribution of longleaf pine across the DI axis is related not only to soil wetness but also to fire ecology; fire suppression has been easiest on wetter sites, which adds to the factors that tend not to favor longleaf pine on such sites. Therefore, likelihood of fire (and even flood) disturbance may be an additional, ecological application of the DI.

Results from the sugar maple FIA data set are also insightful. Although sugar maple grows on a wide range of soil types (Godman et al., 1990), it dominates on rich, mesic sites, as in Lower Michigan (Fig. 8). The FIA–DI data also confirm that sugar maple is rarely found on very dry or wet sites across its range, and graphically show the breadth of its "soil wetness niche" on the landscape.

Limitations of the DI

We are compelled to discuss a few of the limitations of the DI. Base DI values are not derived from actual, long-term soil water contents from suites of soils with these taxonomic characteristics, as these data do not exist. One-time measurement data on the water content of a pedon would be of little or no value in a potential validation exercise or sensitivity analysis, because the DI is an estimate of long-term water content. DI base values are inferred from our knowledge of soil climate and are, we suggest, correct in a *relative sense*, as the drainage classes and soil moisture regimes are arranged along the 0-99 scale (Fig. 1). Complete *validation* of the long-term soil wetness values for all the ~2450 combinations of soils in each of the major drainage classes and soil moisture regimes would take decades, and may not even provide a great deal of additional insight or detail, depending on the climate during the period of study. In short, validation of the DI values for even a few taxonomic classes would not only be cost- and time-prohibitive; it is not really possible. Because the DI is an *ordinal* index, we view our approach, in which the *relative/ranked values* of soil wetness are the focus, as appropriate, informed, acceptable, well-reasoned, and useful.

Because the DI is an ordinal measure of soil wetness, DI values cannot be compared as they might have been with an interval-scale index. For example, a soil with a DI of 50 cannot be assumed to be twice as wet as a soil with a DI of 25. It also should be clear that, like any model based on soil maps, the DI data are only as good as the soil map, and may change quality as map scale and mapping intensity change.

CONCLUSIONS

The Natural Soil Drainage Index (DI), presented in this paper, is formulated to reflect the long-term amount of water that a soil can supply to growing plants under natural conditions. The DI formulation uses existing soil maps as ground truth and returns a number, from 0 to 99, that represents the long-term wetness of the soils in that taxonomic (or map) unit. It is readily calculated, and easily manipulated within a GIS. Maps of index values correlate well with landforms and overall landscape wetness, and ecological applications indicate that it can provide insight into the ecological niches and distributions of trees across the soil wetness continuum. The DI has, therefore, great potential utility across many disciplines, especially as a GIS layer in landscape-scale modeling applications.

In this paper we also present three examples of DI applications within forestry; we can envision many more. We hope that further analysis into the relative frequencies of tree species and the DI will yield additional insight into not only tree species distributions but forest community ecology. The DI may also prove useful in examining the relationships between tree species abundance and various environmental variables. Recent research has shown the importance of moisture, particularly in the form of lake effect snowfall, on the distribution of mesic forest types in northern Lower Michigan (Henne et al., 2007). The utility of the DI in assessing forest health (Krist et al., 2007) is demonstrated through the applications presented here, and there is clear potential for identifying relationships between DI and fire disturbance, much like what has been done with forest habitat types (Pilon, 2006).

Acknowledgments: We thank the U.S. Forest Service for funding, Elizabeth LaPoint for providing FIA plot data, and Jim Ellenwood for helping prepare and analyze data. Dorn Egley and many others at NRCS helped provide us direct access to the Soil Data Mart and other NRCS databases. Jim Steinman provided logistical support. Comments by anonymous reviewers, as well as participants at the 11th North American Forest Soils Conference in Blacksburg, VA, improved the paper. Francis Hole was the inspiration for the DI; we dedicate this paper to his memory.

REFERENCES

Barling, R. D., Moore, I. D., and Grayson, R. G. (1994) A quasi-dynamic wetness index for characterizing the spatial distribution of zones of saturation and soil water content. *Water Resources Research,* Vol. 30, 1029–1044.

Barnes, B. D. and Wagner, W. H. (2008) *Michigan Trees: A Guide to the Trees of the Great Lakes Region*. Ann Arbor, MI: University of Michigan Press.

Barnes, W. J. (1989) A case history of vegetation changes on the Meridean Islands of west-central Wisconsin, USA. *Biological Conservation,* Vol. 49, 1–16.

Barrett, L. R., Liebens, J., Brown, D. G., Schaetzl, R. J., Zuwerink, P., Cate, T. W., and Nolan, D. S. (1995) Relationships between soils and presettlement vegetation in Baraga County, Michigan. *American Midlands Naturalist*, Vol. 134, 264–285.

Bechtold, W. and Patterson, P. (2005) *The Enhanced Forest Inventory and Analysis Program—National Sampling Design and Estimation Procedures*. Asheville, NC: USDA Forest Service, Southern Research Station, General Technical Report SRS-80.

Beven, K. J. and Kirkby, M. J. (1979) A physically based, variable contributing area model of basin hydrology. *Hydrological Science Bulletin*, Vol. 24, 43–69.

Blavet, D., Mathe, E., and Leprun, J. C. (2000) Relations between soil colour and waterlogging duration in a representative hillside of the West African granito-gneissic bedrock. *Catena*, Vol. 39, 187–210.

Borowiecka, B. Z., and Erickson, R. H. (1985) Wisconsin drumlin field and its origin. *Zeitschrift fur Geomorphologie*, Vol. 29, 417–438.

Bourdo, E. A. (1956) A review of the General Land Office survey and of its use in quantitative studies of former forests. *Ecology*, Vol. 37, 754–768.

Boyer, W. D. (1990) *Pinus palustris*, Mill., longleaf pine. In R. M. Burns and B. H. Honkala, tech. coords., *Silvics of North America*. *Vol. 1, Conifers*. Washington, DC: USDA Forest Service, Agriculture Handbook 654, 405–412.

Bragg, D. C., Roberts, D. W., and Crow, T. R. (2004) A hierarchical approach for simulating northern forest dynamics. *Ecological Modelling*, Vol. 173, 31–94.

Brown, D. G. (1998) Mapping historical forest types in Baraga County Michigan, USA as fuzzy sets. *Plant Ecology*, Vol. 134, 97–111.

Burger, T. L. and Kotar, J. (2003) *A Guide to Forest Communities and Habitat Types of Michigan*. Madison, WI: University of Wisconsin Press.

Burns, R. M, and Honkala, B. H. (1990a) *Silvics of North America*. *Vol. 1, Conifers*. Washington, DC: USDA Forest Service, Agriculture Handbook 654.

Burns, R. M. and Honkala, B. H. (1990b) *Silvics of North America. Vol. 2, Hardwoods*. Washington, DC: USDA Forest Service, Agriculture Handbook 654.

Chaplot, V., Walter, C., and Curmi, P. (2000) Improving soil hydromorphy prediction according to DEM resolution and available pedological data. *Geoderma*, Vol. 97, 405–422.

Cohen, J. G. (1996) *Natural Community Abstract for Pine Barrens*. Lansing, MI: Michigan Natural Features Inventory.

Cohen, J. G. (2000) *Natural Community Abstract for Oak-Pine Barrens*. Lansing, MI: Michigan Natural Features Inventory.

Cohen, J. G. (2002a) *Natural Community Abstract for Dry Northern Forest*. Lansing, MI: Michigan Natural Features Inventory.

Cohen, J. G. (2002b) *Natural Community Abstract for Dry-Mesic Northern Forest*. Lansing, MI: Michigan Natural Features Inventory.

Cohen, J. G. (2002c) *Natural Community Abstract for Mesic Northern Forest*. Lansing, MI: Michigan Natural Features Inventory.

Colgan, P. M. and Mickelson, D. M. (1997). Genesis of streamlined landforms and flow history of the Green Bay lobe, Wisconsin, USA. *Sedimentary Geology*, Vol. 111, 14–25.

Comer, P. J., Albert, D. A., Wells, H. A., Hart, B. L., Raab, J. B., Price, D. L., Kashian, D. M., Corner, R. A., and Schuen, D. W. (1995) *Michigan's Presettlement Vegetation, as Interpreted from the General Land Office Surveys 1816–1856*. Lansing, MI: Michigan Natural Features Inventory.

Cox, D. N. (1973) *Soil Survey of Hildago County, New Mexico*. Washington, DC: USDA Soil Conservation Service.

Curtis, J. T. (1959) *The Vegetation of Wisconsin*. Madison, WI: University of Wisconsin Press, 657 pp.

Dahms, D. E. (2002) Glacial stratigraphy of Stough Creek Basin, Wind River Range, Wyoming. *Geomorphology*, Vol. 42, 59–83.

Davidson, E. A. (1995) Spatial covariation of soil organic carbon, clay content, and drainage class at a regional scale. *Landscape Ecology*, Vol. 10, 349–362.

Davidson, E. A. and Lefebvre, P. A. (1993) Estimating regional carbon stocks and spatially covarying edaphic factors using soil maps at three scales. *Biogeochemistry*, Vol. 22, 107–131.

Dodge, S. L. (1997) Presettlement vegetation of Michigan's thumb area. *Michigan Academician*, Vol. 29, 453–471.

Elliott, K. J. and Swank, W. T. (1994) Impacts of drought on tree mortality and growth in a mixed hardwood forest. *Journal of Vegetation Science*, Vol. 5, 229–236.

Evans, C. V. and Franzmeier, D. P. (1988) Color index values to represent wetness and aeration in some Indiana soils. *Geoderma*, Vol. 41, 353–368.

Fox, R. E. and Lee, G. B. (1980) *Soil Survey of Dodge County, Wisconsin*. Washington, DC: USDA Soil Conservation Service.

Gessel, S. P. and Harrison, R. B. (1999) The history of forest soil science and development in North America. In H. K. Steen, ed., *Forest and Wildlife Science in America: A History*. Durham, NC: Forest History Society.

Godman, R. M., Yawney, H. W., and Tubbs, D. H. (1990) *Acer saccharum*, Marsh., sugar maple. In R. M. Burns and B. H. Honkala, tech. coords., *Silvics of North*

America. *Vol. 2, Hardwoods*. Washington, DC: USDA Forest Service, Agriculture Handbook 654, 78–91.

Groffman, P. M. and Tiedje, J.M. (1989) Denitrification in north temperate forest soils—relationships between denitrification and environmental factors, at the landscape scale. *Soil Biology and Biochemistry*, Vol. 21, 621–626.

Groffman, P. M., Tiedje, J. M., Mokma, D. L., and Simkins, S. (1992) Regional scale analysis of denitrification in north temperate forest soils. *Landscape Ecology*, Vol. 7, 45–53.

Harden, J. W. (1982) A quantitative index of soil development from field descriptions: Examples from a chronosequence in central California. *Geoderma*, Vol. 28, 1–28.

Henne, P. D., Sheng Hu, F., and Cleland, D. T. (2007) Lake-effect snow as the dominant control of mesic-forest distribution in Michigan, USA. *Journal of Ecology*, Vol. 95**,** 517–529.

Hillel, D. (1998) *Environmental Soil Physics*. San Diego, CA: Academic Press, 771 pp.

Hole, F. D. (1978) An approach to landscape analysis with emphasis on soils. *Geoderma*, Vol. 21, 1–13.

Hole, F. D. and Campbell, J. B. (1985) *Soil Landscape Analysis*. Totowa, NJ: Rowman and Allanheld.

Hupy, C. M. (2006) The Dynamics of the Forest Transition Zone in Central Lower Michigan, U.S.A.: Two Millennia of Change. Ph.D. dissertation, Department of Geography, Michigan State University.

Hushen, T. W., Kapp, R. O., Bogue, R. D., and Worthington, J. T. (1966) Presettlement forest patterns in Montcalm County, Michigan. *Michigan Botanist*, Vol. 5, 192–211.

Iverson, L. R., Dale, M. E., Scott, C. T., and Prasad, A. (1997) A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests (USA). *Landscape Ecology,* Vol. 12, 331–348.

Jungkunst, H. F., Fiedler, S., and Stahr, K. (2004) N_2O emissions of a mature Norway spruce (*Picea abies*) stand in the Black Forest (southwest Germany) as differentiated by the soil pattern. *Journal of Geophysical Research: Atmospheres*, Vol. 109, Article # D07302.

Krist, F., Sapio, F., and Tkacz, B. (2007) Mapping risk from forest insects and diseases. Fort Collins, CO: USDA Forest Service–Forest Health Technology Enterprise Team, FHTET-2007 06.

Landers, J. L., Van Lear, D. H., and Boyer, W. D. (1995) The longleaf pine forests of the Southeast: Requiem or renaissance? *Journal of Forestry*, Vol. 93, 39–44.

Lookingbill, T., Goldenberg, N. E., and Williams, B. H. (2004) Understory species as soil moisture indicators in Oregon's Western Cascades old-growth forests. *Northwest Science*, Vol. 78, 214–224.

Lookingbill, T. and Urban, D. (2004) An empirical approach towards improved spatial estimates of soil moisture for vegetation analysis. *Landscape Ecology*, Vol. 19, 417–433.

Love, P. M. (1988) *Soil Survey of Knox County and Eastern Part of Whitley County, Kentucky*. Washington, DC: USDA Soil Conservation Service.

Martini, J. A. (1970). Allocation of cation exchange capacity to soil fractions in seven surface soils from Panama and the application of a cation exchange factor as a weathering index. *Soil Science*, Vol. 109, 324–331.

Mladenoff, F. A. and Howell, E. A. (1980) Vegetation changes on the Gogebic Iron Range (Iron County, Wisconsin) from the 1860s to the present. *Transactions of the Wisconsin Academy of Sciences, Arts and Letters*, Vol. 68, 74–89.

Moore, I. D., Gessler, P. E., Nielsen, G. A., and Peterson, G. A. (1993) Soil attribute prediction using terrain analysis. *Soil Science Society of America Journal*, Vol. 57, 443–452.

Moore, I. D., O'Loughlin, E. M., and Burch, G. J. (1988) A contour-based topographic model for hydrological and ecological applications. *Earth Surface Processes and Landforms*, Vol. 13, 305–320.

O'Connell, D. A., Ryan, P. J., McKenzie, N. J., and Ringrose-Voase, A. J. (2000) Quantitative site and soil descriptors to improve the utility of forest soil surveys. *Forest Ecology and Management*, Vol. 138, 107–122.

O'Loughlin, E. M. (1986) Prediction of surface saturation zones in natural catchments by topographic analysis. *Water Resources Research*, Vol. 22, 784–804.

O'Loughlin, E. M. (1990) Modelling soil water status in complex terrain. *Agricultural and Forest Meteorology*, Vol. 50, 23–38.

Ortiz, I., Simon, M., Dorronsoro, C., Martin, F., and Garcia, I. (2002) Soil evolution over the Quaternary period in a Mediterranean climate (SE Spain). *Catena*, Vol. 48, 131–148.

Pilon, J. (2006) Guidelines for red pine management based on ecosystem management principles for state forestland in Michigan. Michigan Department of Natural Resources, Northern Lower Michigan Ecoteam. Manuscript available on-line at http://www.michigan.gov/documents/Red-Pine-Lite_96501_7.pdf and at the Michigan Department of Natural Resources Gaylord Service Center, Gaylord, MI.

Post, W. M., Emanuel, W. R., Zinke, P. J., and Stangenberger, A. G. (1982) Soil carbon pools and world life zones. *Nature*, Vol. 298, 156–159.

Rawls, W. J., Brakensiek, D. L., and Saxton, K. E. (1982) Estimation of soil water properties. *Transactions of the ASAE*, Vol. 25, 1316–1320.

Ritchie, J. T. (1981) Soil water availability. *Plant and Soil*, Vol. 58, 327–338.

Ryan, P. J., McKenzie, N. J., O'Connell, D., Loughhead, A. N., Leppert, P. M., Jacquier, D., and Ashton, L. (2000) Integrating forest soils information across scales: Spatial prediction of soil properties under Australian forests. *Forest Ecology and Management*, Vol. 138, 139–157.

Schaetzl, R. J. (1986) A soilscape analysis of contrasting glacial terrains in Wisconsin. *Annals of the Association of American Geographers*, Vol. 76, 414–425.

Schaetzl, R. J. and Anderson, S. N. (2005) *Soils Genesis and Geomorphology*. Cambridge, UK: Cambridge University Press.

Schaetzl, R. J. and Mokma, D. L. (1988) A numerical index of Podzol and Podzolic soil development. *Physical Geography*, Vol. 9, 232–246.

Soil Survey Staff. (1999) *Soil Taxonomy*. Washington, DC: USDA Soil Conservation Service, Agriculture Handbook 436.

Stephenson, N. L. (1998) Actual evapotranspiration and deficit: Biologically meaningful correlates of vegetation distribution across spatial scales. *Journal of Biogeography*, Vol. 25, 855–870.

Thogmartin, W. E., Knutson, M. G., and Sauer, J. R. (2006) Predicting regional abundance of rare grassland birds with a hierarchical spatial count model. *The Condor*, Vol. 108, 25–46.

Thompson, J. A. and Bell, J. C. (1996) Color index for identifying hydric conditions for seasonally saturated Mollisols in Minnesota. *Soil Science Society of America Journal*, Vol. 60, 1979–1988.

Thompson, J. A., Bell, J. C., and Butler, C. A. (1997) Quantitative soil-landscape modeling for estimating the areal extent of hydromorphic soils. *Soil Science Society of America Journal*, Vol. 61, 971–980.

Ung, C.-H., Bernier, P. Y., Raulier, F., Fournier, R. A., Lambert, M.-C., and Régnière, J. (2001) Biophysical site indices for shade tolerant and intolerant boreal species. *Forest Science*, Vol. 47, 83–95.

U.S. Forest Service. (2007) USDA Forest Service, Forest Inventory and Analysis. Retrieved September 28, 2007 from http://fia.fs.fed.us/library/field-guides-methods-proc/

Van Deusen, P. C., Prisley, S. P., and Lucier, A. A. (1999) Adopting an annual inventory system: Uses perspectives. *Journal of Forestry*, Vol. 97, 11–14.

Vidic, N. J. (1998) Soil-age relationships and correlations: Comparison of chronosequences in the Ljubljana Basin, Slovenia and USA. *Catena*, Vol. 34, 113–129.

Wang, Y. and Larsen, C. P. (2005) Presettlement land survey records of vegetation: Geography characteristics, quality, and modes of analysis. *Progress in Physical Geography*, Vol. 29, 568–598.

White, D. P. (1958) Available water: The key to forest site evaluation. In *Proceedings of the 1st Forest Soils Conference*, East Lansing, MI, 6–11.

Whitney, G. G. (1986) Relation of Michigan's presettlement pine forests to substrate and disturbance history. *Ecology*, Vol. 67, 1548–1559.

Willgoose, G. and Perera, H. (2001) A simple model of saturation excess runoff generation based on geomorphology, steady state soil moisture. *Water Resources Research*, Vol. 37, 147–155.

Wosten, J. H. M., Bouma, J., and Stoffelsen, G. H. (1985) Use of soil survey data for regional soil water simulation models. *Soil Science Society of America Journal*, Vol. 49, 1238–1244.

Zahner, R. (1958) Site-quality relationships of pine forests in southern Arkansas and northern Louisiana. *Forest Science*, Vol. 4, 162–176.

Zaslavsky, D. and Sinai, G. (1981) Surface hydrology, I. Explanation of phenomena. *Journal of the Hydraulics Division of the American Society of Civil Engineering*, Vol. 107(HYI), 1–16.

Zheng, D. L., Hunt, E. R., and Running, S. W. (1996) Comparison of available soil water capacity estimated from topography and soil series information. *Landscape Ecology*, Vol. 11, 3–14.