Minnesota's native plant community classification: A statewide classification of terrestrial and wetland vegetation based on numerical analysis of plot data

Aaseng, Norm E.; Almendinger, John C.; Dana, Robert P.; Hanson, Dan S.; Lee, Michael D.; Rowe, Erika R.; Rusterholz, Kurt A. & Wovcha, Daniel S.

Aaseng, N.E. (Norm.Aaseng@state.mn.us), **Dana, R.P.** (Robert.Dana@state.mn.us), **Rowe, E.R.** (Erika.Rowe@state.mn.us), **Wovcha, D.S.** (Daniel.Wovcha@state.mn.us): Minnesota County Biological Survey, Minnesota Department of Natural Resources, 500 Lafayette Road, Box 25, St. Paul, MN 55155, USA.
Almendinger, J.C. (John.Almendinger@state.mn.us), **Hanson, D. S.** (Dan.Hanson@state.mn.us): Ecological Land Classification Program, Minnesota Department of Natural Resources, 413 Southeast 13th Street, Grand Rapids, MN 55744, USA.
Lee, M.D. (Michael.Lee@state.mn.us): Minnesota County Biological Survey, Minnesota Department of Natural Resources, 940 Industrial Drive, Sauk Rapids, MN 56379, USA.
Rusterholz, K.A. (Kurt.Rusterholz@state.mn.us): Natural Heritage and Nongame Research Program, 500 Lafayette Road, Box 25, St. Paul, MN 55155, USA.

Abstract
The Minnesota Department of Natural Resources completed a new classification of native plant communities for the state of Minnesota in 2003. Researchers used numerical tools, including ordination, cluster analysis, and indicator species analysis, to guide classification of 5,224 vegetation plots spanning most of the range of terrestrial and wetland vegetation in Minnesota. Analyses of plant species data were supplemented with interpretation of soils data and other site data in defining and delineating classification entities. The plant community classification was integrated with Minnesota's ecological land classification system. The resulting plant community classification is hierarchical, with six levels. Among the upper levels is the Ecological System, which groups plant communities according to influence by ecological processes such as flooding or fire. Ecological systems are well suited for biodiversity conservation and forest resource mapping and planning at the landscape scale. The Floristic Region, another important upper level, is based on geographic patterns of plant distribution that became apparent only after numerous rounds of analysis of plot data and development of lower levels of the classification. In some instances these patterns correlate strongly with paleo-vegetation patterns. The lowest levels of the classification correlate with local gradients of moisture and nutrients for terrestrial communities and with water chemistry and water-level fluctuations for wetland communities, and are being applied to site-scale conservation and management activities. The Minnesota Department of Natural Resources has developed a series of tools for use of the classification, including field guides for identification and interpretation of plant communities, and forest management tools centered around native plant community classes.

Abbreviations: MNDNR = Minnesota Department of Natural Resources; ECS = Ecological Land Classification System; USNVC = United States National Vegetation Classification.

Introduction

Vegetation scientists in the Minnesota Department of Natural Resources (MNDNR) completed a revision of the agency's statewide classification of native plant communities in 2003 based primarily on numerical analysis of vegetation plot data. The classification project, begun in 1995, covers most of the range of terrestrial and wetland vegetation in the state and is hierarchical, with six levels (Fig. 1). It replaces a dominance-type classification (Whittaker 1978) of plant communities that was based on the collective field experience of MNDNR plant ecologists and on literature review of existing vegetation studies (MNDNR 1993). This earlier "expert-based" classification was developed mainly for use in documenting the location and floristic quality of plant communities in need of conservation. The earlier classification served this purpose well, but did not meet the MNDNR's broader needs for actively managing vegetation nor did it aid in addressing the importance of landscape-scale context and ecological processes for Minnesota's biodiversity. The hierarchical structure of the new classification enables collection of information that is useful both in documenting the rarity of vegetation (through lower units of the classification) and in guiding management of extensive tracts of vegetation (through upper, broader units of the classification). While the classification itself is empirical, the number and nature of the hierarchical levels were influenced by anticipated use and by expert judgment. One of the most significant decisions affecting the ultimate structure of the classification hierarchy was the matching of classification levels to Minnesota's system of ecological land classification (ECS) units. The integration of the plant community classification with Minnesota's ECS was done to enable assessment of vegetation management issues at scales ranging from broad landscapes to single stands. One corollary benefit of developing a classification through numerical methods is that the data used in developing the classification serve as the scientific foundation for inventory, mapping, and interpretive materials.

Development of a statewide classification based on analysis of vegetation plot data was not practical in Minnesota until the mid-1990s because of the absence of a geographically and ecologically broad set of vegetation data. Collection of vegetation plot data began in Minnesota in the 1960s and continued sporadically through the 1980s. Most of this early data collection was associated with local vegetation studies done either for descriptive purposes or to provide baseline data for environmental assessments of proposed industrial projects. In the late 1980s, broad-scale, systematic collection of plot data was initiated as part of the MNDNR's newly created statewide biological survey. In addition, the development of an ecological land classification for the Chippewa National Forest in the early 1990s resulted in intensive collection of vegetation plot data in the north-central part of the state (Hanson and Hargrave 1996). Although the state's biological survey was just half completed at the start of the MNDNR's classification project, we believed that

Classification Level	Dominant Factors	Example
System Group	Vegetation structure and hydrology	*Upland Forests and Woodlands*
Ecological System	Ecological processes	*Fire-Dependent Forest/Woodland*
Floristic Region	Climate and paleohistory	*Central*
NPC Class	Local environmental conditions	*Central Dry Pine Woodland*
NPC Type	Canopy dominants, substrate, fine-scale environmental conditions	*Jack Pine - (Yarrow) Woodland*
NPC Subtype	Finer distinctions in canopy dominants, substrate, environmental conditions	*Ericaceous Shrub*

Fig. 1. The six levels of Minnesota's native plant community classification.

data collected during the survey, when combined with data from previous local vegetation studies, provided an adequately broad data set to allow a first iteration of a statewide classification based primarily on numerical analysis of vegetation plot data.

Study Area

Minnesota lies near the center of North America and covers approximately 218,500 km^2, extending a maximum of 650 km north to south between latitudes 43.5° and 49° north, and 570 kilometers east to west between longitudes 89.5° and 97° west. The present landscape exhibits strong influence from glacial processes that occurred during the late Wisconsin glaciation, about 35 to 10 ka. During this period, most of Minnesota was either covered by glacial ice at some time or was inundated or eroded by glacial meltwater. As a result, the prominent landforms in the state consist of glacial features such as terminal and ground moraines, lake and outwash plains, and eroded stream valleys. Local relief ranges from less than 10 m on lake and till plains—such as the Red River Valley in northwestern Minnesota—to greater than 100 m in morainic areas in the west-central part of the state, in bedrock-cored highlands flanking Lake Superior in the northeast, and in stream-dissected blufflands in the southeast. The highest point above sea level is 701 m, in the northeastern part of the state; the lowest point is Lake Superior, at 183 m above sea level. Minnesota is known for its numerous lakes and wetland basins, which are most common in areas shaped by ice during the last glaciation.

The climate of Minnesota is continental and influenced through the course of each year by cool, dry polar air masses; warm and often humid air from the Gulf of Mexico and the southwestern United States; and comparatively mild and dry air masses originating over the Pacific Ocean and crossing the western United States (National Climatic Data Center). Mean annual temperature ranges from 2 °C in the northern part of the state to 9 °C in the southeast; the recorded extremes are –51 °C and +46 °C. Mean annual precipitation ranges from 89 cm in the southeastern corner of the state to 48 cm in the northwest. Annual snowfall averages 178 cm along Lake Superior in the northeast and 102 cm along the western and southern borders of the state. About two-thirds of annual precipitation statewide occurs from May through September. Severe drought conditions occur about once every 10 years in the southwestern part of the state and about once in 50 years in the northeast (National Climatic Data Center).

Minnesota encompasses parts of four provinces recognized in the United States' national hierarchical framework of ecological units (McNab et al. 2007, Cleland et al. 1997; MNDNR Ecological Classification System). The *Laurentian Mixed Forest Province*, which traverses northern Minnesota, Wisconsin, and Michigan, covers a little more than 93,750 km^2 in the northeastern part of the state (Fig. 2). In Minnesota, the province is characterized by broad areas of conifer forest, mixed conifer and broad-leaved deciduous forests, and peatlands that have formed on poorly drained glacial lake plains. The *Eastern Broadleaf Forest Province* of the eastern United States covers nearly 48,000 km^2 in the central and southeastern parts of Minnesota, serving as a transition, or ecotone, between semi-arid regions to the west that were historically prairie and mixed coniferous-deciduous forests to the northeast. The predominant native vegetation in this province consists of forests and woodlands of broad-leaved deciduous trees such as oak, basswood, elm, and maple, with smaller areas of oak savanna and prairie (Marschner 1974). The *Tallgrass Aspen Parklands Province* covers a small part (about 11,750 km^2) of the state north of the tip of the Eastern Broadleaf Forest Province; from here the province extends northwestward into Manitoba, Saskatchewan, and Alberta, where it is recognized as the Boreal Plains Ecozone (Marshall and Schut 1999). Low precipitation, limited spring infiltration, and desiccating winds from the Great Plains promote frequent spring fires and severe stress on shrubs and trees, resulting in a landscape composed largely of a mosaic of prairie and fire-maintained woodland communities of aspen and oak. The *Prairie Parkland Province* of the Midwest stretches from north to south across the western third of the state, covering about 65,000 km^2. The province coincides with parts of Minnesota that were historically dominated by tallgrass prairie; in this region a combination of low winter precipitation, short duration of snow cover, and desiccating westerly winds promoted severe spring fire seasons that historically favored grassland over forest vegetation. Forests were restricted to riparian corridors and other sites where water bodies or topographic breaks reduced the spread and severity of fire.

Methods

Collection and Preparation of Data

The MNDNR's new classification is based on numerical analysis of data from 5,224 vegetation plots collected across Minnesota. These data have been collected for many projects over the past 40 years; for the past 20 years the MNDNR has attempted to standardize collection of vegetation plot data in the state through development of collection guidelines and a computerized database that serves as a statewide repository for plot data (Almendinger 1987, MNDNR 2007, MNDNR Natural Heritage Information System Relevé Database, St. Paul, MN, USA). Collection of vegetation plot data by botanists and plant ecologists with the MNDNR largely follows the method of Braun-Blanquet (see Mueller-Dombois and Ellenberg 1974, Westhoff and van der Maarel 1978, or Becking 1957, among others). Surveyors in Minnesota typically use plot sizes of 20 m x 20 m for forested vegetation and 10 m x 10 m for herbaceous and shrub-dominated vegetation. Plots are sited subjectively in areas that appear to represent the native vegetation of Minnesota, with attention paid in particular to uniformity of vegetation and environment and absence of recent human-related disturbance (MNDNR 2007). Within each plot, the vegetation is stratified into layers based on the life-forms and heights of the vascular plant species (following Küchler's life-form and height classes [Küchler 1967]). The cover or abundance of each vascular plant species within each life-form and height-class group is estimated according to the Braun-Blanquet scale (Mueller-Dombois and Ellenberg 1974). Nomenclature for plant species largely follows *Manual of vascular plants of northeastern United States and adjacent Canada* (Gleason and Cronquist 1991), but this is being adapted to *Flora of North America* (Flora of North America Editorial Committee 1993–) as each volume in the series is published, and is modified by *Trees and shrubs of Minnesota* (Smith 2008) for woody species. The surveyor also usually records information on soils, substrate, slope, topographic position, hydrology (where applicable), evidence of natural or human-related disturbance, and other features of the environment in the vicinity of the plot. A complete description of the methodology employed by MNDNR vegetation scientists is available in MNDNR (2007). On

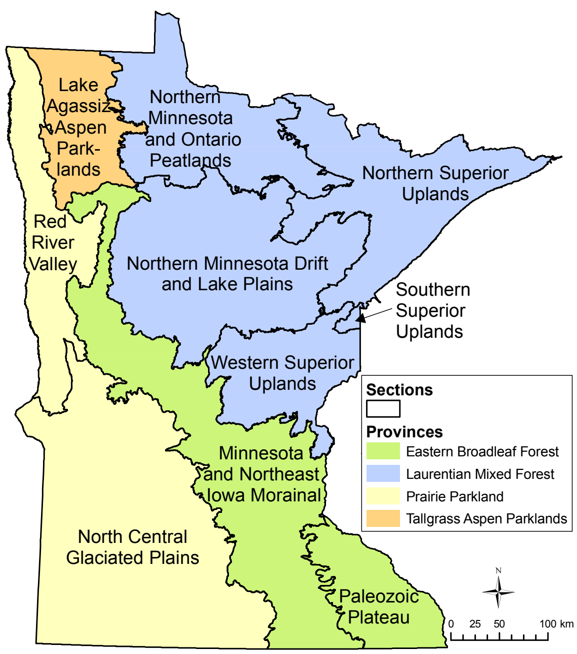

Fig. 2. Ecological land classification system (ECS) provinces and sections in Minnesota.

occasion, MNDNR surveyors dig soil pits in association with relevé plots and record soil profile data for the plot. The methodology used for data collection from soil pits follows that described in Schoeneberger et al. (2002).

A substantial amount of the first two years of the classification project involved acquisition and computerized entry of relevé data from vegetation studies done by researchers not affiliated with the MNDNR. At the end of this acquisition phase, the MNDNR's relevé database contained more than 6,000 relevés. The next phase of the project involved screening of these data for quality and for balance geographically and across the range of vegetation in Minnesota. This led to elimination of relevés where species identification appeared unreliable, where obviously different habitats were included within a plot, or where the plot size was not standard. Redundant relevés collected for purposes other than classification at intensively sampled study sites also were eliminated to prevent skewing results toward the conditions of those sites. Through this screening and elimination process, the initial dataset was reduced to approximately 4,500 relevés that were judged to be methodologically sound and to adequately represent the geographic and ecological range of variation of native vegetation in Minnesota. (Field collection of relevé data continued during the analysis phase of the classification project, which covered a period of approximately six years. By the end of this period, the MNDNR's relevé database contained somewhat more than 7,500 relevés, of which 5,224 were ultimately used in the classification.)

To provide information on the relationship between vegetation and soils, data were collected from soil pits associated with 1,405 relevé plots. Most of these soil pits were concentrated in and near the Chippewa National Forest in north-central Minnesota. Therefore, these soil pit data were augmented with soil and substrate information from soil survey and geologic maps for the remainder of the relevé plot locations in the dataset. Measurements of water chemistry in several peatland studies provided detailed hydrologic information for a subset of the peatland relevés in the dataset (e.g., Glaser et al. [1981] and Janssens et al. [1997]).

Data Analysis—Basic Approach

Analyses of relevé species data were performed by a team of five researchers over a period of about five years using standard classification and ordination techniques and, later in the process, Indicator Species Analysis according to the method of Dufrêne and Legendre (1997). The approach to analyzing relevé species data evolved somewhat during the project, particularly following introduction of Indicator Species Analysis to the group in 1997 and acquisition of PC-ORD (Version 3.15, MjM Software Design, Gleneden Beach, OR, USA), which allowed treatment of datasets with multiple analytical tools. Analyses were also punctuated by time spent developing concepts of the classification hierarchy and incorporating new relevés collected in the five-year period following commencement of the classification project.

Before beginning data analysis, we envisioned a multi-level classification to guide land management and biological inventory at a variety of scales, but were not certain of the specific levels. For the basic unit of the classification, however, we decided to follow the approach of habitat type classifications developed for forest plant communities in the Great Lakes region of the United States beginning in the 1970s and 1980s (see Coffman et al. [1984], Kotar and Coffman [1984], Kotar et al. [1988], and Kotar and Burger [1996]). These classifications were developed using analysis of data on native vegetation and are characterized by basic units (habitat types) that are intended to reflect the biological potential of sites, especially in relation to commercial forestry. The Great Lakes habitat type classifications borrow from habitat type classifications developed for the western United States (see, for example, Daubenmire and Daubenmire [1968], Pfister and Arno [1980], and Wellner [1989]) and from earlier forest classifications developed in Europe (such as those of Cajander [1926]). The development of our classification was for the most part unsupervised—that is, with the exception of prairie communities (see *Development of Ecological Systems* below) analyses were not constrained by the MNDNR's existing plant community classification.

Stratification of Data

During preliminary analyses of statewide datasets from the MNDNR's relevé database, relevés spanning the ecological range of vegetation in Minnesota consistently fell into three general groups in ordination space: forests, peatlands, and prairies. Therefore as a first step, to form manageable datasets for development of the classification we divided the statewide data into forest, peatland, and prairie groups (Fig. 3). To assign relevés to forest, peatland, and prairie datasets we created a subset of about 1,600 relevés for initial classification from the statewide set of 4,500 relevés. This was necessary because the software available to researchers at the beginning of the project was not capable of handling all 4,500 relevés. The 1,600 relevés were chosen to provide equal representation of plant communities from different ecoregions in Minnesota as well as from forest, peatland, and prairie habitats. In this dataset, tree species were stratified into two height classes: canopy trees, which were defined as trees taller than 10 m; and understory trees, which were defined as trees less than 10 m tall and meant to include tree seedlings and saplings. In addition, certain ecologically similar but difficult to identify plant species were lumped into species

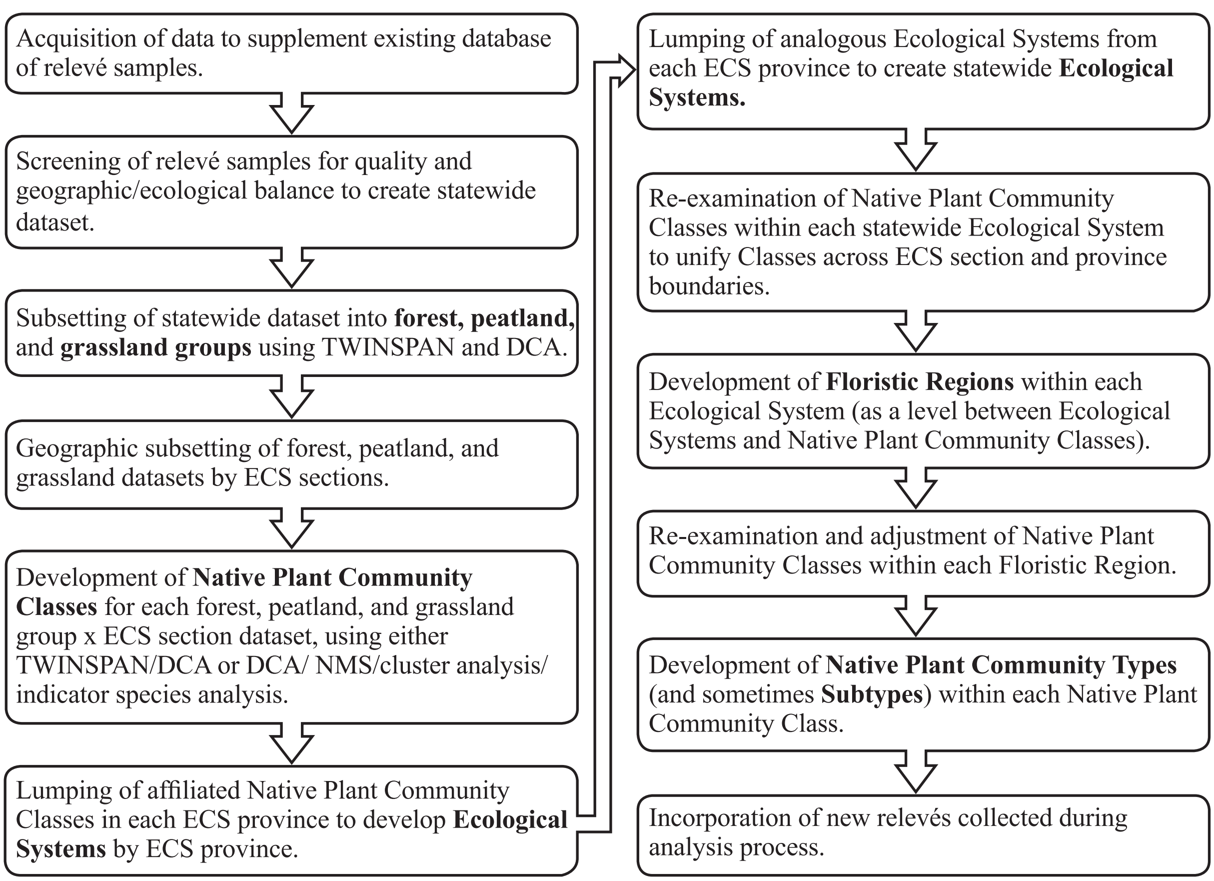

Fig 3. Steps in the analytical process used in developing the classification.

complexes in the datasets. The cover values for species in the analyses were the non-transformed Braun-Blanquet values (i.e., 1–7).

The 1,600 relevés were analyzed with TWINSPAN (as provided in the COINSPAN software of Carleton et al. 1996) and the major groups in the resulting phytosociological table were characterized by assessing the affinity of the diagnostic species for each group with forest, peatland, and prairie habitats on the basis of field observations and understanding of species ecology and distribution in Minnesota. Once distinctive forest, peatland, and prairie groups were identified, they were plotted using Detrended Correspondence Analysis (DCA) (Hill and Gauch 1980) and viewed for cohesiveness in ordination space. Relevés that did not cluster with the rest of their TWINSPAN group in ordination space were examined individually for species composition and environmental attributes and, when warranted, moved to one of the other three groups. Following classification of the 1,600 relevés to these groups, lists were generated of species with high fidelity for each group. These indicator species were then used to assign the remainder of the 4,500 relevés in the database to forest, peatland, or prairie datasets by eliminating all species in the relevés except the indicator species and passively ordinating the relevés with DCA.

Development of Native Plant Community Classes

After stratifying relevés into forest, peatland, and prairie datasets, we began development of one of the basic lower-level units of the classification, modeling our approach after Great Lakes habitat-type classifications. This initial lower unit of our classification, the Native Plant Community Class, was developed using two different analytical approaches. One member of the project team analyzed datasets using TWINSPAN and DCA. The other members used Non-Metric Multi-Dimensional Scaling (NMS), DCA, Cluster Analysis (Ward's method), and Indicator Species Analysis. Both approaches were guided by the philosophy that no single tool or approach was authoritative for determining the validity of a group or the inclusion of a relevé in one group or another. Instead, we decided to use multiple numerical tools along with information on soils and other environmental factors and understanding of species ecology to look for patterns in the datasets and make decisions about the ecological validity and utility of groups.

In both approaches, canopy trees (i.e., trees greater than 10 m tall) were removed from the datasets; all other vascular plant species were retained. The convention of de-emphasizing or excluding canopy trees during analysis has been used in development of habitat type classifications elsewhere in the Great Lakes region (e.g., Coffman et al. [1984], Kotar and Coffman [1984], and Kotar and Burger [1996]) under the hypothesis that the understory species composition of forests in the region is generally more reflective of site conditions than is canopy composition (see *Discussion* below).

We began development of Native Plant Community Classes by geographically subsetting the data for each of the three main datasets according to the ECS sections recognized in Minnesota under the national hierarchical framework of ecological units. Geographically restricted datasets were created to minimize broad, regional gradients in plant species composition related to large-scale factors such as climate, and to heighten patterns related to locally important, habitat-scale factors such as soil moisture and nutrients. There are ten ECS sections in Minnesota, delineated on the basis of regional variation in glacial deposits, elevation, distribution of plants, and climate (Fig. 2). Data from two of these ECS sections—the Western Superior Uplands and the Southern Superior Uplands—were combined in the analysis because of the limited extent of the Southern Superior Uplands in Minnesota and limited relevé data available for the section, resulting in nine geographically delimited datasets. The goal of these analyses was to develop units analogous to habitat types that were defined by a combination of floristics and site characteristics such as soil moisture, soil nutrients, and hydrologic regime.

In the analyses using TWINSPAN and DCA, TWINSPAN was run on each ECS section dataset to construct an initial phytosociological table. The relevés in each group in the table were examined for similarity in habitat or site characteristics, such as soil parent material, presence of semi-permeable horizons, soil drainage classes, and other features that influence soil moisture or nutrient status. We also examined the diagnostic plants at each division for association with certain parameters of soil moisture, soil nutrients, and hydrologic conditions, among other important site or habitat characteristics. The groups generated through TWINSPAN were examined in DCA ordinations for similarity among relevés in different groups and for variability (dispersion) within each group, to determine if any groups should be combined or further divided.

In analyses using NMS, DCA, Cluster Analysis, and Indicator Species Analysis, we first ran an Outlier Analysis on each dataset and removed outlying samples that had species indicative of plot heterogeneity or that had questionable species taxonomy. We then partitioned the datasets using Cluster Analysis (Ward's method). Each successive split in the cluster dendrograms was tested by examining the resulting sum of indicator species values, following the method of Dufrêne and Legendre (1997), with Monte Carlo tests of significance run for at least 1,000 permutations and with species selected as significant indicators at $p < 0.05$. Splitting continued until successive splits no longer yielded an increase in the indicator species sum. The Ward's groups were examined for correlation with site or habitat characteristics by assessing whether the indicator species were associated with certain soil moisture or nutrient levels. The relevés within each group were also examined for cohesiveness of soil, substrate, geography, and other environmental features, and the Ward's groups were screened for signs of influence from factors such as human disturbance or surveyor bias. In conjunction with these examinations, the groups were plotted on NMS ordinations (three dimensional, using Sorensen distance and the axis scores from an initial Bray-Curtis ordination as starting coordinates) and DCA ordinations, which were used to look for individual relevés or groups of relevés that should be moved from one group to another and tested by recalculating indicator species sums. The ordinations were imported into ArcView (Version 3.2, Environmental Systems Research Institute, Redlands, CA, USA) and overlain with soil and other environmental data associated with the relevé plots. In addition, the groups were examined for cohesiveness in three-dimensional space by viewing the ordinations with ArcView's 3-D Analyst extension. Based on examination for ecological meaning and consistency of geography and habitat, and examination of patterns in the ordinations with retesting of indicator species sums, some of the Ward's groups that had been identified in the initial Indicator Species Analysis were combined or parsed into other groups. The Ward's groups were also plotted on ordinations of synecological coordinates for moisture, nutrients, heat, and light (Bakuzis 1959, Bakuzis and Kurmis 1978, Brand and Almendinger, unpubl.) to look for relationships among the groups along environmental gradients.

When separate analyses of Native Plant Community Classes had been completed using the two approaches described above, the results of each were checked and unified by subjecting them to the methods of the other approach. At the end of the process, we had developed Classes separately for nine datasets sorted by ECS section; examples included poor dry pine woodlands, rich mesic hardwood forests, rich spruce swamps, dry savannas, and rich fens. The Classes generally represented identifiable habitat types in Minnesota. In addition, they tended to sort distinctly into groups according to influence of major ecological processes, such as fire-dependent forests, floodplain forests, and emergent marshes. We therefore decided to create a higher level in the classification, the Ecological System, in which Native Plant Community Classes were grouped according to important shared ecological function or processes, with the understanding that such a level would be useful for broad landscape level assessment and resource management.

Development of Ecological Systems

As with development of Native Plant Community Classes, the datasets for development of Ecological Systems were segmented geographically, in this case according to the four provinces delineated in Minnesota's ECS (Fig. 2). Development of Ecological Systems was guided by consideration of the results of analyses of Native Plant Community Classes, along with understanding of important ecological processes, information on Minnesota's native vegetation gained through fieldwork and literature review, and examination of other data such as soils and Public Land Survey bearing-tree records. Because Ecological Systems were meant to reflect ecological processes or functions, a guiding principle in their development was the belief that each System should have a unified disturbance regime, hydrologic regime, nutrient regime, and climate regime, and was likely to be characterized by a distinctive suite of species adapted to these disturbance and environmental regimes.

Ecological Systems were delineated using the two basic analytical approaches described above for Native Plant Community Classes (i.e., TWINSPAN and DCA on the one hand, and NMS, DCA, Cluster Analysis, and Indicator Species Analysis on the other). Canopy trees were removed from the datasets; all other vascular plant species were retained. In both approaches, relevés were labeled in classification dendrograms with their Native Plant Community Class designation to highlight patterns and aid in dividing the datasets into ecologically meaningful groups. Divisions between groups were further examined for ecological meaning by assessing whether the diagnostic plants for each division were known to be strongly associated with important disturbance, hydrologic, nutrient, and climate regimes. We also used information on major non-climatic influences on Minnesota's vegetation from previous studies for guidance in delineating Ecological Systems, including Heinselman (1973, 1978, 1996) and Grimm (1983, 1984) on the role of fire, for example, and Daubenmire (1936) and others on processes in mesic forests.

When separate analyses of Ecological Systems had been completed using the two approaches, the results of each approach were checked using the methods of the other. As an example of the final results, for forested vegetation in the Laurentian Mixed Forest Province we identified four Systems: Fire-Dependent Forests and Woodlands, Mesic Hardwood Forests, Floodplain Forests, and Wet Forests. The development of forested Ecological Systems proceeded likewise for the other ECS provinces in Minnesota (Eastern Broadleaf Forest, Prairie Parkland, and Tallgrass Aspen Parklands). The same basic process was applied to the peatland and prairie datasets. The analysis within the prairie dataset differed somewhat in that the MNDNR's existing classification of prairie communities (MNDNR 1993) was used as a framework rather than developing the classification unconstrained by previous concepts. This was done in part because the existing classification of prairie vegetation was more exhaustive than that for other vegetation types and the units had proven to adequately describe variation in prairies and meet the MNDNR's needs for survey and management.

Unifying Ecological Systems and Native Plant Community Classes Statewide

Following development of Ecological Systems we had separate Ecological System classifications for each of Minnesota's four provinces. These Systems often appeared analogous across province lines and in addition, there appeared to be strong floristic overlap among some Native Plant Community Classes in separate ECS section analyses. We therefore combined data from analogous Systems to create statewide datasets and analyzed them to unify Ecological Systems and Native Plant Community Classes statewide. As an example, the relevés from the Mesic Hardwood Forest System in the Laurentian Mixed Forest Province were combined with those from mesic forest Systems in the Eastern Broadleaf Forest, Prairie Parkland, and Tallgrass Aspen Parklands provinces to create a statewide dataset, and examined for cohesiveness. Each statewide Ecological System dataset was combined successively with other "ecologically adjacent" Systems (adjacency was determined in part by examination of Systems in ordination space) and analyzed to test the seams between statewide Systems using the basic analytical tools used in developing the Systems within each province. Relevés or groups of relevés were sometimes moved from one Ecological System to another based on the results of these analyses.

Once Ecological Systems had been unified across provinces, the Native Plant Community Classes that had been developed within each System in the nine ECS section classifications were re-examined. This was done by combining all of the relevés statewide within each Ecological System and analyzing them with the basic techniques described above for development of Native Plant Community Classes. The starting points for groups in the analyses were the Native Plant Community Classes that had been developed within each of the separate ECS section analyses. The process of unifying Classes resulted in combining some of the existing Classes into new Classes that spanned ECS sections.

Development of Floristic Regions

During analyses of Classes within statewide Ecological Systems, we observed that the relevés within each System typically fell into two or more distinct, geographically separate groups in cluster analyses and ordinations. These groups often correlated with differences in species distributions related to climate or paleohistory (the latter being to some extent an expression of the influence of past climate on plant geography). This led us to reexamine the classification hierarchy and to create another level, the Floristic Region, which was inserted between Ecological Systems and Native Plant Community Classes (Fig. 1). Floristic Regions, therefore, reflect geographic patterns of floristic variation within the System, and are prominent when geography is overlaid on ordinations of the relevés within a given System (Fig. 4).

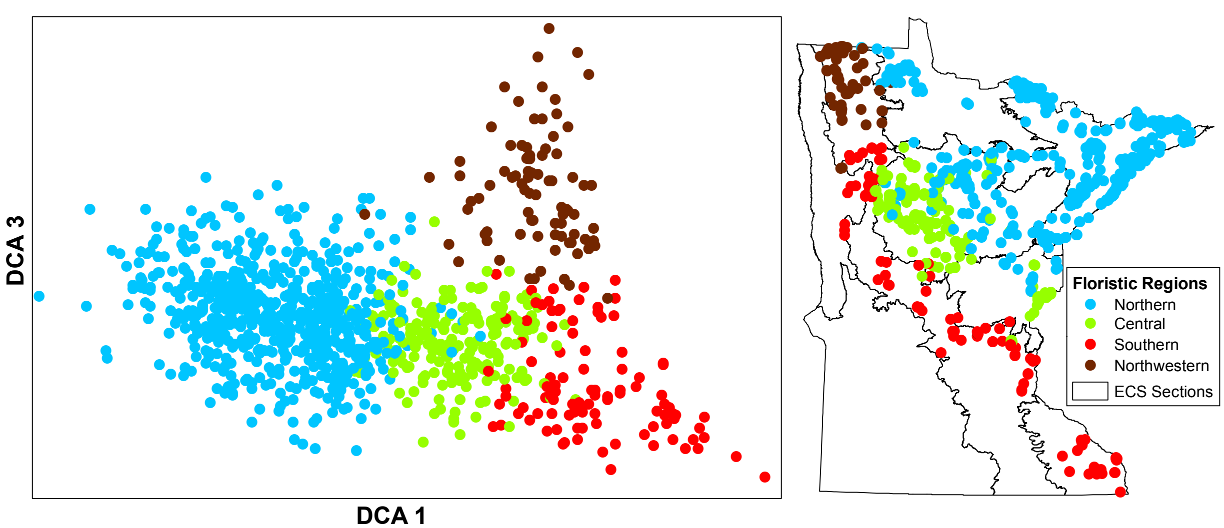

Fig. 4. DCA ordination (axes 1 vs. 3) of relevés in the Fire-Dependent Forest/Woodland System, and their geographic distribution, labeled by northern, central, southern, and northwestern floristic regions.

Floristic Regions were delineated within each System with the techniques used in delineating Native Plant Community Classes and Ecological Systems. Following the delineation of Floristic Regions, datasets were created for each Floristic Region within each System and the existing classification of Native Plant Community Classes was analyzed again. This process led to some adjustments of the Classes within each System. Fig. 5 is an ordination of the four Native Plant Community Classes in the Floodplain Forest System, labeled with the ECS section for each relevé. This ordination illustrates the importance of geography in grouping samples in each System into Plant Community Classes: in the Floodplain System there are northern and southern analogues for communities that occur respectively on low, frequently inundated floodplains and on elevated, less frequently inundated riparian sites such as terraces. The illustration also shows that within the broad north-south split present in the ordination there is much overlap among samples by ECS section, validating our decision to group and analyze Systems and Classes across section and province boundaries to create ecologically and floristically meaningful statewide classification units.

Development of Native Plant Community Types and Subtypes

Many of the Native Plant Community Classes were characterized by significant internal floristic variation that appeared to correlate with geography, differences in vegetation structure, and differences in substrate. Therefore, as a last stage in the classification process, we analyzed the relevés within each of the Native Plant Community Classes to develop lower units—Native Plant

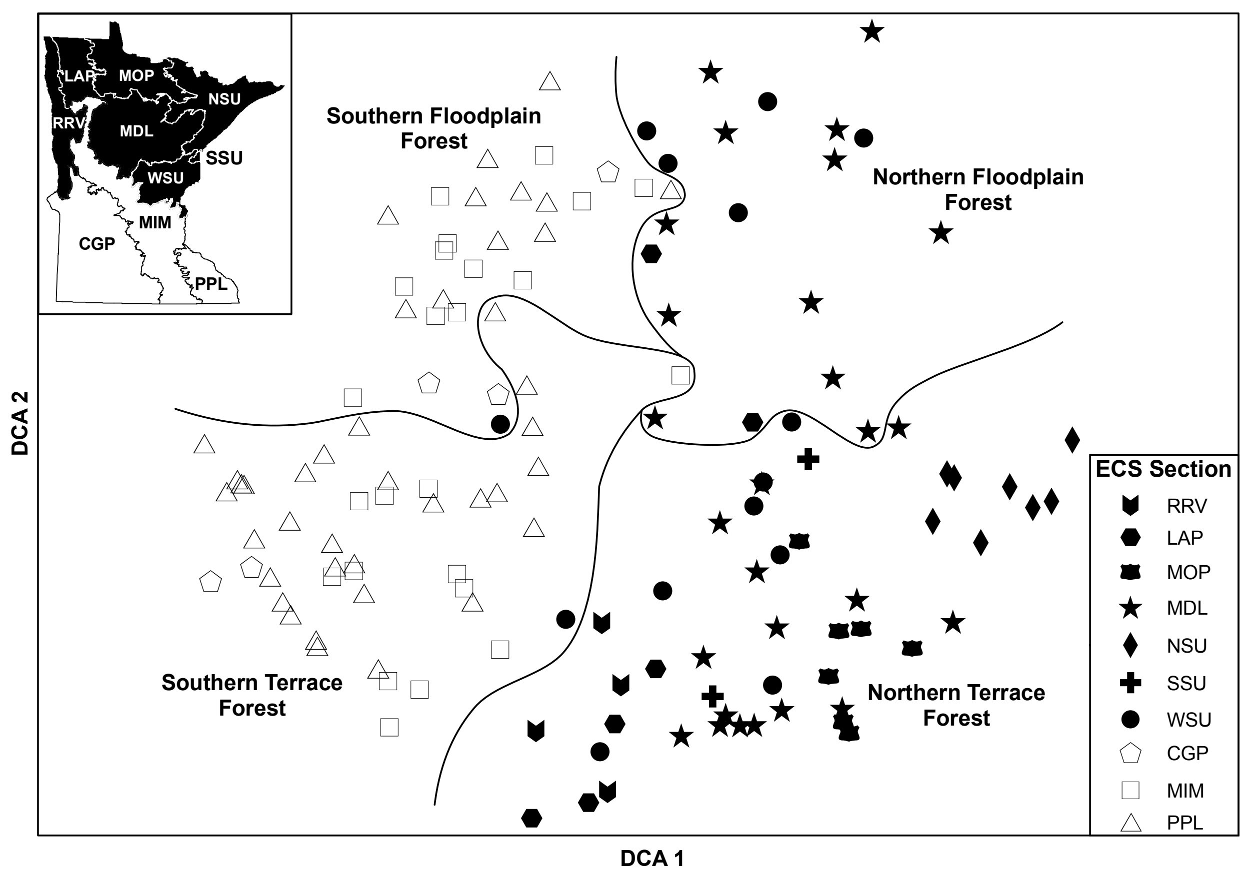

Fig. 5. DCA ordination of relevés in the Floodplain Forest System, labeled by ECS sections. Axis 1 reflects geography (south to north), while axis 2 is related to flooding regime, with forests on active floodplains of large rivers at one end and forests on less frequently flooded river and stream terraces at the other.

Community Types—that reflected finer variation in floristic composition and environmental factors. For forested communities in particular, development of Plant Community Types was prompted by a desire for units that reflected variation in tree canopy composition. Therefore, analyses to develop Plant Community Types were conducted with canopy trees put back into the datasets. For some Plant Community Types we developed yet a lower level, the Subtype. In general, Subtypes were created for Types that appeared to retain floristic variation related to differences in substrate, vegetation structure, or other factors but for which there was not enough plot data or other information to confidently delineate multiple Types. The analytical tools and process used in developing Plant Community Types and Subtypes followed those used in developing Native Plant Community Classes.

Integration of New Relevé Data

Collection of relevé data continued in the field during the period of analysis and development of the classification. Once the classification hierarchy was fully developed and robust datasets had been established for classification entities, new relevés were incorporated during the final two years of the classification project by ordinating and classifying these relevés with existing classified relevés. The process was iterative, first classifying the new relevés into Ecological Systems, using Indicator Analysis, Ward's Analysis, DCA, and NMS. Once the relevés were in Systems, System datasets were created and the analytical process was repeated to assign the new relevés to Floristic Regions. This continued until the new relevés were classified to Native Plant Community Class and then to Type or Subtype.

Creation of System Groups

At the end of the analytical process, we considered how the units of the classification could best be organized in field keys and other products developed for application of the classification (MNDNR 2003, 2005a, 2005b) and decided to create one more classification unit, the System Group (Fig. 3). System Groups are the highest level of the classification and were formed by amalgamating lower levels of the classification, primarily along major physiognomic (forested versus open) and hydrologic (upland versus wetland) splits in vegetation.

Parallel Classification of Data-Poor Communities

After the classification hierarchy was fully developed for forested, peatland, and prairie communities, a parallel hierarchy was developed for non-forested communities for which there were insufficient data to conduct meaningful analyses (MNDNR 2003, 2005a, 2005b). These communities included cliffs and talus slopes, rock outcrop communities, and lake and river shore communities. The classification of these communities, while parallel in organization to that of forested communities and data-rich non-forested communities such as prairies, was developed largely from the field experience of MNDNR plant ecologists, along with review of field survey notes, vegetation plot samples and species lists, information on plant distribution from herbarium records, and existing literature, rather than from numerical analysis of vegetation plot data.

Results

Minnesota's revised native plant community classification is hierarchical, with six levels (Fig. 3). The highest level is the System Group, which was added after the analytical process to aid in organization of field guides and other classification products. There are four System Groups:

Upland Forests and Woodlands; Wetland Forests; Upland Grasslands, Shrublands, and Sparse Vegetation; and Wetland Grasslands, Shrublands, and Marshes (Table 1).

The next level of the classification is the Ecological System: groups of native plant communities unified by strong influence from a major ecological process or set of processes, especially nutrient cycling and natural disturbances. In application of the classification, Ecological Systems provide a prominent place for consideration and discussion of ecological processes. Much of the variability in species composition among the Systems in the classification appears to be related to differences in the seasonal delivery and movement of essential nutrients. Natural disturbances also appear to have strong influence on variability in species composition among Systems, with timing and severity of disturbances especially influential. In total, we recognized 15 Ecological Systems in the classification (Table 1).

Ecological Systems are divided into Floristic Regions, which reflect the distribution of Minnesota's plant species into characteristically northern, northwestern, central, southern, and prairie groups, or floras (Table 1). The most important influences on the plant distribution patterns that form the basis for delineation of Floristic Regions appear to be climate and paleohistory, with modern plant distribution in Minnesota reflecting influence from past as well as present climate regimes.

Upland Forests and Woodlands

Fire-dependent Forest/Woodland System
- Northern Dry-Sand Pine Woodland
- Northern Dry-Bedrock Pine (Oak) Woodland
- Northern Poor Dry-Mesic Mixed Woodland
- Northern Dry-Mesic Mixed Woodland
- Northern Mesic Mixed Forest

- Central Poor Dry Pine Woodland
- Central Dry Pine Woodland
- Central Rich Dry Pine Woodland
- Central Dry Oak-Aspen (Pine) Woodland
- Central Dry-Mesic Pine-Hardwood Forest

- Southern Dry-Mesic Pine-Oak Woodland
- Southern Dry-Mesic Oak-Aspen Forest
- Southern Dry-Mesic Oak (Maple) Woodland
- Southern Dry-Mesic Oak-Hickory Woodland

- Northwestern Dry-Mesic Oak Woodland
- Northwestern Mesic Aspen-Oak Woodland
- Northwestern Wet-Mesic Aspen Woodland

Mesic Hardwood Forest System
- Northern Mesic Hardwood Forest
- Northern Wet-Mesic Boreal Hardwood-Conifer Forest
- Northern Mesic Hardwood (Cedar) Forest
- Northern Wet-Mesic Hardwood Forest
- Northern Rich Mesic Hardwood Forest

- Central Dry-Mesic Oak-Aspen Forest
- Central Mesic Hardwood Forest (Eastern)
- Central Mesic Hardwood Forest (Western)
- Central Mesic Cold-Slope Hardwood-Conifer Forest
- Central Wet-Mesic Hardwood Forest

- Southern Dry-Mesic Oak Forest
- Southern Mesic Oak-Basswood Forest
- Southern Mesic Maple-Basswood Forest
- Southern Wet-Mesic Hardwood Forest

- Northwestern Wet-Mesic Hardwood Forest

Wetland Forests

Floodplain Forest System
- Northern Terrace Forest
- Northern Floodplain Forest

- Southern Terrace Forest
- Southern Floodplain Forest

Wet Forest System
- Northern Wet Cedar Forest
- Northern Wet Ash Swamp
- Northern Very Wet Ash Swamp
- Southern Wet Aspen Forest
- Southern Wet Ash Swamp

- Northwestern Wet Aspen Forest

Forested Rich Peatland System
- Northern Rich Spruce Swamp (Basin)
- Northern Cedar Swamp
- Northern Rich Spruce Swamp (Water Track)
- Northern Rich Tamarack Swamp (Eastern Basin)
- Northern Rich Tamarack Swamp (Water Track)
- Northern Rich Tamarack Swamp (Western Basin)

- Southern Rich Conifer Swamp

- Northwestern Rich Conifer Swamp

Acid Peatland System
- Northern Spruce Bog
- Northern Poor Conifer Swamp

Upland Grasslands, Shrublands, and Sparse Vegetation

Cliff/Talus System
- Northern Dry Cliff
- Northern Open Talus
- Northern Scrub Talus
- Northern Mesic Cliff
- Northern Wet Cliff

- Lake Superior Cliff

- Southern Dry Cliff
- Southern Open Talus
- Southern Mesic Cliff
- Southern Maderate Cliff
- Southern Algific Talus
- Southern Wet Cliff

Rock Outcrop System
- Northern Bedrock Outcrop
- Northern Bedrock Shrubland

- Southern Bedrock Outcrop

Lakeshore System
- Inland Lake Sand/Gravel/Cobble Shore
- Inland Lake Rocky Shore
- Inland Lake Clay/Mud Shore

- Lake Superior Sand/Gravel/Cobble Shore
- Lake Superior Rocky Shore

River Shore System
- Sand/Gravel/Cobble River Shore
- Rocky River Shore
- Clay/Mud River Shore

Upland Prairie System
- Northern Dry Prairie
- Northern Dry Savanna
- Northern Mesic Prairie
- Northern Mesic Savanna

- Southern Dry Prairie
- Southern Dry Savanna
- Southern Mesic Prairie
- Southern Mesic Savanna

Wetland Grasslands, Shrublands, and Marshes

Acid Peatland System
- Northern Open Bog
- Northern Poor Fen

Open Rich Peatland System
- Northern Shrub Shore Fen
- Northern Rich Fen (Water Track)
- Northern Rich Fen (Basin)
- Northern Extremely Rich Fen

- Prairie Rich Fen
- Prairie Extremely Rich Fen

Forested Rich Peatland System
- Northern Rich Alder Swamp

Wet Forest System
- Northern Wet Alder Swamp

Wet Meadow/Carr System
- Northern Wet Meadow/Carr

- Southern Seepage Meadow/Carr
- Southern Basin Wet Meadow/Carr

- Prairie Wet Meadow/Carr

Marsh System
- Northern Mixed Cattail Marsh
- Northern Bulrush-Spikerush Marsh

- Lake Superior Coastal Marsh

- Prairie Mixed Cattail Marsh
- Prairie Bulrush-Arrowhead Marsh

Wetland Prairie System
- Northern Wet Prairie

- Southern Wet Prairie

Table 1. System Groups, Ecological Systems, and Native Plant Community Classes in Minnesota's native plant community classification.

Other factors that correlate with the Floristic Region boundaries within Ecological Systems are disturbance regimes from fire, wind, and flooding, and outbreaks of insects and diseases (MNDNR 2003, 2005a, 2005b).

Native Plant Community Classes, perhaps the most basic and widely applied unit of the classification, relate to local environmental conditions such as moisture and nutrient levels for terrestrial communities and water chemistry and water-level fluctuations for wetland communities. Classes are units of vegetation with uniform soil texture, soil moisture, soil nutrients, topography, and disturbance regimes. Native Plant Community Classes are roughly equivalent to habitat types in other vegetation classifications in the Great Lakes region (Kotar and Burger 2000, Kotar et al. 1988, Kotar and Burger 1996, and Coffman et al. 1984). Native Plant Community Classes change rather gradually along ecological gradients, especially in amounts of water and nutrients available to plants. Therefore, Classes within an Ecological System overlap broadly with one another in species composition. Classes are hypothesized to be persistent entities on a particular piece of land in the absence of climate change or change in major disturbance regime. In total, we recognized 104 Native Plant Community Classes in the classification.

Native Plant Community Types, the level immediately below Classes, are defined by canopy dominants, variation in substrate, or fine-scale differences in environmental factors such as moisture or nutrients. For wooded communities, each Type—unlike each Class—is usually uniform in tree canopy composition; in some cases Native Plant Community Types represent successional stages of a Native Plant Community Class. Type distinctions were also made to describe geographic patterns within a Class, substrate relationships, and variability in dominant species, especially if a group within a Class represented a unit described in previous studies of vegetation in Minnesota. Minnesota's Native Plant Community Types are roughly equivalent to associations in the United States National Vegetation Classification (Jennings et al. 2009, Grossman et al. 1998) and to forest and wetland ecosystems in classifications in nearby Ontario (Sims et al. 1997, Harris et al. 1996). For 31 of the 104 Native Plant Community Classes recognized in the classification, there is just one Type (i.e., the Class was not further divided). Among the other 73 Classes, we delineated 223 Types, an average of about three Types per Class.

The lowest level of the Classification is the Native Plant Community Subtype. Subtypes were not developed universally for all Types, but rather for those where there appeared to be some utility or basis for making fine-scale distinctions within a Type according to canopy phase, substrate, or environmental gradients. In some instances, Subtypes represent apparent trends within Types for which more study and collection of data are needed. In other instances Subtypes are well-documented, fine-scale units of vegetation that are useful for work such as rare plant habitat surveys.

Discussion

In certain aspects Minnesota's classification fits into the tradition of classifications developed by Braun-Blanquet and other European plant scientists beginning in the early 20th century (see Poore [1955a, 1955b, 1955c, 1956], Westhoff and van der Maarel [1978], or Becking [1957], for example). The method of collection of the vegetation data underpinning Minnesota's classification follows in most details the relevé method codified by Braun-Blanquet (Mueller-Dombois and Ellenberg 1974) and the classification is based foremost on treatment of floristic data.

In recent decades the advent of large computerized databases and software packages capable of handling large datasets has been accompanied by interest and activity in the development of large-scale or regional classifications using numerical analysis of vegetation plot data. The results include classifications covering all or much of the range of vegetation for Great Britain (Rodwell 1991–2000), British Columbia, Canada (British Columbia Ministry of Forests and Range), The Netherlands (Schaminée et al. 1995–99), and the state of Mecklenburg-Vorpommern, Germany (Dengler et al. 2005). Among the general features shared by some of these large-scale efforts are a substantial initial investment in collecting (from the field and previous studies) and computerizing relevés, and substantial effort spent maintaining coordination and progress among multiple researchers, sometimes working in different locations and for different institutions. Members of Minnesota's project came from different academic backgrounds and as a result had differences in preference for methodological process and techniques. We resolved these differences in part by focusing on the ecological integrity of the results rather than the formalities of analytical techniques, an approach taken also in the British classification project. Another general aspect of Minnesota's project that appears common to classification projects involving large datasets and a broad range of vegetation is that the process of analysis is iterative, with many rounds of sorting, pooling, and reanalysis of data before arriving at meaningful results (see Rodwell 1991–2000), and with results of analyses assessed and modified according to classification principles developed beforehand (see Dengler et al. 2005). Pfister and Arno's (1980) account of the development of their habitat type classification for forest lands in Montana, USA also describes an iterative process much like that used in the development of Minnesota's classification. We spent some time before we began data analysis testing ways to subset our statewide dataset. Sub-setting or stratification of large datasets is an important consideration that can have considerable influence on classification results (Knollová et al. 2005). Our approach of sub-setting the data by vegetation groups (prairie, peatland, forest) and geographic units (ECS sections and provinces) to develop initial regional classifications, and then comparing and unifying these classifications to create a statewide result, proved workable and helped to reveal interesting patterns or trends in the data. Similar approaches have been used in other large-scale efforts (see British Columbia Ministry of Forests and Range, for example).

We modeled part of our approach to classification after that used in habitat type classifications for forests in the Great Lakes region. One of the basic units of Minnesota's classification, the Native Plant Community Class, was developed to reflect habitat features that have strong influence on plant distribution and growth, such as soil moisture and nutrient content. For forested communities, we removed canopy trees from the data to emphasize understory vegetation in analyses under the hypothesis that understory plants are more immediately sensitive to and therefore more reflective of habitat conditions than are canopy trees. This assumption is an important element of habitat type classifications in the Great Lakes region of the United States and also of forest classifications in Scandinavia and the Baltic states (Frey 1978, Kuusipalo 1985, Kimmins 2004). In these regions, forest canopies comprise relatively few tree species that often have wide ecological amplitude and therefore are not good indicators of habitat conditions. Conversely, the understories in these forests have more diverse species composition and include species with relatively narrow habitat preferences. In Europe, understory species have also been emphasized over tree species in development of forest classifications because forest canopies are viewed as being more widely and more directly altered by silvicultural activities than understory species (Westhoff and van der Maarel 1978, Rodwell 1991–2000). The stability or relatively fast recovery of ground-layer vegetation following disturbance and the strong influence of soil on ground-layer flora have been reported in several studies (see Waring and Major 1964; Grigal and Arneman 1970; Daubenmire 1976; Coffman and Willis 1977; Pfister and Arno 1980; Outcalt and White 1981; Pregitzer and

Barnes 1982; Wang 2000), although in some instances ground-layer flora may not be affected by deeper soil layers that do have an effect on canopy species composition (Carmean 1975, Cleland et al. 1994; but see Daubenmire [1976] for an opposing view of the dynamics of rooting zones of trees versus understory species).

Understory species composition obviously is not immune to influence from disturbance, and is likely to be influenced by biotic or biotically mediated factors such as overstory composition and structure and nutrient cycling rates (Rowe 1956, Carmean 1975, Kuusipalo 1985, Zak et al. 1986, Host and Pregitzer 1991, 1992, Cook 1996) in addition to abiotic properties of sites. Therefore, assuming that understory species composition is more reflective of site conditions than is canopy composition may not be universally warranted (see Cook [1996] or Daubenmire [1952]). In our classification, emphasis of understory species in data analysis did result in entities (Native Plant Community Classes) that plant ecologists familiar with vegetation in Minnesota readily perceive as relating to important environmental gradients in the field. We also used site characteristics such as soil parent material, presence of semi-permeable horizons, soil drainage classes, presence of surface water ponding, and other features that influence soil moisture or nutrient status in making decisions about the delineation of Native Plant Community Classes. Therefore our Native Plant Community Classes (both forested and non-forested) are likely to relate in some measure to habitat or site characteristics whether or not we de-emphasized canopy trees in analyses. And even in classifications derived from analysis of floristic data without deliberate input or consideration of site data, edaphic and climatic factors can play a dominant role in shaping the nature of the communities distinguished in the classification (Rodwell 1991–2000).

During Minnesota's classification project, we kept in contact with the developers of the United States National Vegetation Classification (USNVC) (Grossman et al. 1998) but chose to proceed without following the hierarchy of the USNVC, in large part because of the conservation and resource management needs of the MNDNR. We wanted a classification that deliberately incorporated ecological function and also reflected habitat or site conditions. At the time, the lower-level units of the USNVC—the Alliance and Association—were defined by floristics while the upper, broader levels were defined by physiognomy (Grossman et al. 1998, Jennings et al. 2004), although subsequently the upper and mid-level units of the USNVC have been revised to more clearly reflect ecological processes (Faber-Langendoen et al. 2009). The MNDNR's plant community classification has been crosswalked to the USNVC at the level of Minnesota's Native Plant Community Type (and sometimes Subtype) versus the Association in the USNVC. The relationship between Minnesota's Native Plant Community Types and the USNVC's Associations is occasionally one-to one, but more often one-to-many or many-to-one. It is anticipated that future reexamination of Associations in the USNVC will result in stronger correlation between Minnesota's Native Plant Community Classes or Types and Associations in the USNVC. Entities in Minnesota's classification are also being referenced during the development of units in the Canadian National Vegetation Classification for adjacent parts of Ontario (Faber-Langendoen, pers. comm.).

The conservation organization NatureServe has developed a unit complementary to the USNVC that compares with Minnesota's Ecological Systems in certain aspects. This unit, coincidentally called ecological systems, was created to address needs for conservation and mapping not met at the time by the units of the USNVC (Comer et al. 2003). The two versions of ecological system are often similar in their reflection of important ecological processes and also coincide at times as map units in Minnesota, but the underlying concept of the two differs. NatureServe's ecological systems were developed primarily as spatial entities, and are defined as groups of plant communities—in this case, Associations—that tend to co-occur in "landscapes with similar ecological processes, substrates, and/or environmental gradients" (Comer et al. 2003). The Associations that make up an ecological system in NatureServe's scheme are linked by multiple factors, including bioclimate, biogeographic history, physiography, landform, physical and chemical substrates, landscape juxtaposition, and vegetation structure and composition, in addition to ecological processes. Ecological Systems in Minnesota's classification, in comparison, were conceived mainly in terms of ecological processes and their effect on floristic composition without deliberate consideration of the spatial relationships of the plant communities that compose them. Therefore, the plant communities within an Ecological System in Minnesota's classification do not necessarily occur in association with one-another in the landscape, but rather represent groups of plant communities similar in floristic composition (and also usually in physiognomy) as a result of influence of major ecological processes. Because of this difference in basic concept, each Native Plant Community Class or Type in Minnesota's classification is always a member of just one Ecological System, whereas in NatureServe's scheme a given Association can occur in more than one type of ecological system (Comer et al. 2003).

One of the unexpected results of Minnesota's classification process was the development of the Floristic Region level. The Floristic Region did not become apparent as a useful unit in the classification hierarchy until we were well into analysis of data and development of the hierarchy. The Floristic Regions of several of Minnesota's Ecological Systems correlate with paleo-vegetation patterns, suggesting a lasting legacy of past vegetation. An example is the relationship of the ecotone separating Minnesota's northern forests and grasslands to the Floristic Regions of the classification's upland forest Systems. During the Holocene epoch, this ecotone fluctuated across a wide area in Minnesota and the Midwestern United States in response to change in climate (Webb et al. 1983) and at present the ecotone—often referred to as the tension zone—is a broad zone of overlap of boreal and plains species. The Central Floristic regions of Minnesota's Fire-Dependent Forest/Woodland and Mesic Hardwood Forest systems align well with this ecotone as described for Wisconsin (Curtis 1959) and with the southern boundary of the ecotone as determined for Minnesota (Fig. 6). (Only the approximate southern boundary of the tension zone has been plotted in Minnesota using the kind of analysis of species distributions used to determine the boundaries of the tension zone in Wisconsin [Wheeler et al. 1992].) In the Fire-Dependent Forest/Woodland System, the boundary between the Central Floristic Region and the Northern Floristic Region correlates strongly with the maximum northeastern extent of the prairie-forest border in

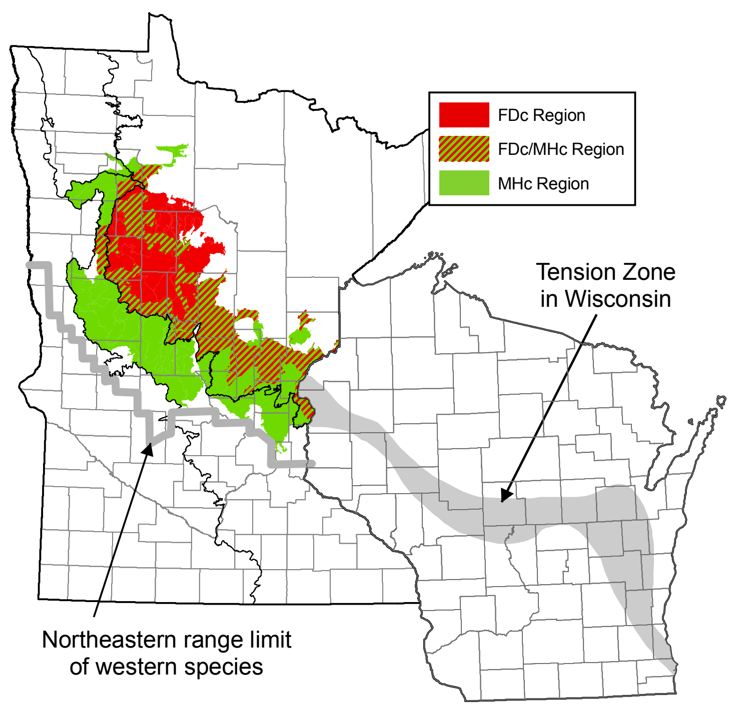

Fig. 6. The Central Floristic regions of the Fire-Dependent Forest/Woodland (FDc) and Mesic Hardwood Forest (MHc) systems in relation to the Tension Zone in Wisconsin as described by Curtis (1959). Also plotted is the collective northeastern range limit of selected western plant species in Minnesota; this limit approximates the southern boundary of the tension zone in Minnesota (Wheeler et al. 1992).

Minnesota during the mid-Holocene, approximately 7 ka (Fig. 7). In correspondence, among the species that differentiate Fire-Dependent Woodlands in the Central Floristic Region from those in the Northern Region is a group with strong affinity for prairie habitats in Minnesota, including *Lithospermum canescens*, *Andropogon gerardii*, *Aster laevis*, *Elymus trachycaulus*, *Aster oolentangiensis*, *Solidago nemoralis*, and *Monarda fistulosa*. Conversely, the Northern Floristic Region of the Fire-Dependent Forest/Woodland System correlates strongly with the distribution of upland conifer bearing trees recorded in Minnesota by public land surveyors in the mid to late 1800s (Fig. 8). Many of the species that distinguish Northern from Central Region Fire-Dependent Woodlands are species strongly affiliated with conifer trees, including *Cornus canadensis*, *Linnaea borealis*, *Lycopodium dendroideum*, *Lycopodium hickeyi*, *Lycopodium clavatum*, *Polypodium virginianum*, *Lycopodium annotinum*, *Coptis trifolia*, *Mitella nuda*, and *Gymnocarpium dryopteris*.

The boundaries of the Floristic Regions are specific for each System. For example, the Northern Floristic Region of the Mesic Hardwood Forest System does not have the same geographic boundaries as the Northern Floristic Region of the Wet Forest System or the Northern Floristic Region of the Upland Prairie System. This specificity is related to patterns of plant geography. Contemporary plant geography in Minnesota is characterized by species with population centers either to the northeast in the boreal forest region or to the southwest in the Great Plains (see Wheeler et al. [1992], for example). There are almost no species with distributions limited to the contact or ecotone between the boreal forests and the grasslands of the Great Plains. In northeastern Minnesota, boreal species occur in Ecological Systems spanning the moisture gradient from dry to wet. Moving southwest, these species are progressively restricted to wetter and wetter habitats until, near the prairie-forest border, boreal species are found only in peatland Systems. Conversely,

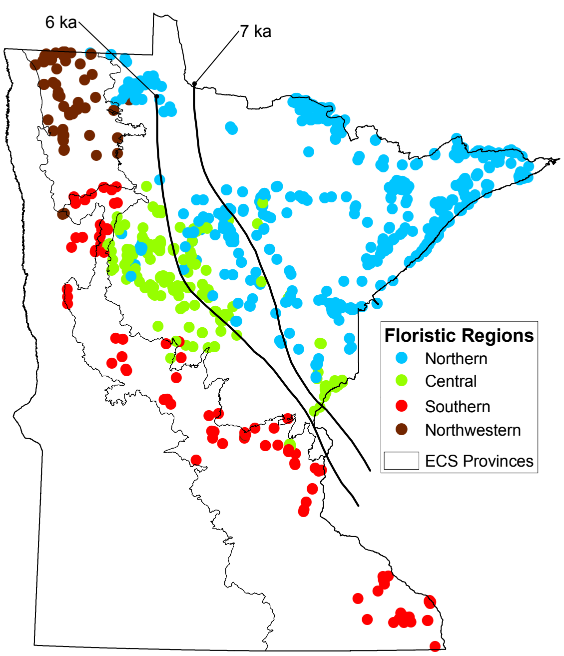

Fig. 7. Relevés in the Northern, Central, Southern, and Northwestern Floristic regions of the Fire-Dependent Forest/Woodland System in comparison with 20% isopolls for prairie-forb pollen at 6 ka and 7 ka (from Webb et al 1983). These isopolls track with the maximum northeastern extent of the prairie-forest border in Minnesota during the mid-Holocene epoch.

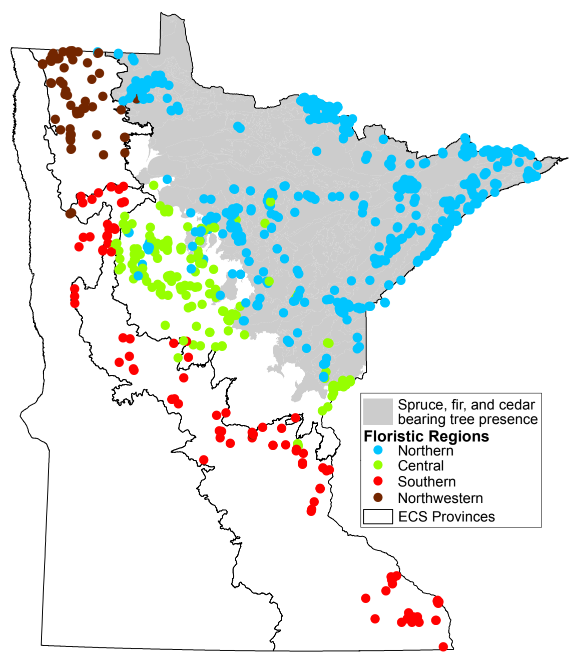

Fig. 8. The Northern Floristic Region of the Fire-Dependent Forest/Woodland System correlates with the distribution of balsam fir, white spruce, and white cedar bearing trees recorded in Minnesota by public land surveyors in the latter half of the 19th Century.

Great Plains species are widespread in the southwestern part of Minnesota, but are progressively restricted to Ecological Systems comprising the driest habitats (and characterized by constant disturbance from factors such as fire) as one moves to the northeast. Similar patterns have been described in Canada, where warmer sites within the boreal forest are often characterized by plant migrants from temperate forests and colder sites are frequented by arctic-alpine plants (Rowe 1956). Similarly, in Finland certain species common in northern forests, in the southern part of the country are restricted to bogs (Tonteri et al. 1990). In Minnesota, the differing geographic patterns of habitat distribution of boreal and plains species ensure that the boundaries of Floristic Regions for Ecological Systems on the dry end of the moisture gradient—such as Fire-Dependent Forests/Woodlands—are substantially different from those on the wet end of the moisture gradient, such as Wet Forests.

The MNDNR's native plant community classification is integrated with Minnesota's ecological land classification system (ECS). During the development of the plant community classification, ECS provinces and sections were used to geographically subset databases and to reduce gradients in the data related to broad patterns of climate. After the plant community classification was completed, ECS units were used to develop geographically delimited keys to Systems and Classes, under the premise that more localized keys are likely to be more accurate in the field. ECS units were also used to discuss distribution of soils characteristic of Native Plant Community Classes. In addition, the land type association level of Minnesota's ECS was used as the base unit for mapping the ranges of Native Plant Community Classes (MNDNR 2003, 2005a, 2005b). New understandings of patterns of vegetation in Minnesota gained in the development and application of the classification are likely to contribute to future refinement of the boundaries of the ECS units themselves.

The MNDNR's classification is one of the few examples in the United States of a classification developed collaboratively for application in sustainable ecosystem management, forest management, and biodiversity survey, research, monitoring, and conservation. The multiple levels built into the classification are intended to make it applicable at a variety of scales. The Ecological System has been a useful level for planning and vegetation management at the landscape scale. For example, the MNDNR has created maps of Ecological Systems within state parks to help with development of park management plans. The MNDNR's state parks are also being mapped to Native Plant Community Classes, including mapping of desired future condition in disturbed areas to guide restoration and management activities. The MNDNR's statewide biological survey is using the Native Plant Community Class, Type, and Subtype as standard units for mapping and description of native plant communities to aid in biodiversity conservation. The levels of Native Plant Community Class and Type have also been used to develop species lists for plant community restoration (Lane and Texler 2009). These lists are being applied by Soil and Water Conservation Districts, non-profit ecological restoration organizations, county and city park managers, county foresters, National Wildlife Refuge managers, and National Forest Service managers in restoration and management on both public and private lands. The MNDNR's Division of Forestry is developing silvicultural interpretations for each forested Native Plant Community Class to aid in forest stand inventory and management. The interpretations provide foresters with information on management options; natural disturbance regimes; stand dynamics; composition and structure of forest growth stages; and tree species behavior, including site suitability and regeneration. The information provided by classifying forest stands to Native Plant Community Class and understanding of the natural dynamics of the Class will ideally allow for stand management that requires the least amount of intervention and investment to achieve a desired condition. To facilitate application of the classification, the MNDNR holds annual training sessions in the use of plant community field guides. These sessions have been attended by natural resource managers from a wide variety of public and private natural resource organizations.

Among the tools commonly developed for application of habitat-type classifications to resource management in the United States are classifications of seral communities within habitat types and classifications of successional pathways. We did not explicitly develop classifications of seral communities within Native Plant Community Classes, the unit of our classification most analogous to habitat types. In some instances, however, the Native Plant Community Types delineated for forested Native Plant Community Classes may represent seral communities within a Class. In addition, we developed basic information on successional pathways within Native Plant Community Classes through analysis of Public Land Survey bearing-tree records (Almendinger 1996). By linking bearing-tree records for individual Public Land Survey section corners to specific Native Plant Community Classes, we identified growth stages for each Class that include tree canopy composition for young, mature, and (where applicable) old-growth stages, and for periods of transition between stages. These growth-stage analyses are being incorporated into management guidelines for stand treatments based on Native Plant Community Classes.

Conclusion

The development of a regional or large-scale plant community classification using analysis of vegetation plot data is time-intensive. In our experience, much of the challenge of such a project lies in the initial collection and management of data, in ironing out differences in philosophy of classification and method among different researchers, and in collectively wading through a long series of seemingly minor decisions necessary to keep the project moving forward. One of the most important parts of the process is familiarization with the dataset and screening of samples to create a geographically and ecologically balanced set of samples of sound taxonomy and representative of native plant communities. As has been stated by others (Williams [1967], for example), the results of any classification project are dependent on the intended use of the classification—there is no single correct classification of any set of samples. We attempted to develop a classification that is applicable both for conservation of native plant communities and for management of forests in Minnesota for timber and wildlife, among other uses. The classification has been applied to these ends for just a few years so its long-term effect is not established, but the classification has served as a tool for new avenues of communication among plant ecologists, foresters, and other resource scientists in Minnesota and has elicited new ways of thinking about vegetation in Minnesota and the factors that influence it. The process of developing the classification illuminated interesting vegetation patterns in Minnesota and has generated discussion about the causes of these patterns.

Acknowledgements

We thank Carmen Converse and Bonita Eliason of the MNDNR's Division of Ecological Resources and Alan Jones of the MNDNR's Division of Forestry for supporting the classification project through its 10 years. We are grateful to Professor C.R. Janssen of Utrecht University and Professor Edward J. Cushing of the University of Minnesota for their roles in introducing and promoting the use of the Braun-Blanquet approach for vegetation study in Minnesota. Don Faber-Langendoen of NatureServe participated in many discussions with us on the relationship of Minnesota's classification to the USNVC and also provided guidance on this manuscript. Many researchers in Minnesota contributed to the collection of the relevé data that enabled the development of the classification. Thomas R. Klein designed numerous graphics and several publications to facilitate understanding and use of the classification.

References

Almendinger, J.C. 1987. *A handbook for collecting relevé data in Minnesota.* Minnesota Department of Natural Resources, St. Paul, MN, US.

Almendinger, J.C. 1996. *Minnesota's bearing tree database.* Minnesota Department of Natural Resources, St. Paul, MN, US.

Bakuzis, E.V. 1959. *Synecological coordinates in forest classification and in reproductive studies.* Ph.D. thesis, University of Minnesota, St. Paul, MN, US.

Bakuzis, E.V. & Kurmis, V. 1978. Provisional list of synecological coordinates and selected ecographs of forest and other plant species in Minnesota. Staff Series Paper 5. Department of Forest Resources, University of Minnesota, St. Paul, MN, US.

Becking, R.W. 1957. The Zürich-Montpellier school of phytosociology. *The Botanical Review* 7: 411–488.

British Columbia Ministry of Forests and Range. Biogeoclimatic Ecosystem Classification and Ecology Research Program. URL: http://www.for.gov.bc.ca/hre/becweb/index.html (accessed April 22, 2010)

Cajander, A.K. 1926. The theory of forest types. *Acta Forestalia Fennica*: 29(3): 1–108.

Carleton, T.J., Stitt, R.H. & Nieppola, J. 1996. Constrained indicator species analysis (COINSPAN): An extension of TWINSPAN. *Journal of Vegetation Science* 7: 125–130.

Carmean, W.H. 1975. Forest site quality evaluation in the United States. *Advances in Agronomy* 27: 209–269.

Cleland, D.T., Hart, J.B., Host, G.E., Pregitzer, K.S. & Ramm, C.W. 1994. *Ecological classification and inventory system of the Huron-Manistee National Forest.* Eastern Region, Forest Service, U.S. Department of Agriculture, Milwaukee, WI, US.

Cleland, D.T., Avers, P.E., McNab, W.H., Jensen, M.E., Bailey, R.G., King, T. & Russell, W.E. 1997. National hierarchical framework of ecological units. In: Boyce, M.S. & Haney, A. (eds.) *Ecosystem management applications for sustainable forest and wildlife resources,* pp. 181–200. Yale University Press, New Haven, CT, US.

Coffman, M.S. & Willis, G.L. 1977. The use of indicator species to classify climax sugar maple and eastern hemlock forests in Upper Michigan. *Forest Ecology and Management* 1: 149–168.

Coffman, M.S., Alyanak, E., Kotar, J. & Ferris, J.E. 1984. *Habitat classification system field guide for upper peninsula of Michigan and northeast Wisconsin.* School of Forestry and Wood Products, Michigan Technological University, Houghton, MI, US.

Comer, P., Faber-Langendoen, D., Evans, R., Gawler, S., Josse, C., Kittel, G., Menard, S., Pyne, M., Reid, M., Schulz, K., Snow, K. & Teague, J. 2003. *Ecological systems of the United States: A working classification of U.S. terrestrial systems.* NatureServe, Arlington, VA, US.

Cook, J.E. 1996. Implications of modern successional theory for habitat typing: A review. *Forest Science* 42: 67–75.

Curtis, J.T. 1959. *The vegetation of Wisconsin: An ordination of plant communities.* University of Wisconsin Press, Madison, WI, US.

Daubenmire, R. 1952. Forest vegetation of northern Idaho and adjacent Washington, and its bearing on concepts of vegetation classification. *Ecological Monographs* 22(4): 301–330.

Daubenmire, R. 1976. The use of vegetation in assessing the productivity of forest lands. *The Botanical Review* 42(2): 115–143.

Daubenmire, R. & Daubenmire, J.B. 1968. *Forest vegetation of eastern Washington and northern Idaho.* Technical Bulletin 60. Reprinted 2002, Agricultural Experiment Station, Washington State University, Pullman, WA, US.

Daubenmire, R.F. 1936. The “Big Woods” of Minnesota: Its structure, and relation to climate, fire, and soils. *Ecological Monographs* 6: 233–268.

Dengler, J., Berg, C. & Jansen, F. 2005. New ideas for modern phytosociological monographs. *Annali di Botanica, Nuova Serie* 5: 49–66.

Dufrêne, M. & Legendre, P. 1997. Species assemblages and indicator species: The need for a flexible asymmetrical approach. *Ecological Monographs* 67(3): 345–366.

Faber-Langendoen, D., Tart, D.L. & Crawford, R.H. 2009. Contours of the revised U.S. national vegetation classification standard. *Bulletin of the Ecological Society of America* 90(1): 87–93.

Flora of North America Editorial Committee (eds.). 1993–. *Flora of North America north of Mexico.* 7+ vols. Oxford University Press, Oxford, UK and New York, NY, US.

Frey, T.E.A. 1978. The Finnish school and forest site-types. In: Whittaker, R.H. (ed.) *Classification of plant communities,* pp. 81–110. Dr. W. Junk Publishers, The Hague, NL.

Glaser, P.H., Wheeler, G.A., Gorham, E. & Wright, H.E., Jr. 1981. The patterned mires of the Red Lake peatland, northern Minnesota: Vegetation, water chemistry and landforms. *Journal of Ecology* 69: 575–599.

Gleason, H.A. & Cronquist, A. 1991. *Manual of vascular plants of northeastern United States and adjacent Canada.* 2nd ed. New York Botanical Garden, New York, NY, US.

Grigal, D.F. & Arneman, H.F. 1970. Quantitative relationships among vegetation and soil classifications from northeastern Minnesota. *Canadian Journal of Botany* 48: 555–566.

Grimm, E.C. 1983. Chronology and dynamics of vegetation change in the prairie-woodland region of southern Minnesota, USA. *New Phytologist* 93: 311–350.

Grimm, E.C. 1984. Fire and other factors controlling the Big Woods vegetation of Minnesota in the mid-nineteenth century. *Ecological Monographs* 54: 291–311.

Grossman, D.H., Faber-Langendoen, D., Weakley, A.S., Anderson, M., Bourgeron, P., Crawford, R., Goodin, K., et al. 1998. *The national vegetation classification system: Development, status, and applications.* Vol. 1 of *International classification of ecological communities: Terrestrial vegetation of the United States.* The Nature Conservancy, Arlington, VA, US.

Hanson, D.S. & Hargrave, B. 1996. Development of a multilevel ecological classification system for the state of Minnesota. *Environmental Monitoring and Assessment* 39: 75–84.

Harris, A.G., McMurray, S.C., Uhlig, P.W.C., Jeglum, J.K., Foster, R.F. & Racey, G.D. 1996. *Field guide to the wetland ecosystem classification for Northwestern Ontario.* Field Guide FG-01. Ontario Ministry of Natural Resources, Northwest Science & Technology, Thunder Bay, ON, CA.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research* 3: 329–382.

Heinselman, M.L. 1978. Fire in wilderness ecosystems. In: Hendee, J.C., Stankey, G.H. & Lucas, R.C. (eds.) *Wilderness management*, pp. 249–278. U.S. Department of Agriculture, Forest Service Miscellaneous Publication 1365. Government Printing Office, Washington DC, US.

Heinselman, M.L. 1996. *The Boundary Waters wilderness ecosystem.* University of Minnesota Press, Minneapolis, MN, US.

Hill, M.O. & Gauch, H.G. 1980. Detrended correspondence analysis: An improved ordination technique. *Vegetatio* 42: 47–58.

Host, G.E. & Pregitzer, K.S. 1991. Ecological species groups for upland forest ecosystems in northwestern lower Michigan. *Forest Ecology and Management* 43: 87–102.

Host, G.E. & Pregitzer, K.S. 1992. Geomorphic influences on ground-flora and overstory composition in upland forests of northwestern lower Michigan. *Canadian Journal of Forest Research* 22: 1547–1555.

Janssens, J.A., Noble, M.G. & Almendinger, J.C. 1997. *Key to peatland types in the Chippewa National Forest.* Report submitted to the USDA Forest Service. Chippewa National Forest, Forest Supervisor's Office, Cass Lake, MN, US.

Jennings, M.D., Faber-Langendoen, D., Loucks, O.L., Peet, R.K. & Roberts, D. 2009. Standards for associations and alliances of the U.S. National Vegetation Classification. *Ecological Monographs* 79: 173–199.

Jennings, M., Faber-Langendoen, D., Peet, R., Loucks, O., Glenn-Lewin, D., Damman, A., Barbour, M., et al. 2004. *Guidelines for describing associations and alliances of the U.S. national vegetation classification, version 4.0*. Vegetation Classification Panel, The Ecological Society of America, Washington DC, US.

Kimmins, J.P. 2004. *Forest ecology: A foundation for sustainable management.* 3rd ed. Prentice-Hall, Upper Saddle River, NJ, US.

Knollová, I., Chytrý, M., Tichý, L. & Hájek, O. 2005. Stratified resampling of phytosociological databases: Some strategies for obtaining more representative data sets for classification studies. *Journal of Vegetation Science* 16: 479–486.

Kotar, J. & Coffman, M. 1984. Habitat-type classification system in Michigan and Wisconsin. In: Bockheim, J.G. (ed.) *Forest land classification: Experiences, problems, perspectives; proceedings of a symposium held at the University of Wisconsin at Madison on March 18–20, 1984,* pp. 100–103. Department of Soil Science, University of Wisconsin, Madison, WI, US.

Kotar, J. & Burger, T.L. 1996. *Field guide to forest communities and habitat types of central and southern Wisconsin.* Department of Forestry, University of Wisconsin-Madison, Madison, WI, US.

Kotar, J. & Burger, T.L. 2000. *Field guide to forest habitat type classification for north central Minnesota.* Terra Silva Consultants, Madison, WI, US.

Kotar, J., Kovach, J.A. & Locey, C.T. 1988. Field guide to forest habitat types of northern Wisconsin. Department of Forestry, University of Wisconsin-Madison and Wisconsin Department of Natural Resources, Madison, WI, US.

Küchler, A.W. 1967. *Vegetation mapping.* Ronald Press Company, New York, NY, US.

Kuusipalo, J. 1985. An ecological study of upland forest site classification in southern Finland. *Acta Forestalia Fennica* 192: 1–77.

Lane, C.P. & Texler, H.D. 2009. Generating quantitative regional plant community descriptions for restoration. *Restoration Ecology* 17(1): 42–50.

Marshall, I.B. & Schut, P.H. 1999. *A national ecological framework for Canada: Overview.* Environmental Quality Branch, Ecosystems Science Directorate, Environment Canada and Research Branch, Agriculture and Agri-Food Canada. Ottawa, ON, CA. URL: http://sis.agr.gc.ca/cansis/nsdb/ecostrat/intro.html (accessed November 12, 2009)

Marschner, F.J. 1974. *The original vegetation of Minnesota, compiled from U.S. General Land Office Survey notes* [map]. 1:500,000. Redrafted from the 1930 original by P.J. Burwell and S.J. Haas under the direction of M.L. Heinselman. North Central Forest Experiment Station, United States Department of Agriculture, St. Paul, MN, US.

McNab, W.H., Cleland, D.T., Freeouf, J.A., Keys, J.E., Jr., Nowacki, G.J. & Carpenter, C.A. (compilers). 2007. *Description of ecological subregions: Sections of the conterminous United States* [CD-ROM]. Gen. Tech. Report WO-76B. Forest Service, U.S. Department of Agriculture, Washington, DC, US.

Minnesota Department of Natural Resources. 1993. *Minnesota's native vegetation: A key to natural communities, Version 1.5.* Biological Report No. 20. Natural Heritage Program, Minnesota Department of Natural Resources, St. Paul, MN, US.

Minnesota Department of Natural Resources. 2003. *Field guide to the native plant communities of Minnesota: The Laurentian Mixed Forest Province.* Ecological Land Classification Program, Minnesota County Biological Survey, and Natural Heritage and Nongame Research Program, Minnesota Department of Natural Resources, St. Paul, MN, US.

Minnesota Department of Natural Resources. 2005a. *Field guide to the native plant communities of Minnesota: The Eastern Broadleaf Forest Province.* Ecological Land Classification Program, Minnesota County Biological Survey, and Natural Heritage and Nongame Research Program, Minnesota Department of Natural Resources, St. Paul, MN, US.

Minnesota Department of Natural Resources. 2005b. *Field guide to the native plant communities of Minnesota: The Prairie Parkland and Tallgrass Aspen Parklands provinces.* Ecological Land Classification Program, Minnesota County Biological Survey, and Natural Heritage and Nongame Research Program, Minnesota Department of Natural Resources, St. Paul, MN, US.

Minnesota Department of Natural Resources. 2007. *A handbook for collecting vegetation plot data in Minnesota: The relevé method.* Minnesota County Biological Survey, Minnesota Natural Heritage and Nongame Research Program, and Ecological Land Classification Program, Biological Report 92. Minnesota Department of Natural Resources, St. Paul, MN, US. URL: http://www.dnr.state.mn.us/eco/mcbs/vegetation_sampling.html

Minnesota Department of Natural Resources. Ecological classification system. URL: http://www.mndnr.gov/ecs/index.html (accessed April 27, 2009)

Mueller-Dombois, D. & Ellenberg, H. 1974. *Aims and methods of vegetation ecology.* John-Wiley and Sons, New York, NY, US.

National Climatic Data Center. *Climate of Minnesota.* Climatography of the United States series no. 60, Climate of the states. Climate Services Branch, National Climatic Data Center, Asheville, NC, US. URL: http://cdo.ncdc.noaa.gov/climatenormals/clim60/states/Clim_MN_01.pdf (accessed October 6, 2009)

Outcalt, K.W. & White, E.H. 1981. Phytosociological changes in understory vegetation following timber harvest in northern Minnesota. *Canadian Journal of Forest Research* 11: 175–183.

Pfister, R.D. & Arno, S.F. 1980. Classifying forest habitat types based on potential climax vegetation. *Forest Science* 26(1): 52–70.

Poore, M.E.D. 1955a. The use of phytosociological methods in ecological investigations. I. The Braun-Blanquet System. *Journal of Ecology* 43: 226–244.

Poore, M.E.D. 1955b. The use of phytosociological methods in ecological investigations. II. Practical issues involved in an attempt to apply the Braun-Blanquet system. *Journal of Ecology* 43: 245–269.

Poore, M.E.D. 1955c. The use of phytosociological methods in ecological investigations. III. Practical application. *Journal of Ecology* 43: 606–651.

Poore, M.E.D. 1956. The use of phytosociological methods in ecological investigations. IV. General discussion of phytosociological problems. *Journal of Ecology* 44: 28–50.

Pregitzer, K.S. & Barnes, B.V. 1982. The use of ground flora to indicate edaphic factors in upland ecosystems of the Cyrus H. McCormick Experimental Forest, upper Michigan. *Canadian Journal of Forest Research* 12: 661–672.

Rodwell, J.S. (ed.). 1991–2000. *British plant communities.* 5 vols. Cambridge University Press, Cambridge, UK.

Rowe, J.S. 1956. Uses of undergrowth plant species in forestry. *Ecology* 37: 461–473.

Schaminée, J.H.J., Stortelder, A.H.F., Westhoff, V., Weeda, E.J. & Hommel, P.W.F.M. (eds.). 1995–99. De vegetatie van Nederland. Deel 1–5. Opulus Press, Uppsala, SE.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C. & Broderson, W.D. (eds.). 2002. *Field book for describing and sampling soils, Version 2.0.* Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE, US.

Sims, R.A., Towill, W.D., Baldwin, K.A., Uhlig, P. & Wickware, G.M. 1997. *Field guide to the forest ecosystem classification for Northwestern Ontario.* Ontario Field Guide FG-03. Northwest Science and Technology, Ontario Ministry of Natural Resources, Thunder Bay, ON, CA.

Smith, W. 2008. *Trees and shrubs of Minnesota.* University of Minnesota Press, Minneapolis, MN, US.

Tonteri, T., Mikkola, K. & Lahti, T. 1990. Compositional gradients in the forest vegetation of Finland. *Journal of Vegetation Science* 1: 691–698.

Wang, G.G. 2000. Use of understory vegetation in classifying soil moisture and nutrient regimes. *Forest Ecology and Management* 129: 93–100.

Waring, R.H. & Major, J. 1964. Some vegetation of the California coastal redwood region in relation to gradients of moisture, nutrients, light, and temperature. *Ecological Monographs* 34: 167–215.

Webb, T.III, Cushing, E.J. & Wright, H.E., Jr. 1983. Holocene changes in the vegetation of the Midwest. In: Wright, H.E., Jr. (ed.) *Late-Quaternary environments of the United States*, pp. 142–165. University of Minnesota Press, Minneapolis, MN, US.

Wellner, C.A. 1989. Classification of habitat types in the western United States. In: Ferguson, D.E., Morgan, P. & Johnson, F.D. (comp.) *Proceedings—Land classifications based on vegetation: Applications for resource management,* pp. 7–21. Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Ogden, UT, US.

Westhoff, V. & van der Maarel, E. 1978. The Braun-Blanquet approach. In: Whittaker, R.H. (ed.) *Classification of plant communities*, pp. 287–399. Dr. W. Junk Publishers, The Hague, NL; Boston, MA, US.

Wheeler, G.A., Cushing, E.J., Gorham, E., Morley, T. & Ownbey, G.B. 1992. A major floristic boundary in Minnesota: An analysis of 280 taxa occurring in the western and southern portions of the state. *Canadian Journal of Botany* 70: 319–333.

Whittaker, R.H. (ed.). 1978. *Classification of plant communities.* Dr. W. Junk Publishers, The Hague, NL.

Williams, W.T. 1967. Numbers, taxonomy, and judgment. *Botanical Review* 33(4): 379–386.

Zak, D.R., Pregitzer, K.S. & Host, G.E. 1986. Landscape variation in nitrogen mineralization and nitrification. *Canadian Journal of Forest Research* 16: 1258–1263.