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Coarse woody type: A new method for analyzing coarse woody debris and forest change

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Abstract

The species composition of both standing live and down dead trees has been used separately to determine forest stand dynamics in large-scale forest ecosystem assessments. The species composition of standing live trees has been used to indicate forest stand diversity while the species composition of down dead trees has been used to indicate wildlife habitat. To assess the ability of combined species information of standing live and down dead trees to indicate forest stand dynamics (i.e., successional trends), the species compositions of standing live trees and coarse woody debris (CWD) were compared using data from forest inventory plots across large-scales. Distinct differences were found between the species composition of standing live trees and that of CWD for nearly half of all study observations. However, there was no predictable shift in species composition along a defined forest succession trajectory with species composition shifts appearing to be successionally forward and backward depending on unique forest stand histories, CWD decay rates, stand structure, species composition, and site attributes. Suggested as a methodology complementary to other techniques such as historical stand reconstruction, differences in species composition of standing live and down dead trees may help indicate historical mortality patterns and successional directions of forest stands.
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Keywords: Coarse woody debris; Coarse woody type; Forest type; Stand reconstruction; Inventory

1. Introduction

Quantifying the attributes (e.g., species composition and density) of any forest stand through time helps refine understanding of stand dynamics (e.g., mortality patterns, succession, and growth). Techniques are available for estimating common stand attributes such as species composition and/or tree size distributions over time (Lorimer, 1985; Zhang et al., 2000; Frelich, 2002), but they are typically expensive or difficult to apply. Long-term forest inventory plots may be used to estimate historical stand attributes; however, plots must be remeasured with the same sample protocols over many decades. Historical stand reconstruction is another technique for estimating historic stand conditions. Stand reconstruction techniques include dendrochronological measurement of fire scars and increment cores from stumps, logs, and living trees; direct measurement of remnant woody evidence; backwards radial growth modeling (Fule et al., 1997; Huffman et al., 2001). The major limitation of historical stand reconstructions is their time consumption and limited spatial scope of application. The vast majority of forest historical information is extremely limited. If one were interested in the past species composition of stands, examination of the identifiable species of coarse woody debris (CWD) might indicate the prior species composition of a given stand. Coupling the identification of CWD species composition with current forest type assessments may be a relatively expeditious method that provides a preliminary assessment of species composition shifts across forest ecosystems.

Forest types (FT), otherwise known as forest cover types, are categories of forest defined by constituent vegetation (Eyre, 1980; Helms, 1998). The single attribute of forest vegetation often used as a delimiter of FT is the species composition of living tree volume/density present in the stand/plot being typed (Eyre, 1980; Helms, 1998). Additionally, FT may be defined either by current or potential vegetation (Daubenmire, 1968; Daniel et al., 1979). Large-scale forest inventories, such as the Forest Inventory and Analysis (FIA) program of the USDA Forest Service, use a definition of FT that deals mainly with the species composition of current tree volume on a plot:

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‘‘classification of forest land based on the species presently forming a plurality of the live-tree stocking’’ (Smith et al., 2001). FT information has been used for decades as a categorical variable for ecological analyses and forms the basis of numerous forest ecosystem analyses and inventory reports (USFS, 1965; Smith et al., 2001; Heinz Center for Science, 2002; Miles et al., 2003). Recent forest resource reports have placed further emphasis on FT analyses (Smith et al., 2001; Heinz Center for Science, 2002) because changes in FTs across the United States may indicate effects of urbanization and climatic variations (Iverson and Prasad, 1998).

The identifiable species composition of down dead trees is often omitted in forest inventories and subsequent analyses because forest typing procedures usually include only living trees. Down and dead trees (CWD) serve as critical habitat for numerous flora and fauna. Flora use the microclimate (moisture, shade, and nutrients) provided by CWD for establishing regeneration (Harmon et al., 1986). CWD provides a diversity (stages of decay, size classes, and species) of habitat for fauna ranging from large mammals to invertebrates (Maser et al., 1979; Harmon et al., 1986; Bull et al., 1997). Besides providing assessments of habitat, CWD may indicate temporal trends in species composition of any particular stand, possibly improving our understanding of stand dynamics (i.e., succession). Many CWD studies to date have quantified only the volumes, sizes, and diameters of CWD with incidental information about CWD species composition (for examples see Goodburn and Lorimer, 1998; Pedlar et al., 2002). Given the importance of CWD, a new categorical variable is proposed that may benefit both CWD assessments and overall inventory analyses. ‘‘Coarse woody type’’ (CWT) is defined as a broad categorization of the species composition of the dead and down tree volume in a forest stand. Because large-scale forest ecosystem assessments may be used to determine both FTs and CWTs on inventory plots, the FT and CWTs may be used separately or in combination to refine our understanding of forest attributes and stand dynamics.

The goal of this study was to determine if FT and CWT comparisons indicate forest ecosystem dynamics (i.e., succession or disturbance) in forests of the North Central United States. Specific objectives were: (1) to examine how CWTs vary by individual FTs across a range of broad forest type groups; (2) to determine if there are any differences in stand attributes (total stand basal area, forest type, stand age, proximity to roads, and site productivity) between observations where CWTs and FTs varied and observations where CWTs and FTs remained identical; (3) to determine if plot-level FT and CWT differences indicate ‘‘hotspots’’ of forest ecosystem disturbance or successional shifts.

2. Methods

2.1. Data

To compare FT and CWT for stands across forest ecosystems of the North Central United States, data from the FIA inventory program were used. CWD inventory data, along with corresponding tree and stand information, were obtained from forested FIA plots ($n = 338$) across Minnesota, Wisconsin, and Michigan during 2001–2003 (Fig. 1). Because there may be different FTs within an individual plot that consists of four spatially separated subplots, separate FTs by plot were treated as separate study observations. Therefore, the total number of observations in this study was 378 because 41 study plots had more than one FT (see forest condition mapping; Bechtold and Patterson, 2005). Because the FIA program adopted a new national sample design in 1999, there is a lack of remeasured plots that enables comparison of this study's findings with longer term plot-level forest type change information.

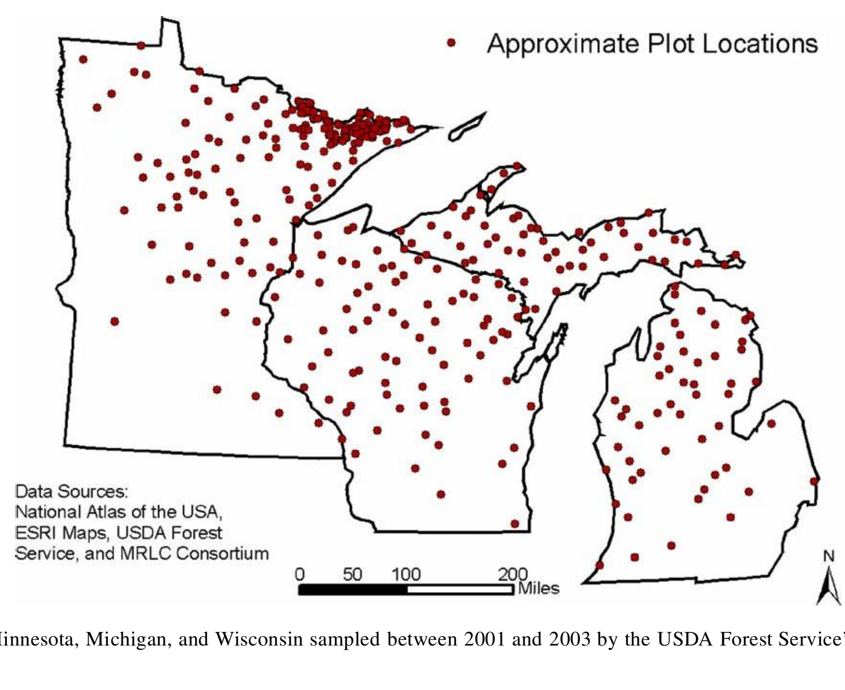

Fig. 1. Plot locations across Minnesota, Michigan, and Wisconsin sampled between 2001 and 2003 by the USDA Forest Service's Forest Inventory and Analysis program.

2.2. Field sample protocols

The FIA program conducts a three-phase inventory of forest attributes of the United States (Bechtold and Patterson, 2005). The FIA sampling design is based on a tessellation of the United States into hexagons approximately 2428 ha in size with at least one permanent plot established in each hexagon. In phase 1, the population of interest is stratified and plots are assigned to strata to increase the precision of estimates. In phase 2, tree and site attributes are measured for plots established in the 2428 ha hexagons. Phase 2 plots consist of four 7.32 m fixed-radius subplots on which standing trees are inventoried. Data used in this study from the second FIA phase were: number of standing trees per hectare (TPH); total standing tree basal area (m^2/ha); stand age (years); physiographic class (25 classes according to increasing water availability); stand quadratic mean diameter (QMD) (cm); distance to roads (nine classes according to distance to improved road from plot center) (for more information, see USDA, 2002).

In phase 3, a 1/16 subset of phase 2 plots are measured for forest health indicators such as down woody materials. Data from phase 3 inventory plots were used in this study to estimate down dead tree information. CWD are sampled during the third phase of the FIA inventory on transects radiating from each FIA subplot center (Woodall and Williams, 2005). As defined by FIA, CWD are down logs with a transect diameter $\geq$7.62 cm and a length $\geq$0.91 m. Information collected for every CWD piece intersected on each of three 7.32 m transects on each FIA subplot are: transect diameter; length; small-end diameter; large-end diameter; decay class; species; evidence of fire; presence of cavities. Transect diameter is the diameter of a down woody piece at the point of intersection with a sampling transect. Length is the length of each CWD piece between the small- and large-end diameters. Decay class is a subjective determination of the amount of decay present in an individual log. Decay class one is the least decayed (freshly fallen log), while decay class five is an extremely decayed log typically consisting of a pile of brown, cubicle rot. The species of each fallen log is identified through determination of species-specific bark, branching, bud, and wood composition attributes (excluding decay class five CWD pieces). If a CWD piece is too decomposed to identify its species, a hierarchy of species identification is followed: species; species group; conifer or hardwood; unknown (for CWD sample protocol details, see Waddell, 2002; Woodall and Williams, 2005).

2.3. Analysis

FTs were determined by forest typing algorithms currently used by FIA to fulfill program reporting requirements. The FT algorithm assigns FTs and FT groups according to the preponderance of stocking by individual species (Bechtold and Patterson, 2005). Stocking is based on an individual tree species, size, and crown class such that forest types essentially reflect the species dominating the majority of standing live volume. Inclusive FT groups were used in this study because of the numerous specific FTs across the North Central states (i.e., oak/hickory instead of red oak, post oak, etc.) (Table 1). The FT groups of this study were as follows: pine; spruce/fir; oak/hickory; elm/ash/cottonwood; maple/beech; aspen/birch (see Smith et al., 2001, pp. 43–44). A CWT was determined for each sample plot based on the species with the plurality of CWD volume per unit area. DeVries' (1986) line-intercept estimators (using small-end, large-end, and total length measurements) were used to determine CWD volume per hectare by species (for application, see Waddell, 2002). To match FT and CWTs, the same CWT groups were used as defined for FTs (Table 1). For additional information about the sample protocol and estimation procedures for the CWD sampled by FIA, see Woodall and Williams (2005). All study plots were stratified into two classes for analysis: (1) plots that had different CWTs and FTs; (2) plots that had the same CWTs and FTs (when the down dead tree biomass species composition type is equivalent to the standing live tree biomass species composition type).

To create a map of "hotspots" of differences in CWT and FT, inverse distance weighting interpolation (weighting power of 1 with inclusion of three nearest neighbors) of previously defined study strata (difference = 1; no difference = 2) was conducted using the approximate plot locations (coordinates

Table 1
Primary species constituents of forest and coarse woody types used in this study

Forest type group[a]	Predominant forest type group constituent tree species
Pines	Jack pine (*Pinus banksiana*), red pine (*Pinus resinosa*), eastern white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*)
Spruce/fir	Balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), red spruce (*Picea rubens*), black spruce (*Picea mariana*), tamarack (*Larix laricina*), northern white-cedar (*Thuja occidentalis*)
Oak/hickory	Post oak (*Quercus stellata*), northern red oak (*Quercus rubra*), white oak (*Quercus alba*), bur oak (*Quercus macrocarpa*), scarlet oak (*Quercus coccinea*), mockernut hickory (*Carya tomentosa*), pignut hickory (*Carya glabra*), sweetgum (*Liquidambar styraciflua*), sassafras (*Sassafras albidum*), yellow-poplar (*Liriodendron tulipifera*)
Elm/ash/cottonwood	American elm (*Ulmus Americana*), cottonwood (*Populus deltoides*), black ash (*Fraxinus nigra*), sycamore (*Plantanus occidentalis*), black willow (*Salix nigra*), green ash (*Fraxinus pennsylvanica*), white ash (*Fraxinus americana*), sugarberry (*Celtis laevigata*), hackberry (*Celtis occidentalis*), river birch (*Betula nigra*)
Maple/beech	Sugar maple (*Acer saccharum*), beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), red maple (*Acer rubra*), silver maple (*Acer saccharinum*), basswood (*Tilia americana*)
Aspen/birch	Aspen (*Populus tremuloides*), paper birch (*Betula papyrifera*), yellow birch (*Betula alleghaniensis*), balsam poplar (*Populus balsamifera*)

[a] See USDA (2002) and Miles et al. (2001).

Table 2
Number of observations by classes defined by current forest type group and coarse woody type

Current forest type	Coarse woody type					
	Pines	Spruce/fir	Oak/hickory	Elm/ash/cottonwood	Maple/beech	Aspen/birch
Pines	19	7	1	1	0	3
Spruce/fir	14	44	1	1	1	12
Oak/hickory	4	3	18	11	3	7
Elm/ash/cottonwood	2	6	4	10	5	3
Maple/beech	1	12	7	12	38	8
Aspen/birch	6	30	3	7	5	69
Total	46	102	34	42	52	102

perturbed as prescribed by law to preserve location confidentiality) of all observations using ARCGIS software (for plots with multiple observations, the strata values were averaged) (for interpolation technique details, see Johnston et al., 2001). Pixels (30 m × 30 m) with a mean value under 1.2 were assigned a high likelihood of a FT/CWT difference, pixels with values between 1.2 and 1.6 were assigned a moderate likelihood, and pixels with values over 1.6 were assigned a low likelihood. A nonforest mask was used to remove nonforest areas from the map based on classified 1992 National Land Cover Dataset (NLCD) imagery (Vogelmann et al., 2001).

3. Results

Of the 378 observations in this study, 183 (48%) had differences between current FT and CWT. By individual FT, the most common CWT was the same as the FT, with differing CWTs distributed among numerous CWTs (Table 2). For example, observations having an aspen/birch FT had CWTs including the entire range of possible CWTs (Table 2). The maple/beech, oak/hickory, and elm/ash/cottonwood FTs had the highest percentage of observations with differing CWTs (51, 61, and 67%, respectively) (Fig. 2).

Comparisons of stand and site attribute means among the two study strata (differences or no differences in FT and CWT by observation) indicated no significant differences in stand/site attributes. To streamline the dataset to FTs that exhibited the most differences between FT and CWTs, the same analysis was conducted using only the maple/beech, oak/hickory, and elm/ash/cottonwood types ($n = 154$). For these FTs, there were some differences in mean site/stand attributes among the study strata (Table 3). Plots showing a difference in FT and CWT had significantly younger mean stand age and smaller quadratic mean diameters than stands with no difference in FT and CWT ($p < 0.05$). Plots showing a difference in FT and CWT occurred on more mesic sites and had less stand basal area per hectare than plots where FT and CWT were the same ($p = 0.11$). There were no significant differences in the strata means for the stand/site attributes of distance to roads and standing trees per hectare.

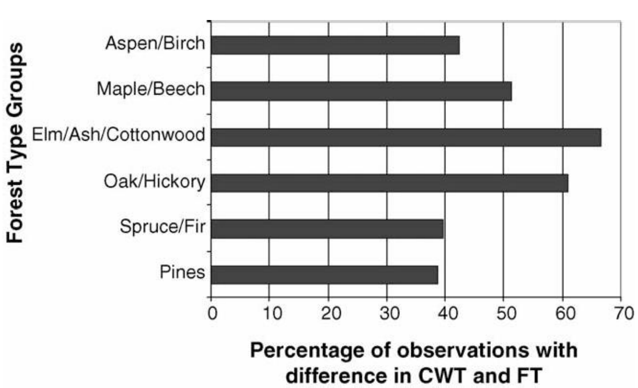

Fig. 2. Percentage of observations having a difference in forest type (FT) and coarse woody type (CWT) by forest type group.

Table 3
Means and associated sample size, standard errors, and p-value for the strata of "differences in forest and coarse woody type," and "no difference in forest and coarse woody type" for the maple/beech, oak/hickory, and elm/ash/cottonwood types

Stand/site attributes[a]	With difference in FT and CWT			No difference in FT and CWT			t-Test p-value
	Mean	n	Std. Err.	Mean	n	Std. Err.	
Distance to roads	4.41	88	0.19	4.67	66	0.20	0.35
Stand age (years)	63.23	88	2.75	75.73	66	3.31	< 0.01
Physiographic Class	22.73	88	0.57	21.58	66	0.44	0.11
Stand basal area (m^2/ha)	17.82	83	1.13	20.34	65	1.08	0.11
Stand trees (ha^{-1})	154.64	83	8.77	153.12	65	9.22	0.91
QMD (cm)	24.43	83	0.55	26.78	65	0.59	< 0.01

[a] Variables are categorical where units not indicated.

The map of interpolated probabilities of differences in FT and CWT can indicate areas where forests may be changing species composition at a relatively fast rate, although the IDW model root mean square error of 0.58 indicates a statistically weak spatial relationship among plots (Fig. 3). The areas with the highest likelihood of a difference in FT and CWT appear randomly dispersed. Although forest areas in central Michigan had a large number of plots with differences in FT and CWT, patches of differences were identified across all the forest ecosystems of the upper Great Lakes.

4. Discussion

In this study, nearly half of all observations (48%) had a CWT that was different from its corresponding FT. This result

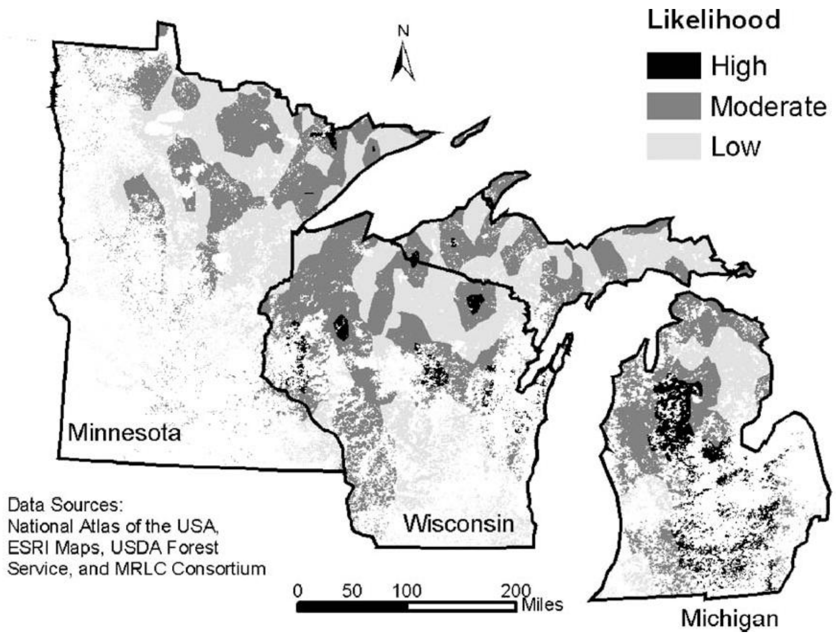

Fig. 3. Likelihood of differences in forest type (FT) and coarse woody type (CWT) across the forests of upper Great Lakes.

indicates a shift in forest species composition at the scale of the individual stand across the upper Great Lakes states during the past several decades. The elm/ash/cottonwood and oak/hickory FTs had the highest rates of differences in FT and CWT, indicating the possible regional development of forests from elm/ash/cottonwood and oak/hickory toward later successional types of spruce/fir and maple/beech (Pallardy et al., 1988; Abrams and Downs, 1990). This may be the result of gap dynamics within the elm/ash/cottonwood and oak/hickory FTs where smaller gaps created by individual treefalls result in future dominance by more shade tolerant species (i.e., *Acer* spp.) while canopy removal and larger gaps may facilitate perpetuation and self-replacement of oak and associated shade midtolerant species (Hibbs, 1982; Abrams and Downs, 1990; Shotola et al., 1992; Taylor and Lorimer, 2003; Abrahamson and Gohn, 2004). However, at the individual FT/CWT level, there was no direction of species composition shifts. For example, 46 observations had a pine CWT, indicating that these stands were primarily composed of pines in the past. Currently, 41% of these stands are still composed of pines, while 30% have become spruce/fir and 13% have become dominated by aspen/birch. The shift of pine communities toward spruce/fir types may be considered forward succession while pine community shifts toward aspen/birch may be considered backward succession because aspen represents an early successional condition, with dominance resulting from possible repetitive stand-replacing burns (Abrams et al., 1985; Frelich and Reich, 1995a). If pine stands were subjected to severe disturbances such as wind events, fire, and/or harvest activities, one might expect the influx of early seral species (aspen and jack pine) which may be considered self-replacement, while the continuation of stand development and density induced mortality may allow late successional species (spruce, fir, and birch) to establish (Abrams and Scott, 1989; Frelich and Reich, 1995b). Overall, differences in FT and CWT indicate there is no region-wide predictable shift in species composition along a defined forest succession trajectory. Rather, species composition shifts appear to be successionally forward and backward depending on unique forest stand histories, stand structure, species composition, and site attributes (Abrams et al., 1985; Abrams and Scott, 1989; McCune and Cottam, 1985).

Results weakly indicated that observations that had a difference in FT and CWT have current stand structures that are usually younger, less dense, on wetter sites, and with a smaller quadratic mean diameter. Therefore, one might expect differences in FT and CWT in stands that were recently disturbed on more productive sites where stand development may occur at a faster rate (Oliver and Larson, 1996). The nonsignificant p-values for a majority of the t-tests among strata means indicate that the possibility of both forward and backward successional trends confounds any clear conclusions. Old stands might have CWTs that are different from their FT because of a species shift towards late successional species. In contrast, the standing live trees in young stands may be entirely composed of pioneer species with the remnants of a previous forest lying on the forest floor from a disturbance. However, despite confounding factors, it does appear that forests sampled in this study are predominantly experiencing species shifts due to stand-level disturbances, rather than latter stages of stand development due to the younger age of stands with FT and CWT differences.

A map of the forest areas where species differences between FT and CWT are the greatest may indicate areas of recent shifts in species composition. Our study found the highest likelihood of differences in CWT and FTs in the central hardwood regions of Wisconsin and Michigan and in coniferous forests of northern Minnesota. While differences in northern Minnesota may be attributable to blowdown effects (for blowdown information see USDA, 2001), the species composition shifts of central hardwoods may be due to advancing ages of hardwood stands regionally. However, maps of interpolated FT and CWT differences will not indicate smaller scale changes across forest ecosystems (i.e., local scales where no plots may be located), and other interpolation techniques maybe superior to inverse distance weighting (e.g., kriging).

Preliminary determination of a CWT by using existing CWD data collected on FIA inventory plots provides an initial framework for developing a formal coarse woody typing algorithm. However, there are many challenges to the development of a coarse woody typing algorithm using FIA data. CWTs may resemble no current FT, especially in forests with a coarse woody species composition that resembles no current tree species community. Another major hurdle is trying to incorporate the uncertainty in species identification and the effect of decay into CWT typing algorithms. Field crews may readily identify the species of some CWD pieces, but may be unable to identify some CWD pieces due to excessive decay. Additionally, there is more certainty in the species identification of a freshly fallen (decay class one) CWD piece than in the identification of a partially rotten (decay class four) CWD piece. Because climate affects coarse woody decay rates, a spatial bias to coarse woody typing algorithms should be acknowledged in large-scale assessments using this study's methodology. Plots located in Minnesota or Wisconsin may have older logs of previous FTs that occupied the plot as opposed to plots in Florida where decay rates are faster, resulting in less chance of CWTs differing from those of current FTs in Florida. Finally, crew measurement error may affect CWD species identification in certain FTs. Some FTs may have CWD that decays rather rapidly, while other FTs in adjacent areas may have CWD that is more resistant to decay. Therefore, field crews may have more uncertainty with species identification in forests with rapidly decaying CWD than in other forests with more decay resistant species such as black walnut (*Juglans nigra*). Although there are ecological and technical limitations to the creation of coarse woody typing algorithms, the possible benefits from a new forest ecosystem indicator warrant future algorithm development.

5. Conclusions

CWTs may give forest ecologists and inventory analysts another categorical variable useful for understanding forest change. Study results suggest that comparisons between FTs and CWTs may serve as an indicator of species composition shifts at landscape scales. Additionally, FTs and CWTs may refine analysis of the complex stand dynamics of the diverse tree species communities in the forests of the upper Lake States. Together with historical stand reconstruction techniques and long-term inventory plot monitoring, methods presented in this study may improve foresters' ability to assess forest change. If CWD species composition can indicate the historical species composition of any particular stand, then CWTs may provide opportunities to refine our understanding of CWD and its role as an indicator of forest health and change.

References

Abrahamson, W.G., Gohn, A.G., 2004. Classification and successional changes of mixed-oak forests at the Mohn Mill Area, Pennsylvania. Castanea 69, 194–206.

Abrams, M.D., Sprugel, D.G., Dickmann, D.I., 1985. Multiple successional pathways on recently disturbed jack pine sites in Michigan. For. Ecol. Manage. 10, 31–48.

Abrams, M.D., Scott, M.L., 1989. Disturbance-mediated accelerated succession in two Michigan forest types. For. Sci. 35, 42–49.

Abrams, M.D., Downs, J.A., 1990. Successional replacement of old-growth white oak by mixed mesophytic hardwoods in southwestern Pennsylvania. Can. J. For. Res. 20, 1864–1870.

Bechtold, W.A., Patterson, P.L. (Eds.), 2005. The enhanced Forest Inventory and Analysis program—national sampling design and estimation procedures. USDA Forest Service General Technical Report SRS-80. Asheville, NC.

Bull, E.L., Parks, C.G., Torgersen, T.R., 1997. Trees and logs important to wildlife in the Interior Columbia River Basin. USDA Forest Service General Technical Report PNW-391, Portland, OR.

Daniel, T.W., Helms, J.A., Baker, F.S., 1979. Principles of Silviculture, second ed. McGraw-Hill, New York.

Daubenmire, R.F., 1968. Plant Communities, a Textbook of Plant Synecology. Harper and Row, New York.

DeVries, P.G., 1986. Sampling Theory for Forest Inventory: A Teach-Yourself Course. Line-Intersect Sampling. Springer-Verlag, Berlin (Chapter 13).

Eyre, F.H. (Ed.), 1980. Forest Cover Types of the United States and Canada. Society of American Foresters, Washington, DC.

Frelich, L.E., 2002. Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen-deciduous Forests. Cambridge University Press, Cambridge, UK.

Frelich, L.E., Reich, P.B., 1995a. A spatial patterns and succession in a Minnesota southern-boreal forest. Ecol. Monogr. 65, 325–346.

Frelich, L.E., Reich, P.B., 1995b. Neighborhood effects, disturbance, and succession in forests of the western Great Lakes Region. Ecoscience 2, 148–158.

Fule, P.Z., Covington, W.W., Moore, M.M., 1997. Determining reference conditions for ecosystem management in southwestern ponderosa pine forests. Ecol. Appl. 7, 895–908.

Goodburn, J.M., Lorimer, C.G., 1998. Cavity trees and coarse woody debris in old growth and managed northern hardwood forests in Wisconsin and Michigan. Can. J. For. Res. 28, 427–438.

Harmon, M.E., Franklin, J.F., Swanson, F.J., et al., 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15, 133–302.

Heinz III, H.J., Center for Science, 2002. The State of the Nation's ecosystems: Measuring the Lands, Waters, and Living Resources of the United States. New York, NY, Cambridge University Press.

Helms, J.A. (Ed.), 1998. The Dictionary of Forestry. Society of American Foresters, Bethesda, MD.

Hibbs, D.E., 1982. Gap dynamics in a hemlock-hardwood forest. Can. J. For. Res. 12, 522–527.

Huffman, D.W., Moore, M.M., Covington, W.W., Crouse, J.E., Fule, P.Z., 2001. Ponderosa pine forest reconstruction: comparisons with historical data. In: USDA Forest Service Proceedings P-22, Fort Collins, CO, pp. 3–7.

Johnston, K., Ver Hoef, J.M., Krivoruchko, K., Lucas, N., 2001. Using ArcGIS Geostatistical Analyst. ESRI, Redlands, CA.

Iverson, L.R., Prasad, A.M., 1998. Predicting abundance of 80 tree species following climate change in the eastern United States. Ecol. Monogr. 68, 465–485.

Lorimer, C.G., 1985. Methodological considerations in the analysis of forest disturbance history. Can. J. For. Res. 15, 200–213.

Maser, C., Anderson, R.G., Cromack, K., Jr., et al., 1979. Dead and down woody material. In: Thomas, J.W. (Tech. Ed.), Wildlife Habitats in Managed Forests: The Blue Mountains of Oregon and Washington. USDA Forest Service Agricultural Handbook 553, Washington, DC, pp. 78–95.

McCune, B., Cottam, G., 1985. The successional status of a southern Wisconsin oak woods. Ecology 66, 1270–1278.

Miles, P.D., Brand, G.J., Mielke, M.E., 2003. Minnesota's forest resources in 2002. USDA Forest Service General Technical Report NC-218, St. Paul, MN.

Miles, P.D., Brand, G. J., Alerich, C.L., Bednar, L.F.; Woudenberg, S.W., Glover, J.F., Ezell, E.N., 2001. The forest inventory and analysis database description and users manual version 1.0. USDA Forest Service General Technical Report NC-218, St. Paul, MN.

Oliver, C.D., Larson, B.C., 1996. Forest Stand Dynamics. John Wiley and Sons, New York.

Pallardy, S.G., Nigh, T.A., Garrett, H.E., 1988. Changes in forest composition in central Missouri: 1968–1982. Am. Midl. Nat. 120, 380–390.

Pedlar, J.H., Pearce, J.L., Venier, L.A., McKenney, D.W., 2002. Coarse woody debris in relation to disturbance and forest type in boreal Canada. For. Ecol. Manage. 158, 189–194.

Shotola, S.J., Weaver, G.T., Robertson, P.A., Ashby, W.C., 1992. Sugar maple invasion of an old-growth oak-hickory forest in southwestern Illinois. Am. Midl. Nat. 127, 125–138.

Smith, B.W., Vissage, J.S., Dar, D.R., Sheffield, R.M., 2001. Forest resources of the United States, 1997. USDA Forest Service General Technical Report NC-219, St. Paul, MN.

Taylor, S.O., Lorimer, C.G., 2003. Loss of oak dominance in dry-mesic deciduous forests predicted by gap capture methods. Plant Ecol. 167, 71–88.

USDA Forest Service, 1965. Timber trends in the United States. USDA Forest Service Research Report 17.

USDA Forest Service, 2001. Final environmental impact statement for the Boundary Waters Canoe Area Wilderness fuel treatments, vol. 1. USDA Forest Service, Superior National Forest Eastern Region. Milwaukee, WI.

USDA Forest Service North Central Research Station, 2002. Forest inventory and analysis national core field guide, vol. II: Field data collection procedures for phase 3 plots. Version 1.6. Section 14. St. Paul, MN, pp. 265–298.

Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., van Driel, N., 2001. Completion of the 1990s National land cover data set for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources. Photogramm. Eng. Remote Sens. 67, 650–662.

Waddell, K.L., 2002. Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecol. Ind. 1, 139–153.

Woodall, C.W., Williams, M.S., 2005. Sampling, estimation, and analysis procedures for the Down Woody Materials indicator. USDA Forest Service, General Technical Report NC-256, St. Paul, MN.

Zhang, Q., Pregitzer, K.S., Reed, D.D., 2000. Historical changes in the forests of the Luc District of the Upper Peninsula of Michigan. Am. Midl. Nat. 143, 94–110.