Ecological Applications, 8(4), 1998, pp. 1072–1083

INTEGRATION OF GIS DATA AND CLASSIFIED SATELLITE IMAGERY FOR REGIONAL FOREST ASSESSMENT

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Abstract. New methods are needed to derive detailed spatial environmental data for large areas, with the increasing interest in landscape ecology and ecosystem management at large scales. We describe a method that integrates several data sources for assessing forest composition across large, heterogeneous landscapes. Multitemporal Landsat Thematic Mapper (TM) satellite data can yield forest classifications with spatially detailed information down to the dominant canopy species level in temperate deciduous and mixed forests. We stratified a large region (10^6 ha) by ecoregions (10^3–10^4 ha). Within each ecoregion, plot-level, field inventory data were aggregated to provide information on secondary and subcanopy tree species occurrence, and tree age class distributions. We derived a probabilistic algorithm to assign information from a point coverage (forest inventory sampling points) and a polygon coverage (ecoregion boundaries) to a raster map (satellite land cover classification). The method was applied to a region in northern Wisconsin, USA. The satellite map captures the occurrence and the patch structure of canopy dominants. The inventory data provide important secondary information on age class and associated species not available with current canopy remote sensing. In this way we derived new maps of tree species distribution and stand age reflecting differences at the ecoregion scale. These maps can be used in assessing forest patterns across regional landscapes, and as input data in models to examine forest landscape change over time. As an example, we discuss the distribution of eastern white pine (*Pinus strobus*) as an associated species and its potential for restoration in our study region. Our method partially fills a current information gap at the landscape scale. However, its applicability is also limited to this scale.

Key words: associated species; data integration; ecoregion; Forest Inventory and Analysis; forest inventory; forest landscape modeling; Geographic Information Systems; Landsat Thematic Mapper; satellite forest classification; secondary species; stand age; subcanopy.

INTRODUCTION

An ideal data source or map for the analysis of forest ecosystems would contain high-resolution spatial information for (a) dominant canopy tree species, (b) associated tree species, and (c) forest stand parameters (e.g., age). Such maps do not exist in digital format for large areas. The goal of our study was to derive a detailed forest map suitable for differentiating among ecoregions (10^3–10^4 ha) within a large, heterogeneous landscape (10^6 ha). The data would be used in assessing regional forest patterns for making resource management decisions and as input for a large-scale, forest landscape simulation model (Mladenoff et al. 1996, He and Mladenoff 1999).

We integrated several data sources for forest mapping at the landscape scale. Classified satellite imagery and forest field inventories have been widely used in forest mapping, but both have shortcomings as spatial data over large areas. Remote sensing of forest ecosystems has been the subject of many studies (e.g., Franklin et al. 1986, Bauer et al. 1994, Woodcock et al. 1994). Satellite imagery is used because it covers large areas (e.g., 32 400 km^2 for one Landsat Thematic Mapper [TM] scene) at high spatial resolution (e.g., 30 m for Landsat TM). Current satellite imagery allows forest classification at the dominant species level, if multiple image dates are used, with an accuracy range of 70–95% (Wolter et al. 1995). The presence of understory vegetation in satellite imagery is generally treated as a source of noise that complicates classification (Spanner et al. 1990). Remote sensing classifications have not been able to provide detailed information on forest understory (Stenback and Congalton 1990, Ghitter et al. 1995, Woodcock et al. 1996).

Estimating forest stand parameters such as age from satellite imagery also faces limitations. In coniferous forests of the western United States, forest age and basal area can be separated into several broad classes (Franklin 1986, Cohen et al. 1995). Crown closure can be successfully mapped, but crown size classes are difficult to separate (Woodcock et al. 1994). Mapping of successional stages is limited to three or four classes (Hall et al. 1991, Fiorella and Ripple 1993). In the

Manuscript received 27 May 1997; revised 29 November 1997; accepted 5 January 1998.

eastern United States, where there is less structural and age range in forest trees, deriving age and size classes from satellite imagery is even less successful (Mladenoff and Host 1994).

Plot-level forest inventories are representative field samples of forest stands for which a variety of parameters are monitored, including associated species and stand age, often over large areas (Birdsey and Schreuder 1992). The most comprehensive forest inventory for the eastern United States is the Forest Inventory and Analysis data set (FIA; Hahn and Hansen 1985). Forest inventory data have been used to predict present and future tree species ranges over the Eastern United States (Iverson and Prasad 1998). The FIA data are limited in their spatial resolution, with 0.4-ha (1-acre) sampling plots, located on the landscape at a density of 1–2 plots/10 km^2. For forest assessments beyond single stands, the FIA sample points need to be aggregated into spatial units such as counties, states, or ecoregions. Ecoregions are areas that may be defined hierarchically at a range of scales, and that are delineated according to their relatively homogeneous characteristics of soils, physiography, and climate (Bailey 1988, Host et al. 1996). Ecoregions are suitable ecological units for aggregating FIA data because of these relatively homogenous environmental characteristics.

On their own, neither satellite-derived forest maps nor forest inventories provide the input necessary for forest landscape modeling. The integration of satellite forest classifications and FIA improves the applicability of both (Lachowski et al. 1992). In our study, we describe how these different data sources can be integrated. Our approach was to derive distributions of age classes and associated species for each dominant tree species mapped in a species-level forest classification by Wolter et al. (1995). These distributions were derived from the FIA data for each of the ecoregions delineated by Host et al. (1996). A probabilistic algorithm then assigned age and associated species for each dominant species pixel, based on their likelihoods of occurrence. We discuss the relevance of the resulting maps for ecosystem management and forest landscape modeling using eastern white pine (*Pinus strobus*) as an example.

Study Region

Our study region is situated in the western part of the Northern Hardwood and Conifer Forest Region of the northern Lake States (Fig. 1), a transitional zone between boreal forests to the north and temperate forests to the south (Pastor and Mladenoff 1992). Tree species diversity is relatively high, with species of both the northern and southern zones. Additionally, species characteristic of the Northern Hardwoods region itself, such as eastern white pine, eastern hemlock (*Tsuga canadensis*), and yellow birch (*Betula alleghaniensis*) reach their maximum importance in this region (Mladenoff and Pastor 1993).

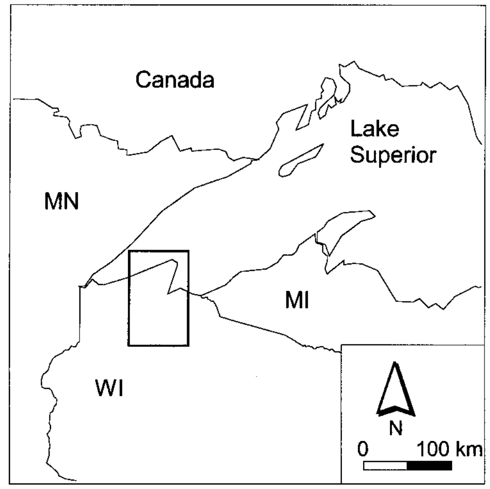

FIG. 1. Study area location (rectangle; size ~29 000 km^2) in the U.S. Midwest (MN = Minnesota, WI = Wisconsin, MI = Michigan).

The physiography and soils of the study region vary from nutrient-poor sands on glacial outwash plains, to silty loams on moraines, and heavy clays of former lake beds. Quaternary geology and mesoclimatic gradients are the greatest determinants of environmental variation in the region, leading to a wide range of different ecosystems. Forests are dominated by hemlock, sugar maple (*Acer saccharum*), trembling aspen (*Populus tremuloides*), white pine, red pine (*Pinus resinosa*), and jack pine (*P. banksiana*), on a gradient from mesic to xeric sites. Less important tree species found along the same gradient are balsam fir (*Abies balsamea*), yellow birch, northern red oak (*Quercus rubra*), big-toothed aspen (*Populus grandidentata*), and pin oak (*Q. ellipsoidalis*) (Curtis 1959).

The landscape-scale forest variation is accompanied by fine-scale variation due to local topography. Topographic relief is moderate (usually <200 m); plains and rolling hills dominate the landscape. The high groundwater table results in lowland stands in glacial depressions dominated by tamarack (*Larix laricina*), black spruce (*Picea mariana*), and white cedar (*Thuja occidentalis*).

The region was extensively altered since European settlement, with large-scale, destructive logging occurring from the mid-1800s to the early 1900s. Repeated severe fires followed logging, and portions of the landscape were in agricultural use at some point in time. Today forests are largely young second and third growth. Tree species composition, age class distribution, and landscape structure are severely altered from the presettlement landscape (Flader 1983, Mladenoff and Pastor 1993, Mladenoff et al. 1993, Pastor and Mladenoff 1993).

Methods

For our study we assumed that for each dominant tree species, its age classes and associated species can

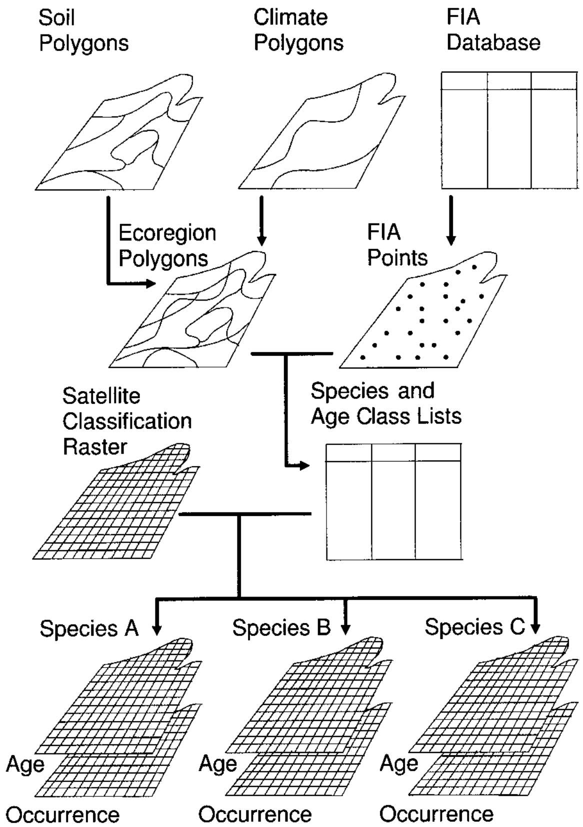

FIG. 2. Flow chart of the data integration algorithm.

be estimated from the FIA database, that they differ between ecoregions, and that this information can be assigned as additional attributes to the satellite classification. Ecoregions were derived from several environmental data layers, and the FIA sampling points were grouped by these ecoregions. Next, we derived the likelihood of age class and associated species occurrence for each of the dominant species mapped in the satellite classification by Wolter et al. (1995). Finally, we assigned age and associated species to each pixel of the satellite classification by using a probabilistic algorithm.

Input data layers

Regional ecosystem classification.—The study region was stratified into smaller ecoregions (10^3–10^4 ha) based on climate and soils (Host et al. 1996). The ecoregion classification was based on a quantitative approach that combines high-resolution climatic data (ZedX 1994), and the state soil geographic database (STATSGO; Soil Survey Staff 1992) (Fig. 2). STATSGO is a generalized soil map with a hierarchical database that contains, for instance, soil components and soil series (Lytle et al. 1996). Quaternary geology and mesoclimatic gradients are the greatest determinants of environmental variation in the region. Soils include very well-drained sandy soil in ecoregions 5 and 9, moderate to well-drained silty clay in ecoregion 8, moderate to well-drained silt in ecoregion 2, well-drained loamy soil in ecoregions 4 and 7, and loam to silty loam soil in ecoregions 10 and 11 (Fig. 3a) (Host et al. 1996). Climatic gradients are mainly due to the influence of Lake Superior, which causes higher precipitation and slightly moderated temperatures in the northern part of our study region. Ecoregion boundaries correspond well with the landscape scale patterns apparent in the dominant forest types from the TM classification (Fig. 3a).

Forest inventory and analysis eastwide database.—The Forest Inventory and Analysis (FIA) data are based on a representative sample of forest stands (Hansen et al. 1992). The Eastwide Data Base (EWDB) contains standardized FIA data for 37 eastern states of the United States (Hahn and Hansen 1985). At the plot level >30 forest stand attributes are recorded, such as current stand type, stand age, species basal area, stand size, slope and aspect. Plot locations have geographic coordinates so that a spatial point coverage of the plots can be generated. Individual tree data, such as species and size, are also recorded in each plot (Hansen et al. 1992).

Satellite forest classification.—The basic forest cover map for our analysis was a dominant species-level forest classification created by Wolter et al. (1995). They used differences in tree species phenology captured in a series of Landsat TM and MSS satellite images from throughout the growing season. Forest types were classified with an overall accuracy of 83.2%. Eleven classes representing dominant tree species and other forest types were mapped as species groups (Wolter et al. 1995).

Integrating FIA, satellite forest map, and ecoregion classification

Integrating the spatial distribution of canopy dominants from the satellite forest map with additional information from the FIA database (associated tree species and age) by ecoregion requires combining the three data coverages: a point coverage (FIA), a polygon coverage (ecoregions) and a raster map (satellite classification) (Fig. 2). The data were integrated in three steps:

1) the dominant species satellite map was stratified by ecoregions;

2) information on subdominant species and age class was extracted from FIA and aggregated for each ecoregion;

3) the information was combined with the satellite-derived forest map to create a new coverage.

Integrating the satellite forest map with the ecoregion classification.—We focused on upland species, and partially aggregated the satellite classification of Wolter et al. (1995). All lowland forests and wetland classes were combined into one class (''lowland''), and all nonforest types were merged as well. Furthermore, mixed forest classes were aggregated with the class of

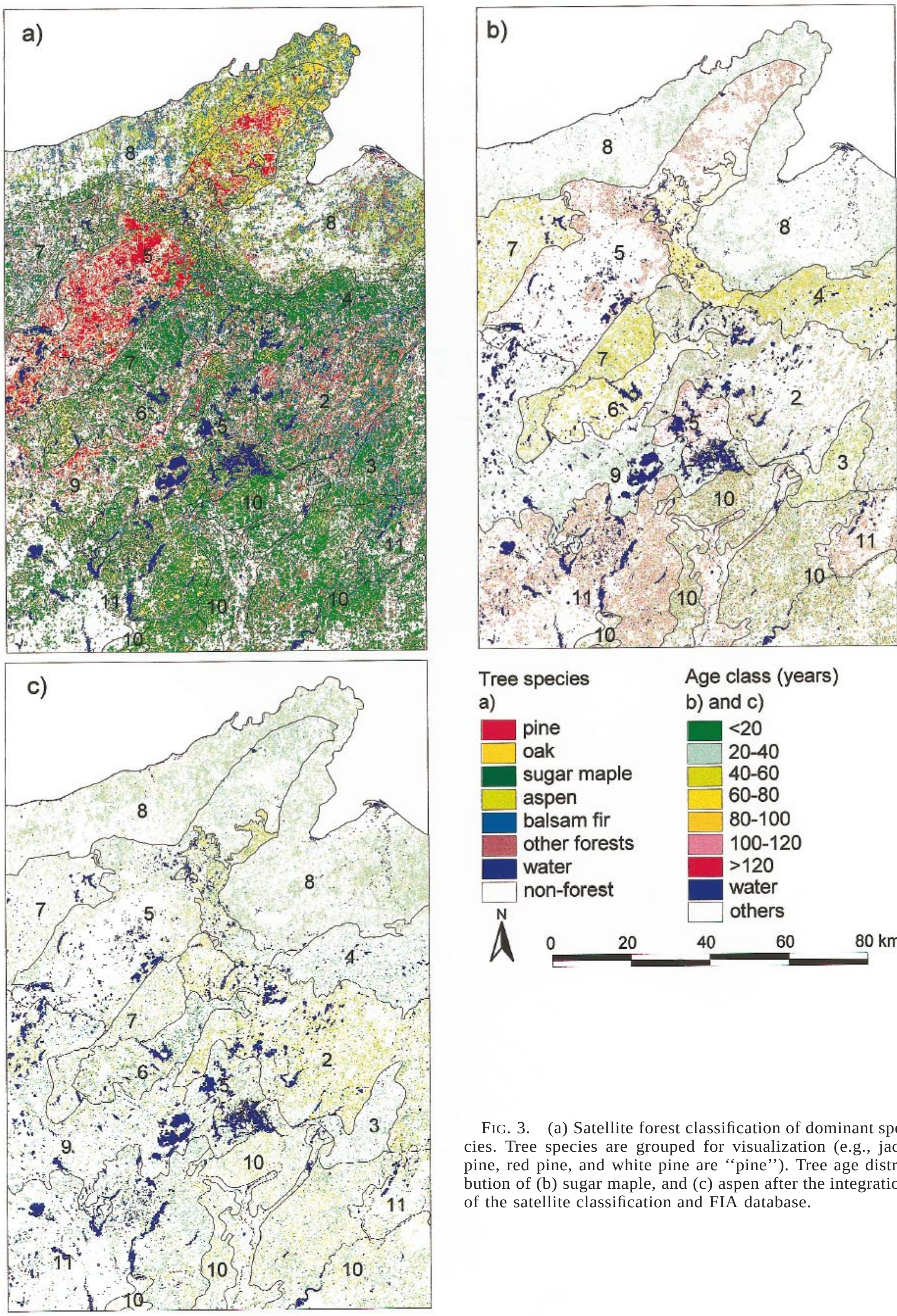

FIG. 3. (a) Satellite forest classification of dominant species. Tree species are grouped for visualization (e.g., jack pine, red pine, and white pine are "pine"). Tree age distribution of (b) sugar maple, and (c) aspen after the integration of the satellite classification and FIA database.

TABLE 1. Percentage occurrence of dominant tree species according to the tree species forest classification based on Landsat imagery (Wolter et al. 1995).

Species†	Ecoregion									
	2	3	4	5	6	7	8	9	10	11
Red pine	4	2	3	8	2	0	1	6	1	1
Jack pine	5	2	2	25	3	1	0	12	1	1
White pine	3	2	2	2	2	1	2	2	0	0
Quaking aspen	8	14	10	12	16	11	38	15	10	7
Big-toothed aspen	2	0	0	2	4	2	7	3	3	2
Paper birch	3	8	4	1	2	1	2	1	6	3
Hemlock/Yellow birch	2	1	2	1	0	0	0	1	1	0
Sugar maple	39	50	58	18	44	60	14	33	71	68
Red maple	0	0	0	0	0	0	0	0	0	0
Red oak	4	1	2	12	14	9	10	9	2	13
Pin oak	3	1	1	5	2	0	1	5	1	1
Balsam fir	27	19	19	13	12	14	24	13	5	6

† Red pine (*Pinus resinosa*), jack pine (*P. banksiana*), white pine (*P. strobus*), quaking aspen (*Populus tremuloides*), big-toothed aspen (*P. grandidentata*), paper birch (*Betula papyrifera*), hemlock (*Tsuga canadensis*), yellow birch (*Betula alleghaniensis*), sugar maple (*Acer saccharum*), red maple (*A. rubrum*), red oak (*Quercus rubra*), pin oak (*Q. ellipsoides*), balsam fir (*Abies balsamea*).

the dominant species (e.g., jack pine–pin oak was merged with the jack pine class). In our study area, mixed classes represent only a small percentage of the landscape (e.g., jack pine–oak 1%), which did not warrant their separation in the analysis. Where mixed classes are more prevalent, they should not be aggregated with dominant classes. The reclassified TM data contained 13 classes: water, lowland, red pine, jack pine, white pine, balsam fir, red oak, pin oak, sugar maple, aspen, paper birch (*Betula papyrifera*), and hemlock–yellow birch. ''Hemlock–yellow birch'' was left as a mixed class because the satellite classification contained neither a single class for ''hemlock'' nor for ''yellow birch'' as a dominant species.

Overlaying the 10 ecoregions and 13 land cover classes in the geographical information system (GIS) ARC/INFO resulted in 103 specific classes. Each class inherits information from both satellite classification and ecoregion stratification (e.g., class 11 represents quaking aspen-dominated forest in ecoregion 2). Some combinations were not present because some ecoregions did not contain all species as dominants. The relative occurrence of tree species in each ecoregion describes regional differences. Jack pine, for example, was the most abundant species on the sandy soils of ecoregion 5, whereas sugar maple dominated most of the other ecoregions (Table 1).

TABLE 2. Analyzed plot level FIA data for quaking aspen in ecoregion 2 as an example for the calculation of the age class distributions.

Stand age (yr)	Occurrence (%)
>80	11.5
>70–80	10.3
>60–70	11.2
>50–60	25.5
>40–50	12.7
>30–40	7.8
>20–30	10.1
>10–20	4.0
0–10	2.7

Generating species statistics for each ecoregion.—We combined stand-level and tree-level FIA data to generate a table of all tree species, ranked by basal area, for all stands. Age class distributions for dominant species are also provided by FIA at the stand level. Thus each record from the derived database contains adequate information to further examine associated species and age classes. After compiling the FIA tables, FIA plot locations were overlaid with the ecoregion polygon coverage to associate all FIA plots with ecoregions. The number of FIA plots per ecoregion varied between 204 (ecoregion 3) and 1451 (ecoregion 10) with a mean of 760.

From the derived stratification of FIA plots by ecoregion, species age class distributions and species associations for each ecoregion were computed. To estimate age class distributions for species dominants, total basal area of each species by ecoregion was first calculated. Total basal area was then grouped according to stand age class, resulting in relative occurrence for each age class. In ecoregion 2, for example, of the quaking aspen in aspen-dominated stands, 25.5% are 51–60 yr, 12.7% are 41–50 yr, 11.5% are older than 80 yr, etc. (Table 2).

Percentage occurrence of the associated species was calculated similarly. From FIA plot data, all stands of dominant species X in age class Y were selected. For this collection of plots, the total basal area of all associated species was compared to the basal area of a single associated species, and the relative occurrence of this associated species was calculated. For example, in ecoregion 2, 50-yr-old quaking aspen-dominated stands contain 25.8% sugar maple, 22.2% white spruce, 16.9% balsam fir, and so forth (Table 3). Thus we ranked secondary species according to their relative occurrence with their associated dominants.

TABLE 3. Analyzed FIA data for quaking aspen in the age class >50–60 yr in ecoregion 2 as an example for the calculation of the associated species occurrences.

Species†	Occurrence (%)
Balsam fir	16.9
White spruce	22.2
White cedar	4.4
Red maple	4.9
Sugar maple	25.8
Yellow birch	4.9
Paper birch	11.6
Big-toothed aspen	8.1
Black cherry	1.4

† White spruce (*Picea glauca*), white cedar (*Thuja occidentalis*), black cherry (*Prunus serotina*).

Probability-driven assignment of forest attributes to the satellite forest classification.—The final step was to assign age and associated species to each pixel of the dominant species map derived from satellite data. Even though we cannot predict the exact spatial location for associated tree species, the relative occurrence on the landscape can be mapped.

A technical limitation of our implementation of this methodology was that only a limited number of forest types could be taken into account. Because our maps were in 8-bit format we were limited to 256 classes—fewer than all of the classes present in the FIA database. This required deciding what forest types should be represented. The decision was made by incorporating certain species age classes only when its relative percentage presence reached a threshold. The thresholds needed to be defined by species and were not generalized. For example, on an absolute scale, sugar maple is much more abundant in most ecoregions than hemlock. A rigid rule that operates with a single threshold of percentage presence might have prevented hemlock from being represented at all in our results. Thus, individual decisions had to be made for each ecoregion.

The percentages of associated species for a dominant species did not always sum to 100%, as some associated species were dropped (Table 4). The relative occurrence, however, determines the probabilities of their occurrence, and these always sum to one. For example, red pine in ecoregion 2 was included in three age classes (90, 60, and 40), which represent 81% relative occurrence. Thus red pine has a 0.444 assignment probability of being 90 yr old, with white pine and quaking aspen as secondary species; a 0.284 probability of being 40 yr old, with balsam fir and big-toothed aspen as secondary species; and a 0.272 assignment probability of being 60 yr old, with white pine, paper birch, and red oak as secondary species (Table 4).

One assumption of our method was that age class distributions and species associations differ between ecoregions. To determine if the differences between ecoregions are significant, we examined the age class distribution of tree species in the FIA database, using a separate-variance t test. Stand age is more suitable for statistical difference tests than the associated species information, because all the FIA plots of one tree species in an ecoregion provide an age class distribution with a mean and a standard deviation. To verify

TABLE 4. Dominant tree species of ecoregion 2 and their age classes, associated species, and relative occurrence according to FIA data and by the data integration algorithm.

Dominant species	Age class (yr)	Associated species†	Relative occurrence (%)	Occurrence probability	Pixel no. theoretical	Pixel no. assigned
Red pine	90	WP, QA	36	0.444	522	515
Red pine	60	WP, PB, RO	22	0.272	319	337
Red pine	40	BF, BA	23	0.284	333	311
Jack pine	50	⋯	100	1.000	1303	1303
White pine	110, 40, 10	RP, YB, QA, RO	100	1.000	955	955
Balsam fir	70	PB, QA	11	0.141	1085	1066
Balsam fir	60	QA, SM, WC, BC	57	0.731	5624	5649
Balsam fir	40	WS, WC, QA	10	0.128	987	981
Red oak	50, 80, 60	BA, SM, PB, WP	100	1.000	1064	1064
Pin oak	50	⋯	100	1.000	924	924
Sugar maple	150	RM, PB, BC	13	0.181	2005	1981
Sugar maple	70	YB, AB	16	0.222	2468	2510
Sugar maple	60	RM, YB, PB	10	0.139	1542	1623
Sugar maple	50	YB, AB	21	0.292	3239	3131
Sugar maple	40	RM, PB, BC	12	0.167	1851	1859
Quaking aspen	60	BF, SM, PB, BA, AB	15	0.183	554	551
Quaking aspen	50	SM, BF, WP, PB, WS	25	0.305	923	929
Quaking aspen	40	RM, WP	12	0.146	443	463
Quaking aspen	20	⋯	10	0.122	369	356
Big-toothed aspen	50, 60	RO, PB, QA, WP, RM	20	0.244	739	698
Paper birch	70, 50	BA, RM, QA	100	1.000	859	859
Yellow birch	100, 90, 50	WC, EH, RM	50	0.500	230	223
Hemlock	130, 100, 50	RM, YB	50	0.500	230	237

† AB (American basswood), BA (big-toothed aspen), BF (balsam fir), BC (black cherry), EH (eastern hemlock), PB (paper birch), QA (quaking aspen), RM (red maple), RO (red oak), RP (red pine), SM (sugar maple), WC (white cedar), WP (white pine), WS (white spruce), YB (yellow birch).

TABLE 5. Tree species with significantly different stand age between ecoregions (95% confidence level, separate-variance *t* test).

Eco-region	Ecoregion 3	4	5	6	7
2	BF, EH, SM, YB, WA, QA, BC, PB	EH, YB	RM, SM, BA, BC, RO, RP, PB	RM, SM, YB, BC, RO, PB	BC, PB, WP
3		QA, BC	QA	WA, WP	EH, SM, YB, QA
4			RM, BA, RO	RM, WA, RO	EH
5					RM, SM, RO, RP, WP
6					EH, RM, SM, YB, RO, WP
7					
8					
9					
10					

Note: BO (bur oak), WA (white ash); see Table 4 for other abbreviations.

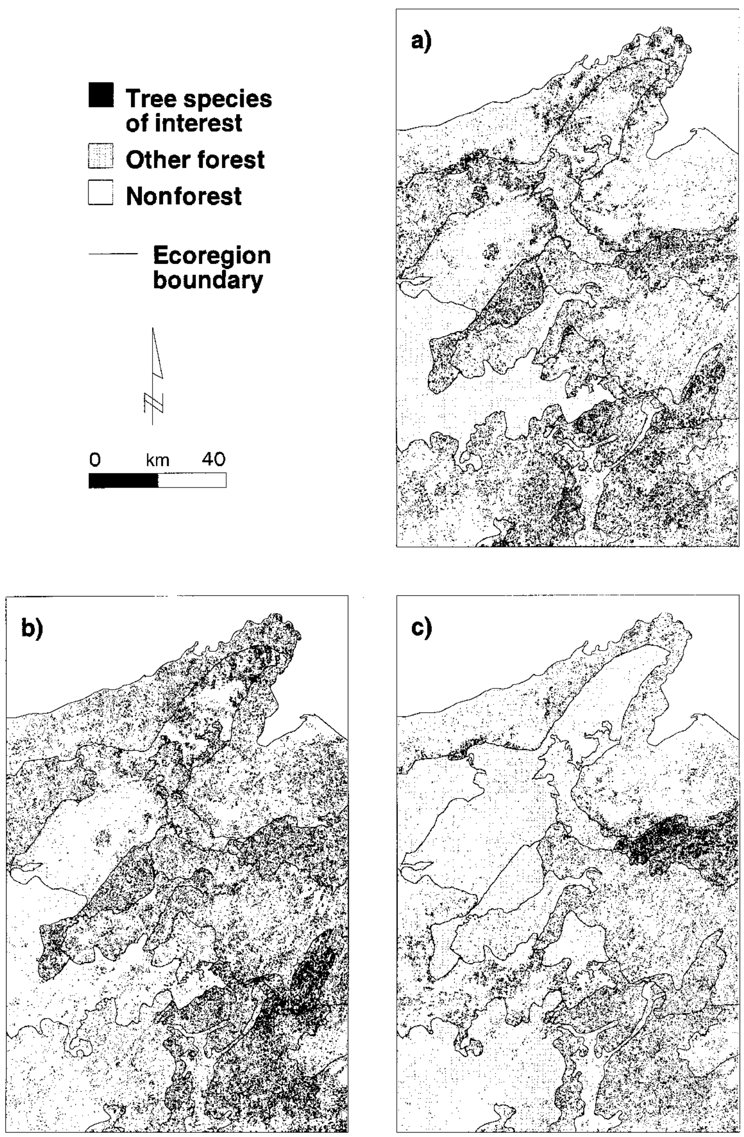

FIG. 4. Spatial distribution of important associated tree species by ecoregion after the integration of satellite classification and FIA database; (a) basswood, (b) red maple, and (c) yellow birch. Refer fo Fig. 3 for ecoregion numbers.

TABLE 5. Extended.

Ecoregion			
8	9	10	11
BF, RM, SM, YB, WA, BA, RO, PB	BF, EH, RM, YB, QA, RO, RP, PB	BF, RM, SM, YB, BA, QA, BC, RO, PB	YB, WA, PB
QA, WP	WP	BC	QA, BC
RM, WA, RO	BF, YB, RO	RM, BA, QA, RO	
BA	BF, BA, BO	QA, BO, RO	RM, BA, BO, RO, PB
WA	BF		WA, RO
RM, SM, YB, WA, WP	BF, EH, YB, RO, RP, WP	BF, RM, SM, YB, QA, WP	YB, WP
	BF, EH, WA	WA, BA, QA, BO, PB	RM, WA, BO, RO, WP
		BA, RO	BF, QA, RO, RP
			RM, BA, QA, RO, PB

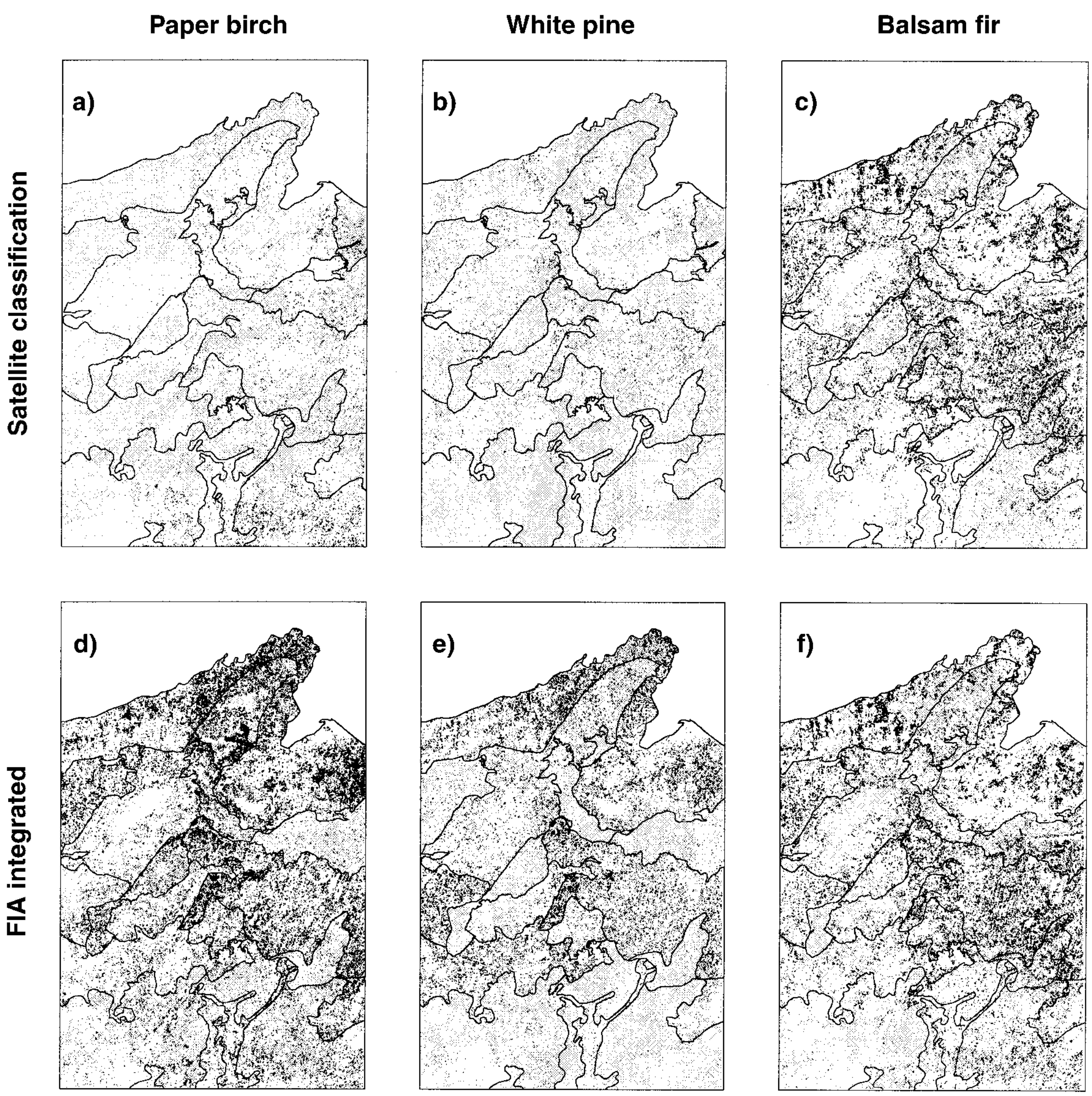

FIG. 5. Species distribution maps based on the satellite forest classification alone and on the data integration method (for key see Fig. 4). Refer to Fig. 3 for ecoregion numbers.

TABLE 6. Relative occurrence (%) of associated tree species in each ecoregion after the data integration.

Species	Ecoregion 2	3	4	5	6	7	8	9	10	11
Red pine	3	0	0	22	2	1	4	12	0	0
Jack pine	0	0	0	8	0	0	0	18	0	0
White pine	11	0	0	27	2	1	22	21	0	2
Quaking aspen	38	9	15	38	34	20	10	16	24	20
Big-toothed aspen	10	14	2	40	16	9	14	17	0	26
Paper birch	35	0	0	20	23	28	33	15	4	11
Yellow birch	30	20	56	1	42	0	12	17	23	3
Hemlock	1	23	18	12	0	0	4	16	5	5
Sugar maple	29	3	17	0	0	6	12	0	6	16
Red maple	28	53	28	13	23	31	21	4	38	10
Red oak	7	14	0	31	52	37	8	10	23	47
Pin oak	0	0	0	9	2	0	0	7	0	0
Basswood	22	34	27	14	47	25	15	0	31	35
Black cherry	33	8	10	0	0	0	0	5	0	5
White oak	0	0	0	0	1	15	0	17	2	15
White spruce	7	14	9	3	2	6	8	0	3	3
White cedar	24	0	0	3	0	0	5	1	3	0
Balsam fir	6	8	4	2	0	1	0	1	6	0
White ash	0	61	0	1	39	0	17	0	29	21
Bur oak	0	0	0	2	0	0	0	0	0	2

our probabilistic assignment algorithm, we compared the theoretical distribution of forest types according to the FIA database with the distribution after the random assignment of age and associated species using *F* test statistics.

RESULTS AND DISCUSSION

The integration of the satellite forest map and FIA database produced landscape-scale forest attributes that could not be otherwise mapped. In this section, first the results of the verification of our algorithm are presented. Second, maps of associated species and of dominant species age are discussed. Third, we present an example for the potential usefulness of these data by examining the spatial distribution of white pine as an associated species, and therefore the possibilities for white pine restoration in the different ecoregions of our study region.

Verification.—We verified our algorithm using the *F* test statistic, which revealed that the theoretical distribution and the distribution after the random assignment were not significantly different (Table 4). We conclude, therefore, that the method performed according to our assumptions.

The separate-variance *t* test for significant differences between ecoregions in the age of tree species reveals strong heterogeneity in stand ages across our study region (Table 5). For the majority of the comparisons between ecoregions, up to nine tree species age class distributions were significantly different. Only in three cases could no significant difference in the age classes be found (ecoregions 5 vs. 6; 4 vs. 11; and 6 vs. 10). However, when examining species associations for these cases, differences are revealed. For example, quaking aspen in the 50-yr age class is associated in ecoregion 5 with red pine and paper birch, in ecoregion 6 with red oak, in ecoregion 4 with sugar maple, red maple (*Acer rubrum*), yellow birch, and eastern hemlock, in ecoregion 10 with red maple, sugar maple, and red oak, and in ecoregion 11 with paper birch, red maple, red oak, and white oak. Many more differences occur for other tree species and other age

TABLE 7. Mean stand age (years) of tree species according to the FIA and satellite classification integration algorithm.

Species	Ecoregion 2	3	4	5	6	7	8	9	10	11
Red pine	68	100	100	61	60	90	90	80	100	60
Jack pine	50	50	50	45	10	50	50	50	50	50
White pine	110	80	10	120	80	100	60	80	50	150
Balsam fir	59	70	53	55	20	70	60	70	40	80
Red oak	80	20	80	52	53	64	62	59	20	80
Pin oak	50	50	50	40	60	···	50	60	50	50
Sugar maple	72	63	72	117	67	71	52	60	66	83
Quaking aspen	46	60	58	45	64	55	53	45	46	40
Big-toothed aspen	60	···	···	80	60	50	47	60	60	80
Paper birch	70	70	60	50	50	60	60	30	60	80
Yellow birch	100	60	50	···	···	···	···	···	···	100
Hemlock	130	80	140	60	100	150	120	30	130	···

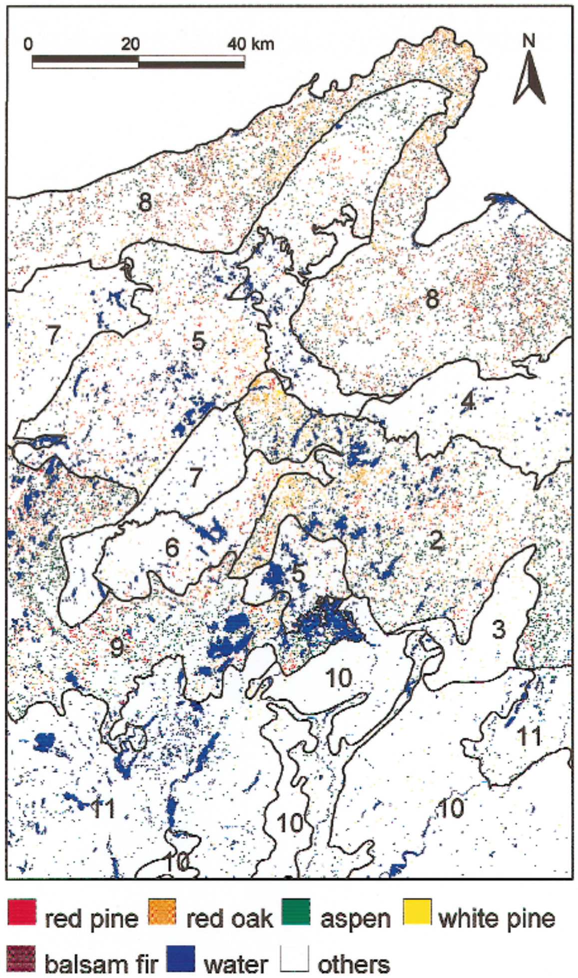

FIG. 6. Dominant species that have white pine as an associated species.

classes. This analysis demonstrates that all ecoregions are distinct in terms of their forest composition as represented in the FIA database.

Associated species maps.—A result of our algorithm is a representation of the spatial distribution of tree species that could not be identified by the satellite classification. Basswood (*Tilia americana*), red maple, and yellow birch rarely dominate the canopy, and do not have phenological peaks that separate them from more prevalent species in satellite imagery (Wolter et al. 1995). Our methodology captures the occurrence of these species and also partly their patchiness through association with dominants on the landscape (Fig. 4). Basswood, for example, is shown to be more important in the maple-dominated forest in the southern part of our study site (Fig. 4a, ecoregions 3 and 10) than on the sandy soils of the Pine Barrens (ecoregion 5). This spatial distribution corresponds to field observations.

Tree species identified by the satellite classification can be compared with our maps generated from the FIA integration. Certain species like paper birch and white pine are more widely distributed according to our analysis than suggested by the satellite classification (Fig. 5a b, d and e). Even though the satellite classification contains classes for these two species, they are seldom dominant in a stand and therefore under-represented in a map of dominants only. Paper birch is widespread, especially in the boreal forests along the shore of Lake Superior (Fig. 5d, ecoregion 8). The same applies for white pine, which is present in the understory of many aspen–birch stands. Balsam fir is an example of a species that is well mapped by the satellite classification, and the FIA integration does not increase its abundance (Fig. 5c and f). The FIA data integration did not add additional balsam fir as an associated species.

The relative occurrence of all associated tree species in the different ecoregions can be evaluated in addition to the map analysis (Table 6). The percentages refer to the area occupied by an associated tree species in an ecoregion. They sum up to >100% per ecoregion because several associated species can be located in one pixel. The relative occurrence reveals, for example, that balsam fir is a less important associated species in the region than basswood, red maple, yellow birch, paper birch, and white pine (Table 6).

Age maps.—Our algorithm assigned age classes for each pixel, thus allowing analysis of age-class distribution differences among ecoregions (Fig. 3b and c; Table 7). In the map and in the calculation of the means, the oldest trees are used to define stand age. In a given stand, shade tolerant tree species may be present in different age classes. In ecoregion 2, for example, white pine is listed as being present in some stands in age classes of 110, 40, and 10 yr (Table 4).

In our study area, quaking aspen is managed for pulpwood in short rotation cycles. This is revealed in the age map, which shows mostly values between 40 and 100 yr for quaking aspen (Fig. 3c). Young stands especially are situated in ecoregions 7 and 8. In the case of sugar maple, the age distribution is more varied (Fig. 3b). Ecoregions 5 and 11 show stands predominantly older than 100 yr, whereas most stands in ecoregions 3 and 8 are ~50 years old. Mean stand ages of other species, for instance eastern hemlock and white pine, reveal differences between ecoregions throughout our study region (Table 7).

Application to forest restoration.—As an example of the use of our results for ecosystem management we assessed possibilities for white pine restoration. White pine was abundant before European settlement but heavily logged since the second half of the 19th century. It occurred in northern hardwood stands as an associated species with sugar maple on mesic sites as well as in relatively few stands on sandy soils. Today, the association of white pine with sugar maple on mesic sites represents only 0.3% of the occurrences of white pine as an associated species (Fig. 6). Currently, white pine is mostly an associate of red oak, red pine, and aspen. Being more shade tolerant than red pine and aspen, and similar in shade tolerance to red oak, white pine can be expected to persist in the northern parts of ecoregions 8 and 9, and in the western parts of ecoregion 2. These would be possible focus areas for white pine restoration in our study area because white pine does occur. However, efforts should be made to resemble the species mix typical for northern hardwoods, i.e., to manage for sugar maple–white pine stands. In ecoregions such as numbers 10 and 11, it will be necessary to plant white pine, if its restoration is a goal here. An evaluation like this requires a combination of satellite classification and FIA database. The satellite data do not contain associated species information (Fig. 5b and e) and the FIA database does not contain the continuously spatial information.

Besides management decisions, our data are also valuable for forest landscape models, for which tree age and associated species occurrence are often necessary inputs. Spatial models incorporating seed dispersal, for instance, perform considerably differently when only dominant species are regarded as possible seed sources. Incorporating associated species as seed sources may lead to a different successional path after a disturbance event. In the case of white pine, for example, long-term simulations starting only with satellite data (Fig. 5b) cannot predict white pine accurately. White pine is almost absent as a dominant species, but widespread as an associated species (Fig. 5e), which will affect modeling results when competition and seed dispersal are taken into account (Mladenoff et al. 1996, He and Mladenoff 1999).

The maps resulting from our methodology should not be misunderstood as a spatially precise representation of all forest canopy species or to be useful at all scales. Due to probabilistic assignment, a specific location may not exhibit the same stand age and associated species on the map as on the ground. The maps are not designed and not suitable for forest management on the local scale. However, using the satellite classification preserves important information on dominant species patch structure and spatial distributions in the landscape. Also, the maps of the probabilistically assigned attributes, age and associated species, reveal patch structure (Figs. 3, 4, and 5). These patches are not forest stands; we did not take autocorrelation of stand age and associated species into account. We were not able to do this because the FIA database sampling resolution is too coarse to estimate autocorrelation at small spatial distances. Another possible approach to preserve stand level patchiness might be to use an image segmentation algorithm on the unclassified satellite data (Woodcock and Harward 1992, Woodcock et al. 1994), to classify each of the derived patches according to its dominant species, and also to assign age and associated species to patches rather than pixels.

Conclusions

Our study focuses on the distribution of forest tree species associations and stand age at the regional landscape scale. At this resolution our integrated mapping approach fills an information gap that currently cannot be addressed by any other single method. The approach of integrating satellite forest classification and forest inventory data provides a new approach to derive detailed data for forest landscapes. Probabilistic assignment of ancillary data derived from the FIA database provides sufficient detail to capture differences among ecoregions. The resulting spatial representation of the forest landscape can be used in regional forest assessment and as input for forest landscape modeling. We believe the data are appropriate for answering questions where the spatial information adequately differentiates ecoregions (10^3–10^4 ha) at the regional scale ($>10^4$ ha).

Landscape ecologists are rarely provided with digital data sources of all desired ecological parameters. Over large areas, ground surveys are often not feasible and other methods of assessment need to be developed. GIS-based methods of data integration can enhance available information and help to fill current gaps in large-scale data.

Acknowledgments

This work was funded by the U.S. Forest Service Northern Global Change Program. We appreciate comments from Barry DeZonia, Janet Franklin, and one anonymous reviewer that significantly improved the manuscript.

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