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Predicting the Spatial Distribution of Aspen Growth Potential in the Upper Great Lakes Region

Eric J. Gustafson, Sue M. Lietz, and John L. Wright

ABSTRACT. One way to increase aspen yields is to produce aspen on sites where aspen growth potential is highest. Aspen growth rates are typically predicted using site index, but this is impractical for landscape-level assessments. We tested the hypothesis that aspen growth can be predicted from site and climate variables and generated a model to map the spatial variability of aspen growth potential across the upper Great Lakes region. The model predicting aspen growth from climate and site characteristics performed nearly as well as the site index model. Sites currently growing aspen have a somewhat lower growth potential than do nonaspen upland sites. The mean growth potential of national forest sites is lower than on other ownerships, except in Michigan. Upland sites with the highest aspen growth potential had higher growth potential than sites currently growing aspen, suggesting that productivity could be increased by shifting the location of aspen production. Only 6.7% of the highest growth sites are located on national forests across the region. The spatially explicit nature of these results may facilitate cooperative planning to better optimize where aspen will be managed across a subregion to enhance regional productivity and to focus management where the potential for production is the greatest. FOR. SCI. 49(4):499–508.

Key Words: Growth and yield, model, climate, topography, landscape ecology, forest management planning.

FORESTS ARE MANAGED for multiple uses and benefits to provide people with aesthetic and recreational experiences, maintain biological diversity, and to produce a variety of wood products (Behan 1990, Kessler et al. 1992). Aspen (*Populus* spp.) is of particular importance in the northern Great Lakes region (Minnesota, Wisconsin, and Michigan), which contains 63% of the U.S. aspen acreage (Cleland et al. 2001). Aspen is used as a source of wood fiber for products such as paper, lumber, wood composite building materials and biofuel (Einspahr and Wyckoff 1990). Given the steadily rising demand for these products, coupled with a decline in aspen acreage and the increasing pressure to produce noncommodity benefits from forests, many forest managers desire to increase fiber production while mitigating impacts on other uses of the forest (Behan 1990, Jaakko Pöyry Consulting 1994). Given recent trends in public opinion, it appears unlikely that additional land allocations for fiber production will be made on public lands. Future de-

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mands for wood fiber and bioenergy will be met with concomitant yield increases in both traditional and nontraditional (e.g., intensive culture) fiber sources (Zsuffa et al. 1996). One way to help achieve these gains is to produce aspen on those sites where aspen growth potential is highest (Carmean 1975, Jaakko Pöyry Consulting 1994).

A large body of research on the growth and yield of aspen exists for the region, including stocking guides (Graham et al. 1963), site index curves (Carmean et al. 1989), silvicultural prescriptions (Burns and Honkala 1990), and yield tables (Perala 1977, Schlaegel 1971). This research has been successfully applied for stand-level management throughout the region. However, little attention has been paid to the spatial variation in growth potential across the region. Such information may have important value for management decisions made to allocate lands for various management objectives, including allocating land for fiber production.

Landscape ecology encourages an explicit focus on the spatial characteristics of ecological and human-dominated systems (Turner 1989, Gustafson 1998). It also encourages a broad-scale view for understanding and managing ecosystems. Foresters have traditionally focused management decisions at the stand level and have only recently begun to examine how multiple-use management objectives might be better achieved by considering a much larger spatial context (Crow and Gustafson 1997a). Landscape ecology is particularly relevant to the spatial implementation of management decisions, and provides a framework to guide the development of spatially explicit management options (Crow and Gustafson 1997b). Consideration of the spatial location of land allocations for fiber production may increase efficiency and help to optimize the sustained production of multiple benefits from managed forests.

Volume growth is recognized as the ultimate standard of site quality, but because volume growth is difficult to estimate in the field, site index has become the most widely used method to evaluate the potential of a site to grow trees (Carmean 1975). Site index is estimated by measuring the age (by coring) and height of dominant trees that have grown unsuppressed in a stand. This method has proved useful for stand-level silvicultural purposes but is impractical for landscape-level assessments because estimating the site index of all stands on a landscape is not feasible. Our thesis is that aspen growth rates can be predicted from site and climate characteristics whose spatial distributions are currently available in map form, and that these predictions will be as accurate as those derived from site index values. For example, precipitation and temperature are known to affect tree growth (Fritts 1976, p. 207–237), and site characteristics such as soil, drainage, and topographic position determine distribution and growth (Graham et al. 1963, p. 56). Iverson et al. (1997) used topographic and soil information to predict site index and forest composition in a 475 ha forest in southern Ohio. Hansen et al. (2000) used soil parent material, topography, and cover type to predict and map aboveground primary productivity in the Greater Yellowstone Ecosystem. Bateman and Lovett (2000) used forest inventory, climate, soils, and topographic data to predict and map tree growth in Wales.

In this study, we tested hypotheses related to our thesis, and constructed a model to predict aspen volume growth from site variables. Our objectives were to: (1) develop and test statistical models to predict aspen growth potential as a function of site and climate conditions across the northern Great Lakes region; (2) compare the accuracy of the predictions from this model to predictions derived from site index; (3) map the spatial variability of aspen growth potential across the region; and (4) assess the potential for aspen productivity gains by comparing the growth potential of the land currently managed for aspen with the growth potential of an equal area of land having the highest aspen growth potential.

Methods

Study Area and Growth Data

We constructed aspen growth potential models using growth and site data within the Laurentian Mixed Forest Ecological Province (Keys et al. 1995) in the states of Minnesota, Wisconsin, and Michigan (Figure 1). We used growth data collected by the USDA Forest Service Forest Inventory and Analysis (FIA) Unit of the North Central Research Station. These data were collected as part of the periodic inventory of the forested land in the region using standard protocols among the three states (Hansen et al. 1992). Data on aspen growth were derived from the FIA plots in the study area on which trees were physically measured during successive inventory cycles. Minnesota inventories were completed in 1977 and 1990, Wisconsin in 1983 and 1996, and Michigan in 1980 and 1993. We used only plots deemed fully stocked by FIA field crews in at least one of the two inventories in each state. Because some plots were fully stocked with trees not measured (e.g., seedlings and saplings), we did not include plots with fewer than 10 measured trees. Because we were interested in growth potential, we did not include plots that were significantly disturbed by timber harvest (>10% of basal area removed), grazing, or where basal area of growing stock did not increase. We did not include trees whose diameter apparently shrank >2.5 cm between inventories. For trees whose diameter apparently shrank <2.5 cm between inventories, we assumed that the diameter was actually unchanged.

For the purposes of this study we defined the aspen type to include quaking aspen (*Populus tremuloides*, Michx.); bigtooth aspen (*Populus grandidentata*, Michx.); balsam poplar (*Populus balsamifera*, L.); and paper birch (*Betula papyrifera*, Marsh.). Very few pure aspen plots exist in the study area. We selected plots with greater than 50% of the plot basal area contributed by aspen and birch, resulting in 1,463 plots in Minnesota, 209 plots in Wisconsin, and 397 plots in Michigan (Figure 1). Within these plots dominated by aspen, we considered the growth of all species on the plot, because it was not possible to separate effects of site conditions on the growth of individual aspen trees from the effects of competition by trees of other species within the plot (Edgar and Burk 2001).

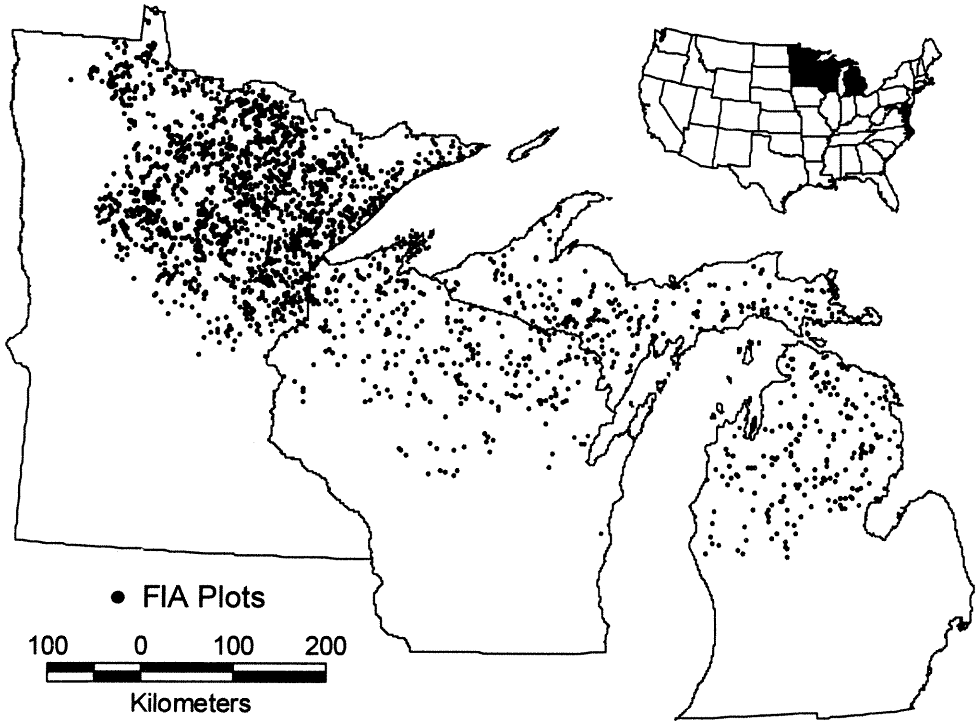

Figure 1. Map of the study area. Closed circles show the approximate locations of the FIA plots used to build and validate the models.

We quantified growth for each plot by estimating volume increment (m^3/ha) using the trees on the plot that were physically measured in successive FIA surveys and the tree expansion factors (inverse of variable radius plot size) (Hansen et al. 1992). Volume measures were calculated for the complete tree (to a 0 cm top) using Hahn's (1984) volume equations for the Lakes States. The volume increment was converted to an annual rate by dividing the volume increment by the number of growing seasons (assuming a 5 month season when computing fractional growing seasons) between plot measurements.

Climate Data

We used climate data from EarthInfo, Inc. (Boulder, Colorado), collected at weather stations throughout the study area, and processed as in Potter and Cate (1999). For each state, we used climate data for the specific time period between FIA inventories in that state. This was expected to more accurately reflect the climate conditions experienced by the trees on the FIA plots than if we used longer term climate averages.

Growing degree-days (*GDD*) is a cumulative heat unit index calculated by

$$GDD = \sum_{i=1}^{365}\left(\left(\frac{T\max_i + T\min_i}{2}\right) - T_{base}\right) \qquad (1)$$

where $T_{\max}$ is the high temperature on day i, $T_{\min}$ is the low temperature for day i, and T_{base} = 5°C (Baskerville and Emin 1969). Number of optimum growing days (*OGD*) is the average number of days per year when the mean daily temperature is between 15 and 20°C (Fritts 1976). Number of frost-free days (*FFD*) is the average number of days per year when the low temperature is >0°C. Maximum temperature (*MXT*) is the average high temperature for the month of July, and minimum temperature (*MNT*) is the average minimum temperature for the month of January. The mean annual precipitation (*P*) is the average annual precipitation (in water-equivalent inches). The mean growing season precipitation (*GSP*) is the average precipitation for the months of May through September.

We estimated climatic moisture deficit for each plot based on potential evapotranspiration (*PET*) and precipitation (*P*). *PET* was calculated for each month (i) using the Thornthwaite (1948) water balance method:

$$PET_i = 1.6\,(10\,T_i\,/\,I)^a \qquad (2)$$

where *PET* is monthly potential evapotranspiration (cm), T_i is mean temperature (°C) in month i, I is an annual heat index calculated by

$$I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514} \qquad (3)$$

and a is an empirically derived exponent:

$$a = 6.75 * 10^{-7} I^3 - 7.71 * 10^{-5} I^2 + 1.79 * 10^{-2} I + 0.49 \qquad (4)$$

We calculated moisture deficit (*md*) for each month of the growing season using $md_i = PET_i - P_i$. We also calculated mean *md* for the growing season months (May–September).

Site Characteristics Data

Several topographic characteristics recorded by FIA inventory crews were included as potential predictive variables for our study: slope (%) and aspect at the plot center, slope position, and slope shape. Slope was converted to slope angle (β). Aspect (a) was transformed (ta) using a cosine transformation (Beers et al. 1966) to produce continuous values with a minimum (0.0) for an azimuth of 22° and a maximum (2.0) for an azimuth of 202°.

$$ta = \cos(22 - a) + 1 \quad (5)$$

A solar insolation index (s) was computed from slope angle (β) and aspect using

$$s = 2 - \sin\left(\left(\frac{\beta}{90}\right) 180\right) ta \quad (6)$$

For each FIA plot location, we calculated the topographic moisture index $\ln(\alpha / \tan \beta)$ (Moore et al. 1993), where α is the upslope area draining across the plot center, and β is the slope at plot center. Alpha was calculated from a 30 m DEM using the FLOWDIRECTION and FLOWACCUM functions of Arc Grid (Environmental Systems Research Institute, Inc., Redlands, CA). The flow direction grid identified the steepest downslope direction from the centroid of each grid cell. The flow accumulation grid derived from the flow direction grid shows the accumulated flow of water to each cell as water moves down slope. Ridge tops have values of 0 (i.e., no accumulation) while the toe of slopes have relatively large values. The FIA inventory crews estimated β in the field at each plot center.

FIA crews visually estimate the dominant soil drainage condition for each plot, recording that estimate in a variable they call physiographic class (pc), using an integer code ranging from 3 to 8 (Table 1). Because aspen grows best in mesic conditions (Graham et al. 1963), we transformed this variable using a sine transformation:

$$tpc = \sin(((pc - 2) / 6) * 180) \quad (7)$$

The other soil variable used was the percentage of the soil association with > 5 in. of water holding capacity. This was calculated from the State Soil Geographic (STATSGO) database using the depth of each soil layer and the available water capacity of each layer (technique described in U.S. Department of Agriculture 1994, pp. 7–13). We would have preferred to have soils data with a finer resolution than STATSGO, but they were not available in digital form for much of the study area.

Georeferencing FIA Plot Locations

Accurate map coordinates for each plot were required to correctly assign the moisture index, but the FIA database carries only approximate coordinates that are sometimes several kilometers off. In collaboration with the NC-FIA Unit, the plot coordinates were corrected by visually transferring plot locations from the aerial photographs FIA used to establish plot locations, to a georeferenced Landsat Thematic Mapper (TM) image. We acquired TM imagery from the Multi-Resolution Land Characteristics (MRLC) Consortium of federal agencies. These Landsat scenes were registered to a Universal Transverse Mercator (UTM) ground control coordinate system and had a planimetric error (root mean square error) of less than one pixel. The Landsat scene was displayed as a backdrop using Arc/Info 7.2, and the FIA plot locations were overlaid on the image. An analyst visually compared the aerial photo and the Landsat scene and moved each FIA point to the Landsat pixel corresponding to the plot location shown on the photograph. We tested the accuracy of these corrected coordinates by tabulating the differences between our corrected coordinates and coordinates determined using a GPS unit for 714 plots. Seventy percent of the corrected coordinates were within 90 m of the GPS coordinate, and 80% were within 120 m. We calculated a semivariogram from the moisture index map, which showed a sill at 120 m. This indicates high spatial autocorrelation in moisture index values within 120 m of each other, giving us confidence that the errors in plot coordinates cause relatively small errors in estimates of moisture index.

Model Development and Testing

Model development and hypothesis testing were conducted using a subset of the FIA aspen plots. We randomly selected 20% of the plots (n = 291) and reserved them for model validation; we used the remaining plots (n = 1,192) for model development. When several variables were available to represent a site characteristic (e.g., annual precipitation and growing season precipitation), we calculated Pearson correlation coefficients (r), and selected the variable that was most correlated with the dependent variable.

We constructed a linear regression model to test the hypothesis that five site and climate characteristics can be used to predict the mean annual volume increment (*mavi*) of trees in aspen plots. These characteristics are topographic position, precipitation, temperature, moisture deficit, and soil drainage. It is well known that annual volume growth rate is related to the size of the trees in a stand (Daniel et al. 1979, p. 318, Walters and Ek 1993), and that this relationship is quadratic. We wished to control for this dominant driver by including it as a covariate in our models, to allow us to test for the effect of other, more subtle site factors. We evaluated the correlation between *mavi* and stand age, stand size class, stand density, and total plot volume, selecting the variable with the highest correlation coefficient as the covariate. We also included the quadratic covariate term. The model took the form:

Table 1. Physiographic class codes and transformed values.

FIA code	Description	Transformed value
3	Xeric—very dry soils	0.4999
4	Xeromesic—moderately dry soils	0.8659
5	Mesic—deep, well-drained soils	1.0000
6	Hydromesic—moderately wet soils	0.8662
7	Hydric—very wet soils such as peat or muck	0.5004
8	Bottomland—flooding influences growth	0.0006

$$mavi = y + \beta a + \beta a^2 + \beta b + \beta c + \beta d + \beta e + \beta f + \varepsilon \quad (8)$$

where a is the stand development covariate, b is the topographic variable, c is the precipitation variable, d is the temperature variable, e is the moisture deficit variable, and f is the soil drainage class variable. Unexplained model error (ε) includes other factors likely to influence aspen growth [such as depth to water table (Graham et al. 1963) and soil nutrients], but that were not measured.

We used the model to calculate t-tests ($\alpha = 0.05$) for each slope estimate (ß) to test the null hypothesis that ß = 0 for each characteristic. To ensure that our model did not exhibit multicollinearity among independent variables, we verified that the variance inflation factor for each ß was <10 (Mendenhall and Sincich 1989, p. 236). We then constructed a predictive model using only variables with ß significantly greater than 0. To assess the predictive ability of this model, we compared the predictions of the model to *mavi* measured on each FIA plot in the validation data set. We plotted predicted against observed growth, and used the SAS (SAS Institute 1990, p. 1384) TEST statement to test the joint hypotheses that the intercept was equal to 0.0 and that the slope was equal to 1.0 (Dent and Blackie 1979).

We also constructed an alternative model using site index (*si*) and the covariate (a) as the independent variables:

$$mavi = y + \beta a + \beta a^2 + \beta si + \varepsilon \quad (9)$$

We only used plots where site index was calculated using site index curves for an aspen species ($n = 919$). We tested the predictive ability of this model in the same way that we tested the site characteristics model.

Mapping Growth Potential and Assessing Possible Productivity Gains

We used the validated model to generate a grid-cell map of aspen growth potential (cell size = 30 m) across the study area. We fixed the value of the covariate (total plot volume) equal to the mean total volume (3.14 m^3/ha) on the aspen plots in our combined datasets. Because there is no map of the spatial distribution of physiographic classes, we could not map the predictions of the full site characteristics model. We fitted a model without the physiographic class variable ($F_{6,1177} = 191.94$, $P > F < 0.0001$, $R^2 = 0.50$), which is given by

$$mavi = -0.3163 + 0.0749a - 0.00002a^2 - 0.0061b + 0.0070c + 0.0025d + 0.0230e \quad (10)$$

where *mavi* is the average annual volume increment per hectare (m^3/ha/yr), a is total plot volume (m^3/ha), b is moisture index (unitless), c is growing season precipitation (cm), d is number of optimum growing days, and e is June moisture deficit (cm). Because the climate data we used to build the models exhibited discontinuities at state borders, we created a region-wide map by kriging 44-yr (1950–1993) climate averages.

We then used a GIS to assess the predicted growth potential on all cells classified as aspen in a Landsat Thematic Mapper (TM) forest type classification map of the study area. The TM classification was produced by the USGS GAP analysis program as described by Scott et al. (1993). The classification accuracy of upland forest types varied between 72 and 93%, depending on the state and ecological region. This map was the best spatially explicit representation of aspen distribution available across our entire study area. To determine if sites where aspen is currently growing have higher growth potential than the average forested site across the region, we calculated the mean growth potential of cells that were classified as aspen in the TM map, and compared it to the mean growth potential of all upland forest and shrubland cells in the study area. By limiting the comparison to upland and shrubland cells, we assumed that sites currently in wetland or lowland types are unsuitable for aspen. We conducted a similar analysis to determine if the growth potential of sites managed for aspen varies between national forests (within purchase boundaries) and other owner types. National forest was the only ownership type for which we had accurate maps across all states. Finally, to estimate the potential to increase aspen productivity by shifting the location of aspen production, we compared the average growth potential of cells currently classified as aspen in the TM map to the average growth potential of an equal number of cells (that are currently forested) having the highest aspen growth values. We identified a growth potential threshold for each state, such that the cells with values above the threshold had a cumulative area approximately equal to the area that is currently growing aspen in that state. Given the area currently allocated to aspen production, the threshold identifies an equal area of land having the highest growth potential. The thresholds used for each state were: MN, 0.450; WI, 0.517; Upper MI, 0.475; Lower MI, 0.517.

Results

Growth Model and Hypothesis Testing

The results of our correlation analysis between *mavi* and site and climate characteristics are given in Table 2. We chose moisture to represent the topographic variables, growing season precipitation, and optimum growing days to represent precipitation and temperature, June moisture deficit as the moisture deficit variable, and physiographic class to represent the soil variables because they were the most correlated with *mavi*. It is worth noting here that our model predicts growth using mean climate values and is not expected to account for extreme events such as isolated droughts.

The fitted regression model [Equation (8)] provided a test of the null hypothesis that the slope associated with each site or climate parameter (β) was equal to zero. The null hypothesis was rejected for all parameters (Table 3). We regressed the predicted values against the actual growth (Figure 2a) and were not able to reject the joint hypotheses that the intercept was equal to zero and the slope was equal to 1.0 ($F_{2,287} = 1.41$, $P > F = 0.25$), giving us confidence that the model has some predictive value. The ANOVA for the site index model is given in Table 4 for comparison with the site characteristics model (Table 3). We regressed the predicted values against observed growth for the site index model (Figure 2b) and were not able to reject the joint hypotheses that the intercept

Table 2. Pearson's correlation coefficient (*r*) between mean annual volume increment (*mavi*) and site and climate characteristics.

Variable	(*r*)	*P* > *r*
Stand characteristics (covariate)		
Stand age	0.287	< 0.0001
Stand age squared	0.222	< 0.0001
Total plot volume*	0.654	< 0.0001
Total plot volume squared*	0.487	< 0.0001
Topographic characteristics		
Slope	0.030	0.30
Slope position	–0.099	0.0007
Slope shape	0.106	0.0006
Slope length	–0.034	0.25
Aspect (transformed)	0.044	0.13
Solar insolation index	–0.072	0.01
Moisture index*	–0.135	< 0.0001
Precipitation		
Annual precipitation	0.033	0.26
Growing season precipitation*	0.066	0.02
Temperature		
Minimum January temperature	–0.012	0.68
Maximum July temperature	0.162	< 0.0001
Growing degree days	0.214	< 0.0001
# of optimum growing days*	0.231	< 0.0001
# of frost-free days	0.057	0.05
Moisture deficit (*PET-P*)		
May moisture deficit	0.148	< 0.0001
June moisture deficit*	0.182	< 0.0001
July moisture deficit	0.10	0.0008
August moisture deficit	0.072	0.01
September moisture deficit	0.064	0.03
Growing season moisture deficit	0.129	< 0.0001
Soil characteristics		
% water holding capacity	–0.067	0.02
Physiographic class (transformed)*	0.203	< 0.0001

* Variable selected to represent each characteristic in model development and hypothesis testing.

was equal to zero and the slope was equal to 1.0 ($F_{2,231} = 0.88$, $P > F = 0.42$), giving us confidence that this model also has predictive value. Examination of the sums of squares shows that site index (Table 4) is somewhat better at predicting growth than the site characteristics model (Table 3) in the absence of the covariate. Site index alone explains about 5% of the variation in growth and the five site characteristics together explain about 2% of the variation.

Spatial Distribution of Growth Potential

Figure 3 shows the spatial distribution of aspen growth potential across the study area as calculated by equation 10. The broad scale variation reflects climate pattern, and the fine-scale variation (seen in insets) reflects topographic effects.

A comparison of sites currently growing aspen with upland sites not growing aspen shows that aspen sites have a somewhat lower growth potential (0.04–2.1% lower, depending on state) than do the nonaspen sites (Table 5). This trend also holds between owner types, with the exception of sites outside of national forests in Lower Michigan, where aspen sites have a slightly higher growth potential (0.5%) than nonaspen upland sites. A comparison of aspen sites within national forests to similar sites in other ownerships shows that the mean growth potential of sites within national forests is lower (0.2–9.2%) than sites in other ownerships (Table 5), except in Upper Michigan, where growth potential in national forests is 3.3% higher than on other ownerships. A similar comparison of the growth potential of nonaspen upland sites shows that growth potential within

Table 3. ANOVA and parameter estimates (m³/ha/yr) for the regression model predicting aspen growth from site and climate characteristics. The model produced an *F*-value of 169.88 with a probability of a greater *F* < 0.0001. R^2 = 0.50.

Source	df	Type III SS	Slope estimate	SE	*T* value	*Pr* > |*t*|
Intercept			–0.5227	0.08997	–5.81	< 0.0001
Total plot volume	1	8.793	0.0733	0.00345	21.26	< 0.0001
Total plot volume squared	1	1.182	–0.00002	0.000003	–7.79	< 0.0001
Moisture index	1	0.078	–0.0044	0.00220	–2.00	0.04
Growing season precipitation	1	0.135	0.0079	0.00301	2.63	0.009
Optimum growing days	1	0.160	0.0024	0.00084	2.87	0.004
June moisture deficit	1	0.072	0.0229	0.01189	1.92	0.05
Soil drainage class	1	0.378	0.2091	0.04745	4.41	< 0.0001
Error	1170	22.766				
Total	1177	45.906				

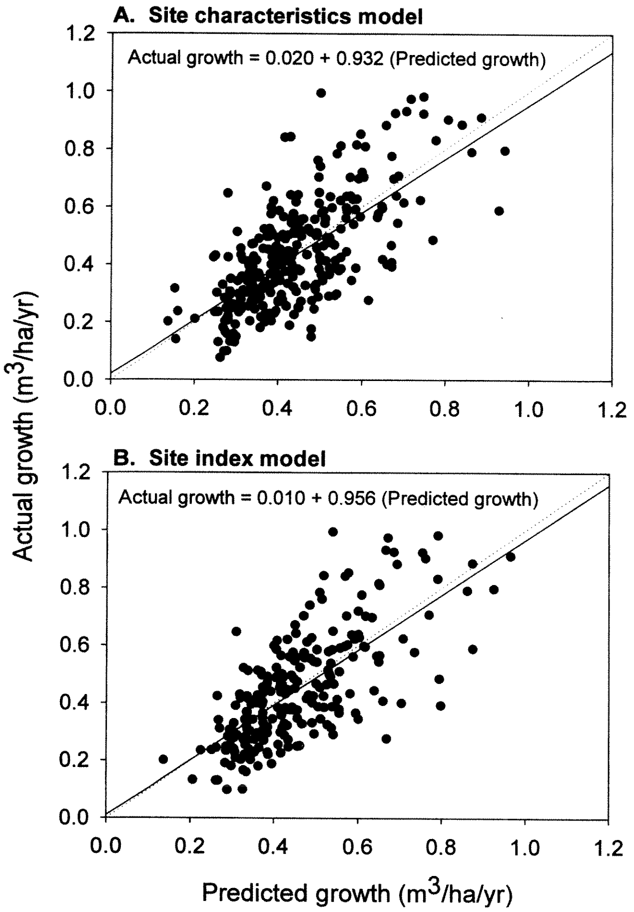

Figure 2. Plot of predicted growth against actual growth on validation plots for the site characteristics model (A) and the site index model (B). Dotted lines represent the joint hypotheses of slope = 1.0 and intercept = 0.0.

national forests is less (3.2–8.9%) than on other ownerships in Minnesota and Wisconsin, but is higher on national forests (2.2–2.9%) in both parts of Michigan.

A comparison of the growth potential of sites currently managed for aspen with an equal area of the highest growth potential sites (Figure 4, Table 5; current aspen v. best growth) shows that the sites with the highest aspen growth potential had a 6.7% higher (all states) aspen growth potential than sites currently growing aspen. These values were 6.5% higher in Minnesota, 7.8% higher in Wisconsin, 9.3% higher in Upper Michigan, and 4.8% higher in Lower Michigan. This comparison accounts for those sites that currently grow aspen and are also high growth potential sites (MN = 1,654,356 ha; WI = 100,865 ha; Upper MI = 31,195 ha; Lower MI = 127,942 ha). Examination of the areal distribution of best growth sites by ownership (Table 5) reveals that only 6.7% of the high growth sites are located on national forests across the region, with individual states ranging from 0.8% in Wisconsin to 35% in Lower Michigan.

Discussion

The model predicting aspen growth from climate and site characteristics performed nearly as well as the site index model, thus achieving our main objective. The model provides the ability to examine the spatial variability in aspen growth potential without the expense of collecting site index estimates in the field. Our results also support our original thesis that site and climate characteristics can be used to predict potential aspen growth rates.

Both the site characteristics model and the site index model explain a significant amount of the variability in aspen growth. Some of the unexplained variability is likely caused by variation in soil nutrients and water availability (Voigt et al. 1957, Graham et al. 1963, p. 66–67). Improved soil and hydrologic maps across the region may become available in digital form in the near future, which will allow us to include these factors in future predictive spatial models. Based on the results of Iverson et al. (1997), we believe this could significantly improve the predictive ability of our model. Errors in plot coordinates (up to 120 m) likely resulted in some error in moisture index estimation. We were also unable to control for stem density, past history of the stand (including insect defoliation events), age distribution of the trees on each plot, and the composition of the trees that were not aspen or birch. Each of these factors likely contributed to the error terms of the models (Edgar and Burk 2001).

Although site index is almost universally used to predict site quality, it has long been recognized that it is not perfectly correlated with volume growth (Mader 1963, Sammi 1965, Carmean 1975). Height and volume growth may vary independently under various environmental conditions (climate, soil, topography, stocking density) (Mader 1963). Volume growth is considered the ultimate measure of site quality, but its estimation in the field for management purposes has been deemed impractical (Mader 1963, Carmean 1975). In our study, we explicitly included in our predictive model many of the environmental factors known to affect volume growth. Even though some important environmental factors were poorly represented in our data set (e.g., soil characteristics), our model predicted volume growth as well as site index did. Because digital spatial data have recently become readily available for large areas, their integration may allow reasonable predictions of volume growth to be made without expensive field data collection efforts. Because improved digital data layers are rapidly being developed (e.g., county-level soil surveys), this approach may soon allow very accurate prediction of volume growth across large areas.

Table 4. ANOVA and parameter estimates (m^3/ha/yr) for the regression model predicting aspen growth from site index. The model produced an F-value of 323.00 with a probability of a greater $F < 0.0001$. $R^2 = 0.51$.

Source	df	Type III SS	Slope estimate	SE	T value	$Pr > \|t\|$
Intercept			–0.0366	0.03124	–1.17	0.24
Total plot volume	1	6.351	0.0705	0.00395	17.86	< 0.0001
Total plot volume squared	1	0.6727	–0.00002	0.000003	–5.81	< 0.0001
Site index	1	1.811	0.0043	0.00045	9.54	< 0.0001
Error	915	18.214				
Total	918	37.502				

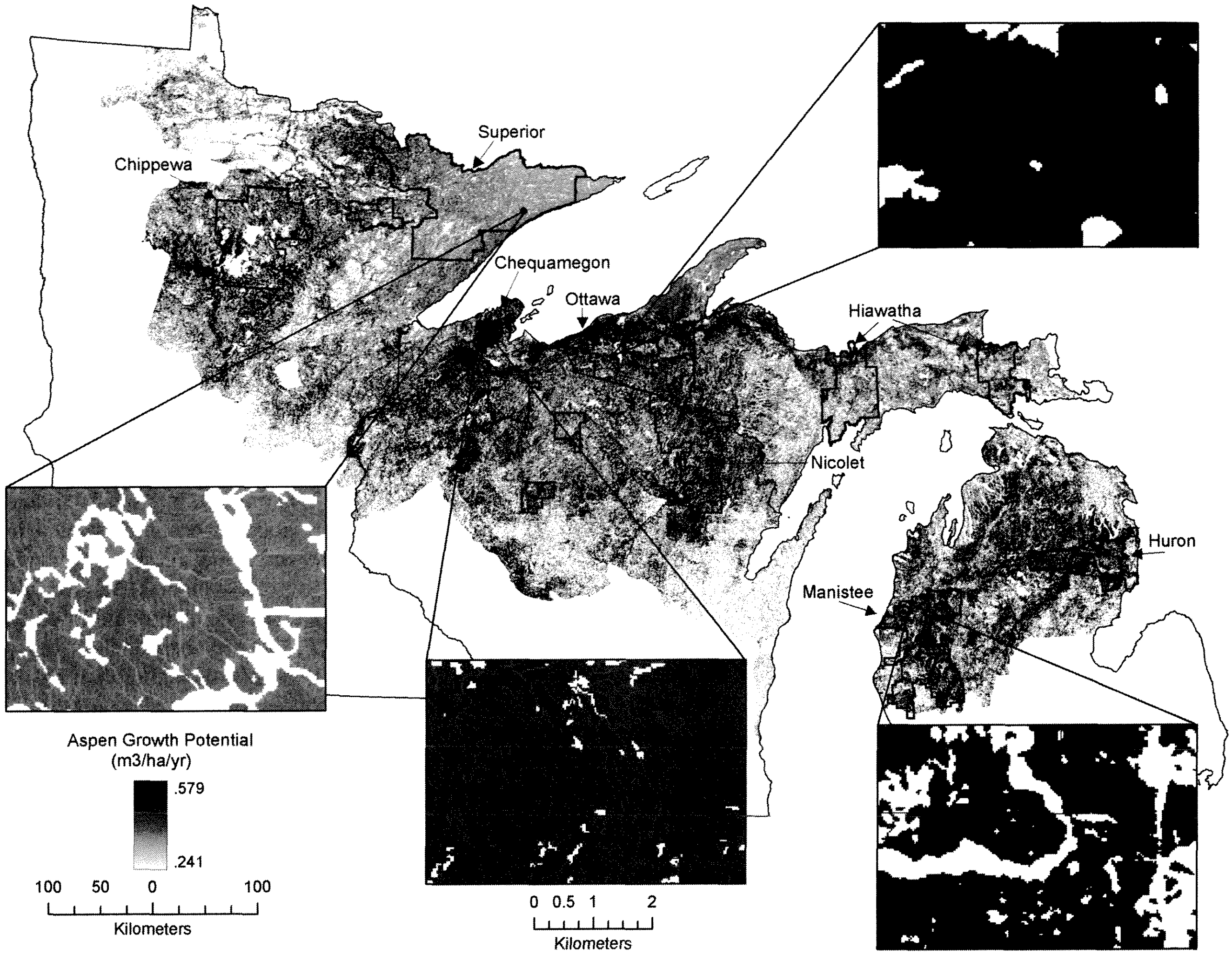

Figure 3. Map showing the spatial distribution of aspen growth potential across the study area. Growth potential values were produced by applying Equation (10) to each cell (0.09 ha) of the map. Polygons represent the boundaries of the national forests within the study area. The regional pattern is related to climate variables, and the insets show the effect of topography on growth potential.

Table 5. Comparison of mean aspen growth potential among ownerships and land uses.

	All ownerships		National forests		Other ownerships	
State	Area (ha)[1]	Mean growth potential (m^3/ha/yr)	Area (ha)[1]	Mean growth potential (m^3/ha/yr)	Area (ha)[1]	Mean growth potential (m^3/ha/yr)
Current aspen						
MN	2,597,576	0.454	319561	0.417	2278015	0.460
WI	884,418	0.488	122407	0.485	762011	0.489
Upper MI	265,431	0.440	61815	0.452	203615	0.437
Lower MI	533,405	0.506	81826	0.505	451580	0.506
All states	4,280,831	0.467	585610	0.447	3695221	0.470
Current nonaspen upland forest						
MN	1,464,531	0.455	185474	0.419	1279057	0.460
WI	2,880,666	0.499	439921	0.486	2440745	0.502
Upper MI	2,567,972	0.443	819755	0.452	1748217	0.439
Lower MI	1657,744	0.506	450452	0.515	1207292	0.503
All states	8,570,914	0.477	1895603	0.472	6675311	0.478
Best growth sites[2]						
MN	2,576,468	0.486	140416	0.491	2436051	0.486
WI	882,260	0.530	6943	0.519	875317	0.530
Upper MI	256,946	0.485	79917	0.479	177030	0.488
Lower MI	516,382	0.532	183120	0.537	333263	0.529
All states	4,232,056	0.500	410396	0.510	3821660	0.499

[1] Area derived from satellite imagery.

[2] Upland forest cells having the highest aspen growth potential, covering an area approximately equal to the area currently growing aspen across all ownerships. Note that these cells are not evenly distributed between national forests and other ownerships.

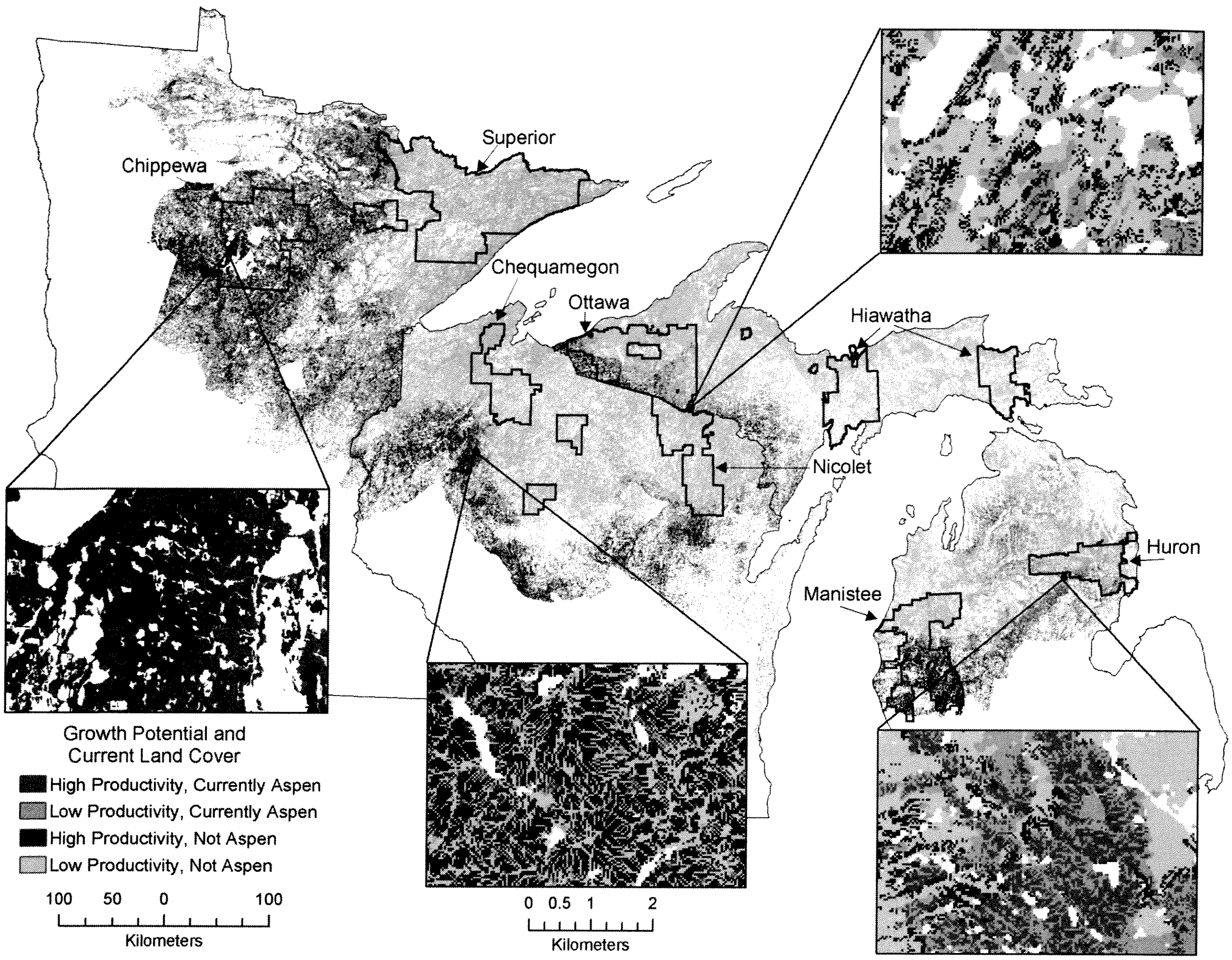

Figure 4. Map showing the current location of aspen with respect to the highest growth potential sites. The high growth potential sites have a cumulative area approximately equal to the area currently in aspen for each state. Because each state has a different threshold to identify high growth potential, discontinuities exist at state borders (see text for thresholds used).

Applicability of Approach

We believe that spatially explicit predictions of aspen growth potential can provide useful information for landscape-scale forest management planning. Because land allocations are typically made in relatively large blocks, the ability to visualize the growth potential of large areas would be useful to help planners optimize the multiple benefits derived from forest lands. For example, National Forest planners might use such a map to help delineate Management Area boundaries, selecting blocks of land with high aspen growth potential for aspen management.

We found that aspen is currently grown on sites with less than average growth potential across most states and ownerships. It is possible that significant gains in aspen productivity could be realized by shifting aspen production to more productive sites. However, it is likely that good sites for aspen are also good sites for other valuable tree species, and that the more productive sites are already dedicated to producing other forest commodities. Managers may also find these results useful for strategic planning to meet aspen demand in the future. For example, the best aspen growth sites within Wisconsin and Upper Michigan National Forests have less growth potential, and Minnesota and Lower Michigan National Forests have higher growth potential, than sites found on other ownerships. Because these other lands have state, county and industrial owners, the growth potential map could facilitate cooperative planning to better optimize where aspen will be managed across a sub-region to enhance regional productivity, and to focus management were the potential for production is the greatest.

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