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A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests (U.S.A.)

Louis R. Iverson, Martin E. Dale, Charles T. Scott and Anantha Prasad
USDA Forest Service, Northeastern Forest Experiment Station, 359 Main Road, Delaware, OH 43015, U.S.A.

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Abstract

A geographic information system (GIS) approach was used in conjunction with forest-plot data to develop an integrated moisture index (IMI), which was then used to predict forest productivity (site index) and species composition for forests in Ohio. In this region, typical of eastern hardwoods across the Midwest and southern Appalachians, topographic aspect and position (rather than elevation) change drastically at the fine scale and strongly influence many ecological functions. Elevational contours, soil series mapping units, and plot locations were digitized for the Vinton Furnace Experimental Forest in southeastern Ohio and gridded to 7.5-m cells for GIS modeling. Several landscape features (a slope-aspect shading index, cumulative flow of water downslope, curvature of the landscape, and water-holding capacity of the soil) were used to create the IMI, which was then statistically analyzed with site-index values and composition data for plots. On the basis of IMI values for forest land harvested in the past 30 years, we estimated oak site index and the percentage composition of two major species groups in the region: oak (*Quercus* spp.), and yellow poplar (*Liriodendron tulipifera*) plus black cherry (*Prunus serotina*). The derived statistical relationships were then applied in the GIS to create maps of site index and composition, and verified with independent data. The maps show the oaks will dominate on dry, ridge top positions (*i.e.*, low site index), while the yellow poplar and black cherry will predominate on mesic sites. Digital elevation models with coarser resolution (1:24K, 1:100K, 1:250K) also were tested in the same manner. We had generally good success for 1:24K, moderate success for 1:100K, but no success for 1:250K data. This simple and portable approach has the advantage of using readily available GIS information which is time-invariant and requires no fieldwork. The IMI can be used to better manage forest resources where moisture is limiting and to predict how the resource will change under various forms of ecosystem management.

Introduction

Ohio is typical among many midwest and eastern states in that it is undergoing a conversion of its oak-hickory forests, *e.g.*, white oak (*Quercus alba*), chestnut oak (*Q. prinus*), scarlet oak (*Q. coccinea*), black oak (*Q. velutina*), northern red oak (*Q. rubra*), shagbark hickory (*Carya ovata*), and mockernut hickory (*C. tomentosa*) to primarily maple (*Acer rubrum* and *A. sacc harum*) and yellow poplar (*Liriodendron tulipifera*) forests. Data from the USDA Forest Service inventories between 1968 and 1991 (Kingsley and Mayer 1970; Dennis and Birch 1981; Griffith *et al.* 1993) indicate that the proportion of total overall volume in oak and hickory (*Carya* spp.) declined substantially relative to maple, black cherry (*Prunus serotina*), and yellow poplar (Fig. 1). Although absolute growing-stock volumes tended to increase for most species in Ohio as the secondary forests matured, there was a shift in the relative importance of species: red oaks, white oaks, and hickories declined by 41, 31, and 22 percent, respectively, while red maple, sugar maple, black cher-

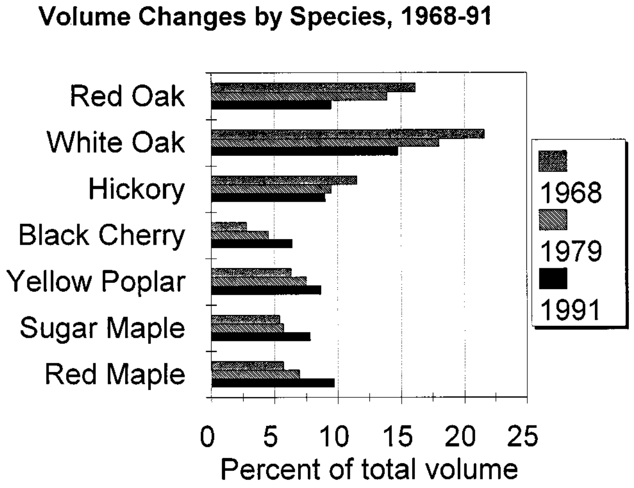

Fig. 1. Forest inventory trends for seven main species or species groups in Ohio, 1968–91. (Source: Kingsley and Mayer 1970; Dennis and Birch 1981; Griffith et al. 1993)

ry, and yellow poplar increased by 70, 44, 129, and 38 percent, respectively, in relative total volume. This trend in relative proportions corroborates a pattern seen regionwide, *e.g.*, in Illinois (Iverson *et al.* 1989; Iverson 1994), Pennsylvania (Abrams and Nowacki 1992), and several other eastern states (Powell *et al.* 1993). This trend has prompted a large scientific effort to assess the problem and search for management solutions (*e.g.*, Loftis and McGee 1993), including this study designed to employ simple and portable computer mapping techniques to assess natural oak regeneration capability. Management strategies to 'adjust' the natural tendencies could then be implemented.

Several factors contribute to the decline of oaks in eastern forests. Oaks do not regenerate well under closed canopies in the absence of fire, and thus are declining while more shade-tolerant species are thriving (Heiligmann *et al.* 1985; Hilt 1985; Loftis and McGee 1993). In addition, when light and moisture are not limiting (*e.g.*, after a clearcut), yellow poplar and black cherry grow exceedingly fast, out competing the oak (Beck 1990; Marquis 1990). The success of oak regeneration after a canopy-changing disturbance seems to follow a moisture gradient, that is, regeneration of oak is adequately only under dry conditions in which it can compete successfully with more mesic species.

Site index, defined as an average height of individual dominant trees in the stand at a specified age (*e.g.*, the height of white oak in feet at 50 years of age) has been the most widely-used site-evaluation measure in North America since the early part of this century (Roth 1916; Frothingham 1921; Mader 1963; Jones 1969). Other measures, such as vegetation approaches (*e.g.*, ordination or classification) or environmental approaches (*e.g.*, factorial or environmental ordination or soil surveys) also are used. A recent effort in Minnesota shows the potential of a relative stocking index (the ratio of a stand's measured density to the 'norm' predicted from inventory data by cover type) as a measure of site quality (Berguson *et al.* 1994). Although site index is still favored by many forest scientists as a direct and easy method for evaluating site productivity, this measure is limited because it assumes that height growth has not been influenced by stand density or stand history, a situation that is difficult to confirm (Monserud 1984; Berguson *et al.* 1994). The simple computer mapping technique developed for this study is intended to enhance the capability to estimate site productivity across landscapes.

It has been known for some time that the distribution and growth (*i.e.*, site index) of trees in this geographic region are correlated with local topography and soils, but these relationships are difficult to quantify and map (Merz 1953; Trimble and Weitzman 1956; Trimble 1964; Carmean 1965; Tajchman and Boyles 1993). McNab (1993) devised a topographic index based on eight slope gradients that was related to yellow poplar site index in the southern Appalachians. Fralish (1994) found a strong relationship between stand basal area and soil and topographic factors in southern Illinois. He found this association related mostly to the soil-water reservoir. Slope angle, aspect, and position, and effective soil depth were the primary factors controlling the amount of water in the soil-water reservoir. White (1958) also concluded that any measure of site productivity is mostly an estimate of the amount of available soil water, the exception being if the site has a prevailing water table within 2 m of the surface where ground water would be available for tree growth (Loucks 1962). In British Columbia, Wang and Klinka (1991) found that the site index for lodgepole pine can be estimated reasonably well with a soil-moisture model. Allen and Peet (1990) found a subjective topographic moisture index was correlated to a compositional gradient in Colorado. Slope angle, aspect, and position have also been combined in various ways to relate to vegetation patterns (*e.g.*, Lieffers and Larkin-Lieffers 1987; Lloyd *et al.* 1994). Host *et al.* (1987) reported that forest successional pathways in Michigan were strongly related to topographic and edaphic conditions, again, largely via variations in moisture availability. In addition, a wetness index that features some of the same landscape elements as in this study has been used in hydrologic research (Beven 1986; Band and Wood 1988). A further review of predictive vegetation mapping techniques can be found in Franklin (1995).

These relationships indicate that geographic information system (GIS) technology may be ideally suited to model moisture level across landscapes, and, by extension, the potential to regenerate oak forests. Digital elevation models (DEM) (US Geological Survey 1987) have been useful in deriving topographic features associated with landscape processes (Jenson and Dominque 1988; Skidmore 1990; Twery *et al.* 1991; Garten *et al.* 1994; Mitasova *et al.* 1996). Digital elevation data also have been used in combination with remotely sensed and other data to map forest composition and biomass (Fox *et al.* 1985; Frank and Thorne 1985; Iverson *et al.* 1994).

The objectives of this study were to: 1) evaluate the quality of DEM data (relative to topographic and moisture indices) created at four scales of resolution, 2) create an easily generated model which estimated the integrated moisture index (IMI) based on DEM and soils data, and 3) test the potential for using the IMI, as calibrated from field data, to estimate oak site index and tree-species composition of the "next forest", that is, the forest that will result following the removal of the current, 100+ year-old, oak-dominated canopy. The objective with the index is to enable a simple and general model of moisture that can be easily implemented within a GIS, and which is not specifically tied to the current vegetation pattern (current vegetation does not even factor into the index), but can be specifically applied depending on the data collected and landscape ecological or management needs.

2. Methods

The objectives in this study were addressed by developing the integrated moisture index based on four factors that affect moisture levels in forest ecosystems. The IMI was then applied and refined on the study area in southeastern Ohio at four different scales of resolution. Finally, it was used to predict site index and species composition for selected species in the study area.

2.1. Study area

The study area was the Vinton Furnace Experimental Forest in Vinton County, Ohio (Fig. 2). It is part of the unglaciated Allegheny Plateau with its dissected topography and less than 100 m of total relief. It was carved from Pennsylvanian strata consisting of a variety of sandstones, shales, and clays of variable composition, resistance, and continuity of distribution (Beatley and Bartley 1959). The land was clearcut in the mid- to late-1800s to furnish charcoal for several iron furnaces in the region. The 475-ha forest is now owned by Mead Paper Corporation and has been managed as a research forest by the USDA Forest Service since the early 1950s. The forest has grown back with oak dominating the canopy, and has been the site of extensive research on cutting practices and uneven- and even-age silviculture of oak-hickory forests (*e.g.*, Hilt and Dale 1982; Hilt 1985). The current overstory is dominated by oak and hickory, and the species composition of the northerly and southerly aspects is similar (Table 1). Conditions for establishment in the late 1800s likely were influenced to a much greater degree by fire than presently, so that oaks were able to successfully compete on either exposure (Crow 1988).

The upland forests are mostly a complex mosaic of oak-hickory and mixed oak communities, with some oak-yellow poplar and mixed mesophytic communities in ravines and other mesic

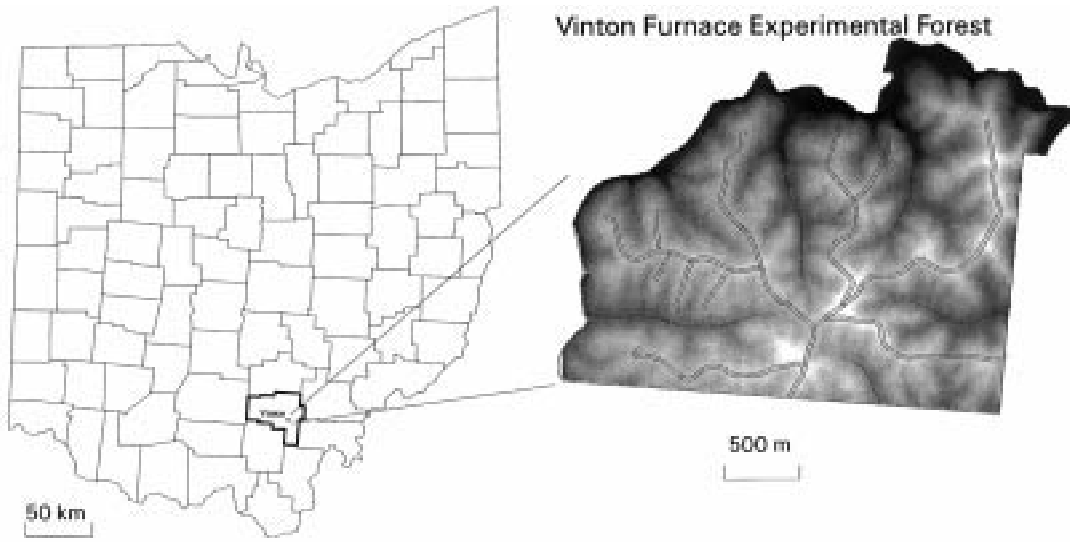

Fig. 2. The Vinton Furnace Experimental Forest located in southeastern Ohio. Grayscale shading represents the elevation of the area. See Fig. 6a for the elevation scale bar.

Table 1. Species composition of current (120+ year old) uncut forest on southern vs. northern exposures; data are based on areas of 11 ha (southern) and 8 ha (northern) at Vinton Furnace Experimental Forest.

	Southern Exposure		Northern Exposure	
	No. stems/ha	Basal area (m^2/ha)	No. stems/ha	Basal area (m^2/ha)
White oaks	118.3	11.8	99.0	10.5
Black oaks	24.5	4.5	37.8	6.5
Hickory	20.5	0.8	22.5	0.8
Yellow poplar	11.4	0.7	17.8	1.4
Red maple	63.5	1.7	39.5	2.0
Other	14.3	0.7	29.1	1.0
Total	252.4	20.4	245.8	22.2

sites (Beatley and Bartley 1959). The oak-hickory (especially chestnut oak) community is indicative of locations with low soil moisture during parts of the year, while yellow poplar and especially yellow buckeye (*Aesculus octandra*) and beech (*Fagus grandifolia*) are indicative of locations providing constant and relatively high levels of soil moisture. Thus, these complex mosaics are driven primarily by the underlying complexities in topography and soils.

2.2. Integrated Moisture Index

The IMI was developed to integrate GIS-derived topographic and soil features of the landscape into a single index that can be statistically related with a number of ecological processes across a landscape (Fig. 3). The intention was to provide a relative rating of moisture that can be related to specific processes wherever moisture is seen to be the primary driving factor. In this case, the resulting IMI was used to predict forest site productivity and composition, but many other ecological processes, including understory composition and richness, soil nitrogen, aluminium, and pH, and bird distributions, are currently being related to IMI as well. Assuming reasonably similar climate, elevation, disturbance history, and soil fertility among upland sites, variation in plant distribution and productivity will be driven primarily by moisture availability. Moisture levels are higher where direct solar radiation is minimized (the hillshade variable in the IMI model), in lower positions on slopes (flow accumulation) or in depressions (curvature), and in soils capable of storing high amounts of water (total water holding capacity). These four factors were modeled, via GIS, in the IMI.

Hillshade essentially captures the effects of differential solar radiation due to variation in slope

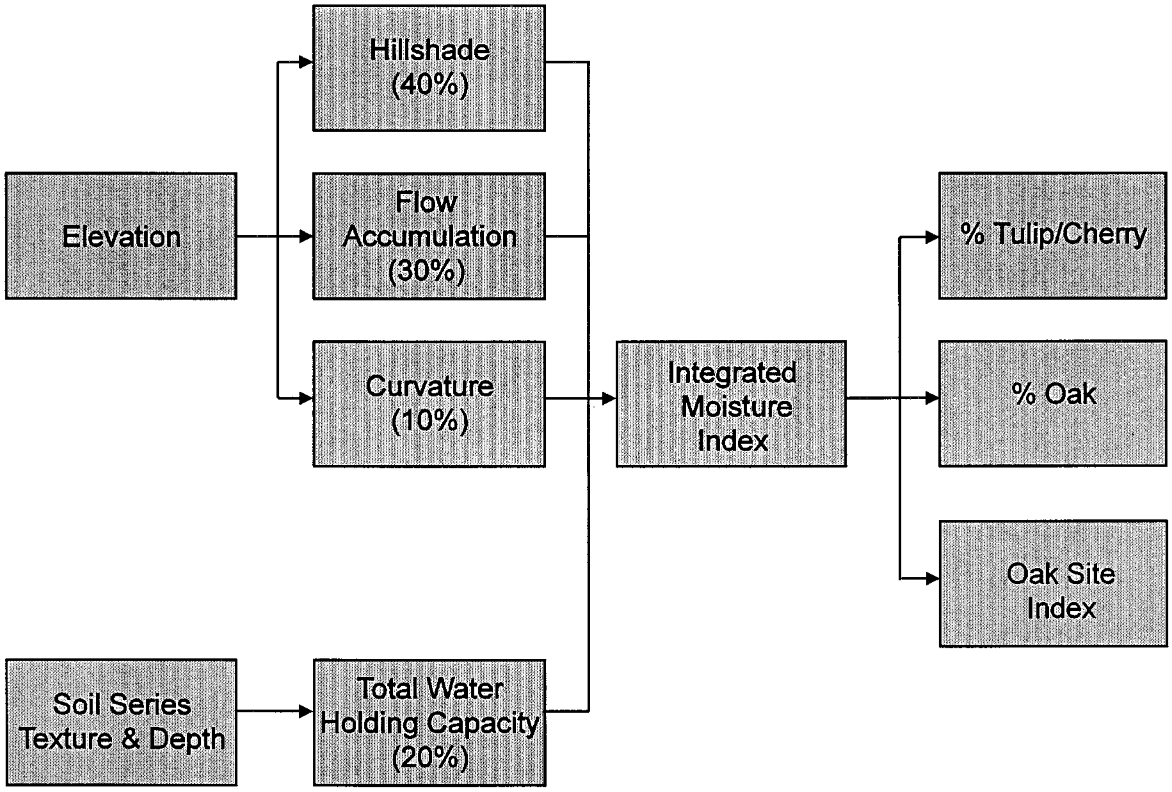

Fig. 3. Flow diagram of the GIS process to derive IMI and related products.

angle, aspect, and position, and to account for shading from adjacent hills. The latter component of hillshade was minimal because, although heavily dissected, the maximum relief change was less than 100 m and cliffs are rare in the area. Maximum cumulative solar radiation over a year will occur on steep, south-facing slopes (Lee and Baumgartner 1966). Because of the added drying potential of higher afternoon temperatures, maximum drying of soil will occur on aspects slightly west of south (SSW). Thus, the highest moisture levels will be found on NNE aspects, a solar azimuth of 22 degrees. A solar altitude of 45 degrees was used to approximate a growing season average. The "hillshade" command in Arc/Info Grid (Environ. Sys. Res. Inst. 1994), operating on the digital elevation data for the site, was used to create a hillshade map with increasing scores equivalent to increasing moisture content (Fig. 4a).

Flow accumulation represents the accumulated flow of water downslope as water moves via gravity. It is related to position on the slope where the bottoms of slopes accumulate much more moisture than ridgetops. The Arc/Info program "flow accumulation" basically counts the number of cells sending water downslope to the cell being evaluated; ridgetops would have a flow accumulation of only one while the valley bottoms would have maximum accumulation. Thus, increasing scores contribute to increasing IMI (Fig. 4b). The map shows the dissected nature of the area, with the road and trail network following the ridgelines and the many small stream valleys showing higher scores because of water flowing downslope.

Curvature is a measure of shape of the landscape, whether it is flat, convex, or concave. The Arc/Info program "curvature" assesses surrounding cells to calculate a curvature, with increasing positive scores representing increasing concavity. Concave surfaces, or depressions, will accumulate moisture and thus positively contribute to the IMI (Fig. 4c). The curvature map generally assigns small coves and depressions with higher scores, and small knolls with lower scores. Algorithms for

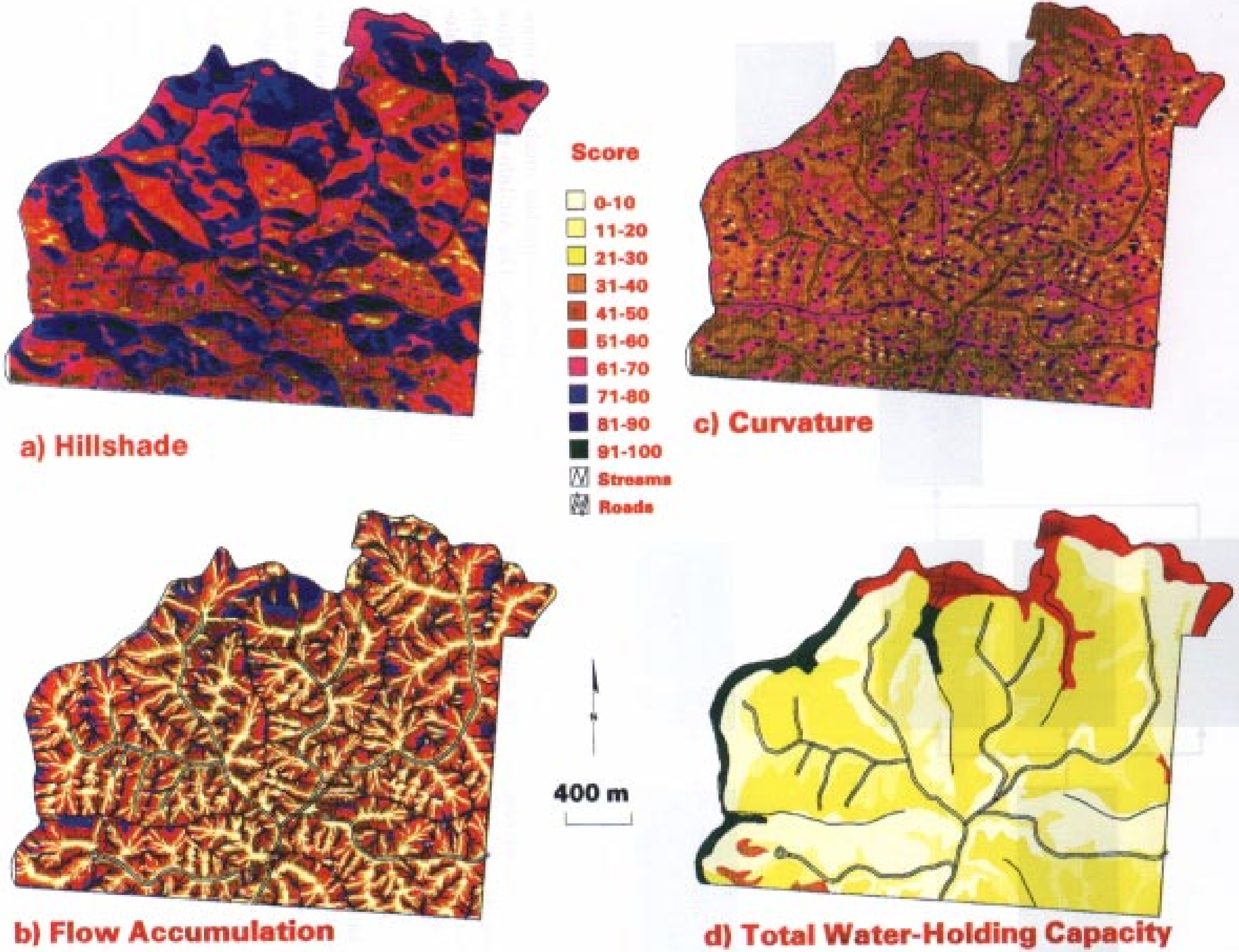

Fig. 4. Maps representing 0- to 100 scores for: a) hillshade, b) flow accumulation, c) curvature, and d) total water-holding capacity for the Vinton Furnace Experimental Forest with DIG (7.5-m) data.

flow accumulation and curvature are given in Jenson and Domingue (1988).

Total available water-holding capacity was derived from a digitized soil-series map, originally compiled at a scale of 1:15,840 by the USDA Natural Resources Conservation Service. Using the attributes from these soil maps, soil depth (A plus B horizons, the zones of most biological activity) and available water-holding capacity (per unit depth) were multiplied to estimate the total amount of water available to plants in the A and B horizons. In several instances, the mapping unit was a soil complex consisting of two or more soil series; in these cases, weighted averages were calculated based on the percentage of each soil series in the complex. There were 12 different soil series or complexes on the site, with a wide difference in total water holding capacity between the bottomland soils and the upland soils (Fig. 4d). The upland soils are mostly shallow soils with bedrock close to the surface, which severely restricted the total water-holding capacity. Soils in the valleys were generally deeper and siltier. This pattern created a map with sharp boundaries of total available water-holding capacity depending on the mapped soil series/complex. A continuous soil-property map would be preferable using GIS and fuzzy logic, as is being developed by some researchers (*e.g.*, Zhu 1994).

Hillshade, flow accumulation, curvature, and total water-holding capacity were standardised to a 0 to 100 score to facilitate calculation of the IMI. Numerous iterations associated with on-site visits and field experience were used to select the relative weights to combine hillshade, flow accumulation, total water-holding capacity, and curvature into a single IMI value for the GIS model. The final IMI score could then potentially range from 0 to 100, with increasing scores indicating increasing moisture levels. The weights were not statistically optimized due to insufficient hard data, but three years of testing has shown it to provide effective results over a number of applications in Ohio. We also tested the model output projections of percent oak with an independent data set of 24 plots from another site 3 km away. The literature and experience support the idea that, in this geographic region, moisture availability is controlled by the intensity and duration of radiation (hillshade), micro- and macro-topography related to water infiltration and runoff (flow accumulation and curvature), and capacity of soil horizons to store and release moisture over time (total water-holding capacity).

2.3. IMI comparison by DEM scale

Four scales of resolution were evaluated to compare their effectiveness in estimating IMI:

(1) Digitized contours (from the McArthur, Ohio, quadrangle 7.5-minute USGS topographic map), which were converted to elevation points, kriged, and gridded (using commands “arcpoint”, “pointgrid” and “kriging”) into Arc/Info Grid at a resolution of 7.5 m [hereafter referred to as DIG data];

(2) USGS 7.5-minute DEM data for the McArthur quadrangle (1:24,000 scale, 30-m resolution) [24K];

(3) USGS 1:100,000 Digital Line Graph (DLG) hypsography data (elevational contours) for the Wellston, Ohio, quadrangle, interpolated and rasterized at 30-m resolution [100K]; and,

(4) USGS 3 arc-second DEM data for the Columbus-E quadrangle (1:250,000 scale), resampled via cubic convolution in Arc/Info Grid from geographic coordinates with variable-size cells to a constant cell resolution of 60 m [250K]. Information on quality and formats of (2), (3), and (4) is found in publications of the U.S. Geological Survey (1987, 1989).

To calculate IMI, elevation data must be in a digital elevation model (DEM), or a grid of interpolated cells covering the entire area. Therefore, the contoured data (DIG and 100K) had to be converted to DEM data. Three methods were used to interpolate the contour data, all using Arc/Info Grid software: “spline”, “topogrid”, and “kriging”. On the basis of optimizing correlations to the 24K DEM data (using Arc/Info’s “correlation” command to compare grids), kriging was selected to create DEMs from the contours of the DIG and 100K data (Dubrule 1984; Robertson 1987; Journel 1989; Oliver and Webster 1990).

After the DEMs were built for all four sources of data, they had to be resampled to similar cell sizes so that direct comparisons among IMI maps could be made. The DEMs had been created with cell sizes as multiples of 7.5 m: 7.5 m for DIG, 30 m for 24K and 100K, and 60 m for 250K. To smooth the coarser data and allow consistent GIS methodology, a reduction in grid cell size to 7.5 m (using "resample" with bilinear interpolation in Arc/Info Grid) was conducted in even, multiple steps; the 24K and 100K data were resampled to 15, then 7.5 m, and the 250K data were resampled to 30, 15, and finally 7.5 m. Bilinear resampling uses the four nearest cells to calculate a weighted average for each cell, and the processing in sequential steps allowed a much more detailed final DEM relative to, for example, directly resampling the 250K data from 60 to 7.5 m. To assess the effects of this smoothing process, all GIS processing was conducted with a grain size of 30 m as well as 7.5 m. In this case, resampling was done to increase the DIG data in multiple steps (15, 30 m) to a cell size of 30 m.

IMI values were calculated for each scale, separated into 10 classes, and compared using areal estimates by class. Additionally, pixel-by-pixel comparisons for all map pairs (with 7.5- and 30-m grain size) were made using cross correlation, which in Arc/Info Grid yields a correlation coefficient between two maps.

2.4. Predicting site index and composition

Field estimates of white oak site index and percent composition of oaks (mostly white, chestnut, scarlet, black, and northern red), red maple, yellow poplar, black cherry, and several minor species were made for twenty-three 0.04 ha plots with known locations. These sites had been harvested in 1965 and had regenerated in the absence of fire. As such, they represent the ecological conditions that presently occur when the old, oak-dominated canopy is removed by human or natural causes. These plots are ecologically representative of much of southern Ohio and beyond. Average IMI scores were obtained for the cells occupying each plot (using the "zonalstats" function in Arc/Info Grid), and statistically related to site index and percent composition of oaks, red maples, and yellow poplar plus black cherry. Linear regression was used to estimate site index, while logistic regression was used to estimate percent composition (so that estimates did not extend beyond the 0–100% range). Yellow poplar and black cherry were combined, as were the oaks, because of their close association in the stands studied. Linear and logistic regressions were performed in S-PLUS (StatSci 1993).

Regression analysis of IMI with field-plot estimates was used to convert the IMI scores to GIS-modeled estimates of oak site index and percent oak or percent yellow poplar plus black cherry. No attempt was made to develop a GIS model of red maple composition, because the IMI-maple regression had an R^2 near zero.

3. Results

3.1. IMI generation

The GIS-modeled map of IMI (Fig. 5a–c) reveals a general pattern of low scores (drier conditions) at the ridgetops and south to southwest facing slopes, especially where the soils are shallow. The deep soils and high flow accumulation along the Elk Fork river (the northern boundary of the study area) are apparent with the highest IMI scores. Equally apparent is the extremely heterogeneous nature of the landscape; for example, one can find nearly the entire range of IMI scores within any 20-ha area.

3.2. IMI comparison by DEM scale

The smoothing process, whereby coarse elevation data (*e.g.*, 100K and 250K) were consecutively resampled to a common cell size of 7.5 m, resulted in more realistic portrayals of elevation compared to the original source data. However, variation in the quality of data is apparent (Figs. 5–6). In the case of 250K data, misregistration placed some ridges in the valleys and vice versa. This exercise once again reveals the danger in trying to extract local phenomena from coarse-resolution data. By contrast, the DIG, 24K, and 100K elevation data appeared similar visually and statistically, as confirmed by the correlation statistics (Fig. 6, Table 2).

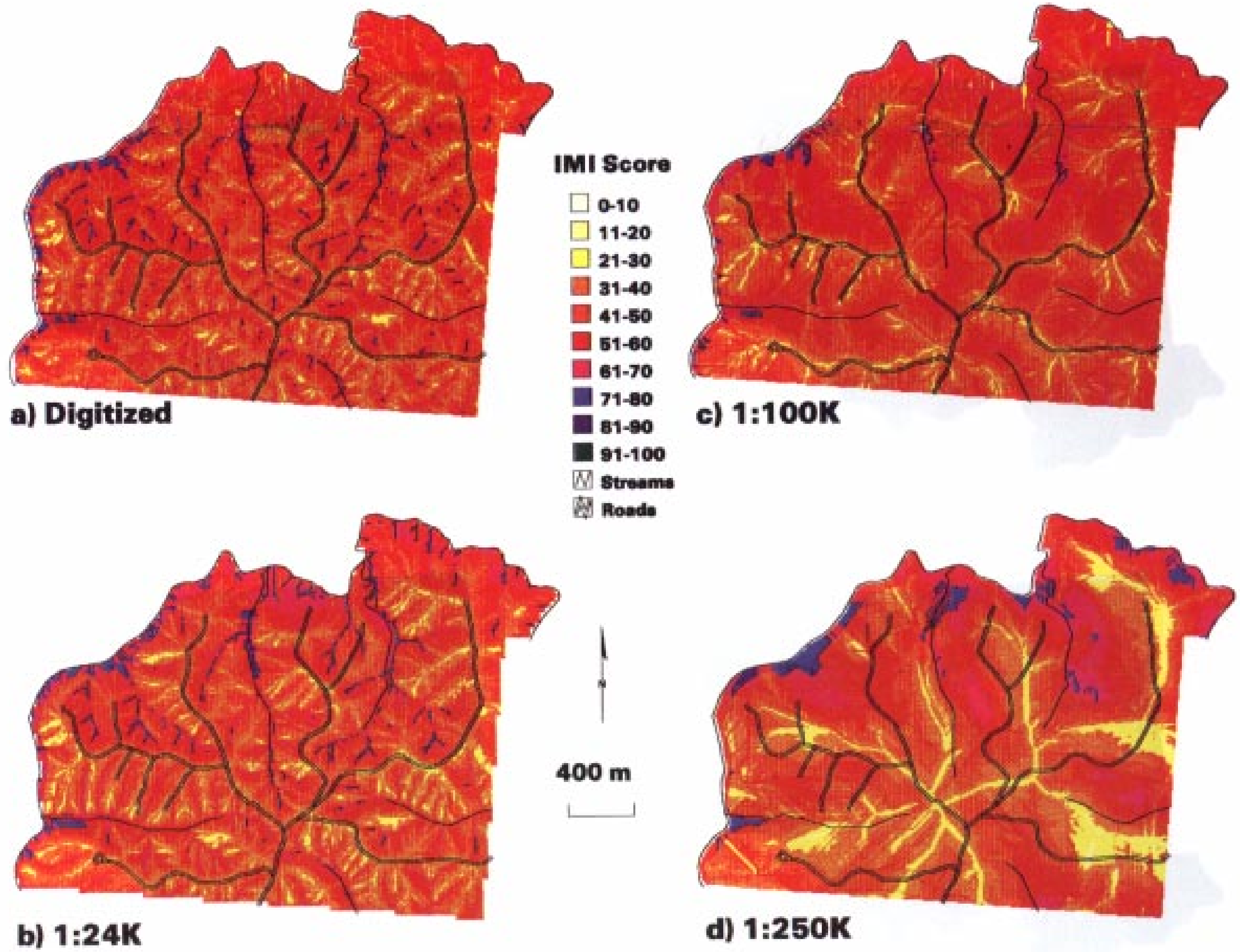

Fig. 5. IMI maps produced from data at four scales: (a) DIG, (b) 24K, (c) 100K, and (d) 250K.

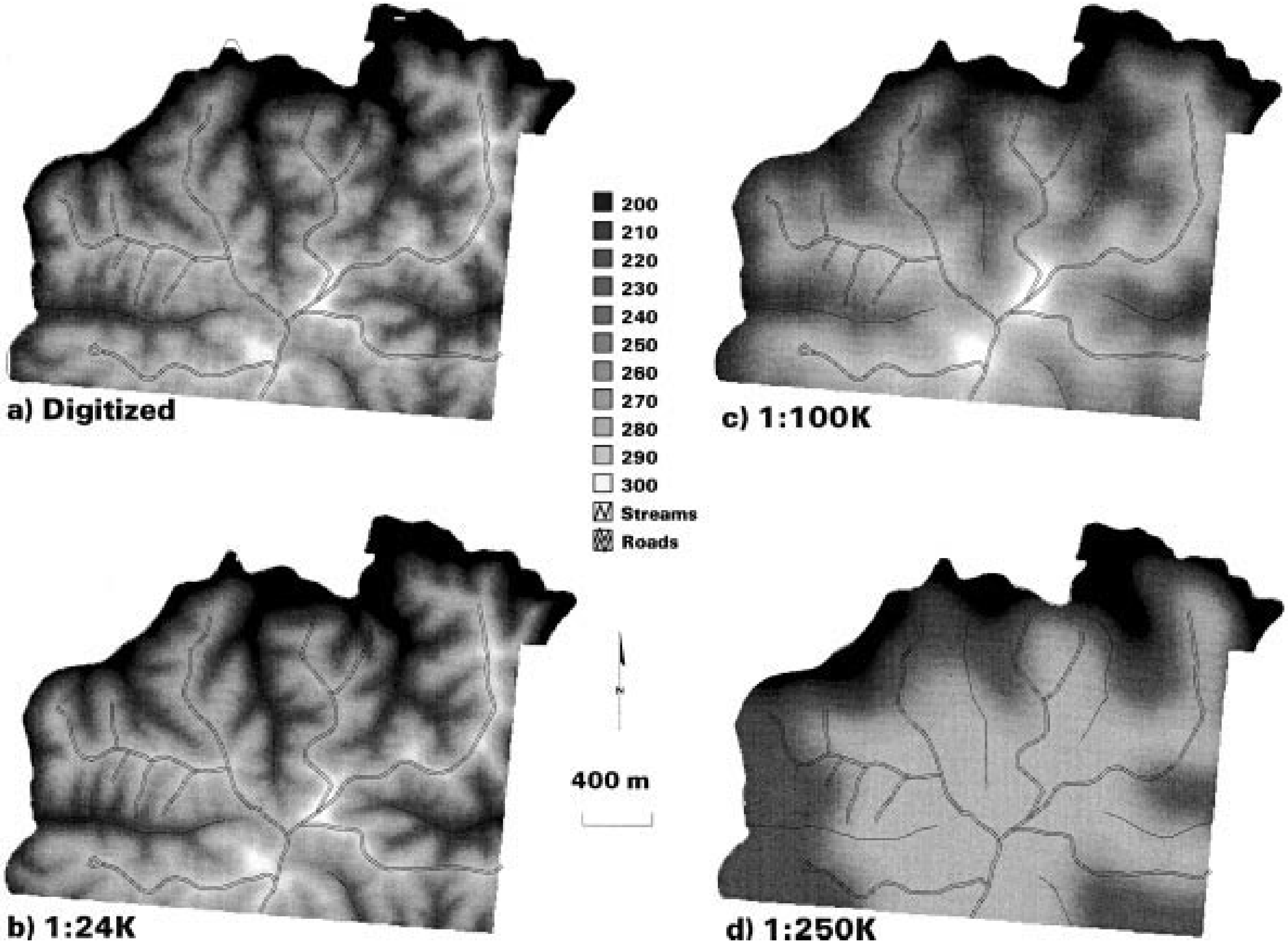

Fig. 6. Elevation maps produced from data at four scales: (a) DIG, (b) 24K, (c) 100K, and (d) 250K.

Table 2. Cross correlation statistics for 7.5 m grain size data among the four scales of data for maps of elevations, hillshade, flow accumulation, curvature, and integrated moisture index (n = ~93,700). Because of the large number of samples, any correlation coefficient above 0.25 can be considered highly significant (P < 0.001).

	DIG× 24K	DIG× 100K	DIG× 250K	24K× 100K	24K× 250K	100K× 250K
Elevation	0.943	0.948	0.610	0.945	0.634	0.678
Hillshade	0.860	0.715	0.053	0.812	0.081	0.148
Flow accum.	0.392	0.264	–0.021	0.370	–0.009	–0.022
Curvature	0.462	0.291	0.009	0.355	0.007	0.033
IMI	0.645	0.524	0.191	0.630	0.217	0.204

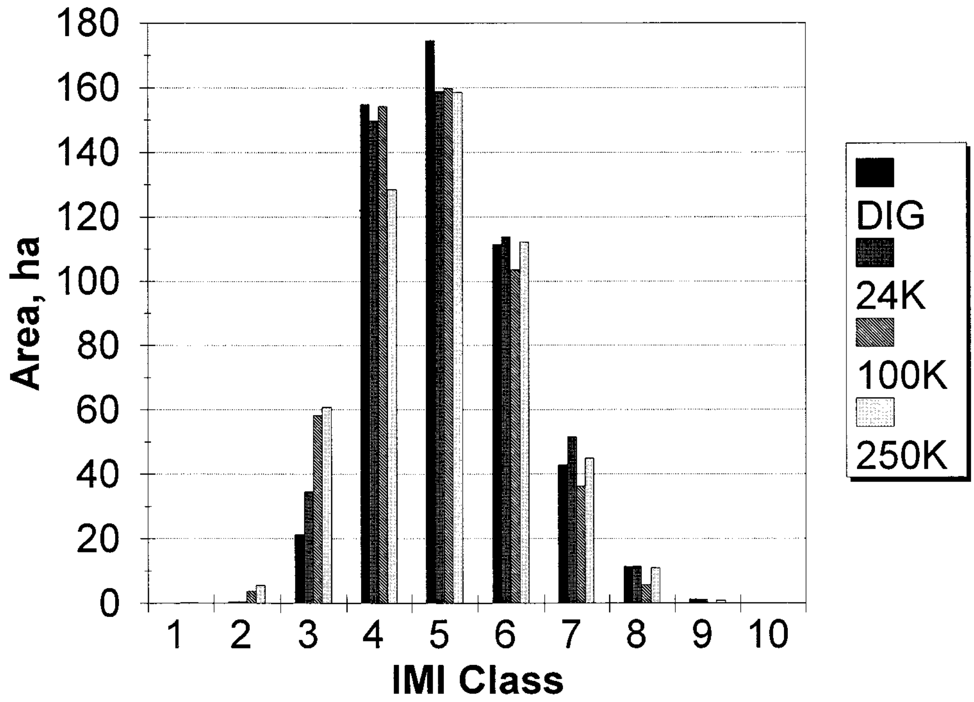

Fig. 7. Histogram of area occupied by each of five classes of IMI for DIG, 24K, 100K, and 250K data.

The derived IMI values were compared among scales in several ways. A histogram of IMI scores for the four datasets possess a similar distribution (Fig. 7). Even the 250K data do not differ markedly from the other data sources in overall distribution of IMI.

The same soils data (Fig. 4d for DIG data) were used for each of the four scales of analysis, but the other three input variables (Fig. 4a, b, c) were derived from different elevation data sources. For each of hillshade, flow accumulation, curvature, and IMI, the DIG data were most correlated with 24K data, with a slight degradation of DIG to 100K (Table 2). After DIG × 24K, the best correlations were with 24K × 100K data. This close relationship can be attributed to the fact that the 100K topographic maps, even though relatively coarse grained, were created by generalizing from 1:24,000 topographic map sheets (U.S. Geological Survey 1989). The correlation analysis also showed that the derived files from the 250K elevation data were poorly correlated with those from the other data sources.

Among variables, flow accumulation and cur-

Table 3. Cross correlation statistics for 30-m grain size data among the four scales of data for maps of elevations, hillshade, flow accumulation, curvature, and integrated moisture index (n = ~5900). Because of the large number of samples, any correlation coefficient above 0.25 can be considered highly significant (P < 0.001).

	DIG× 24K	DIG× 100K	DIG× 250K	24K× 100K	24K× 250K	100K× 250K
Elevation	0.947	0.919	0.608	0.910	0.611	0.667
Hillshade	0.935	0.696	0.042	0.676	0.031	0.160
Flow accum.	0.565	0.307	–0.051	0.257	–0.038	–0.003
Curvature	0.557	0.300	0.019	0.229	0.021	0.009
IMI	0.770	0.532	0.106	0.485	0.123	0.181

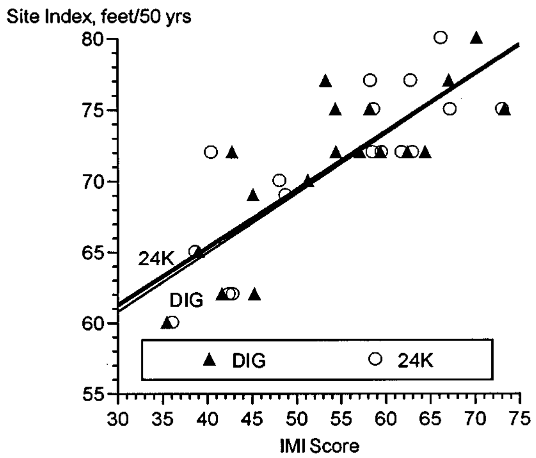

Fig. 8. Linear regression relationship between oak site index and IMI (DIG and 24K data) for 23 plots in the Vinton Furnace Experimental Forest. R^2 values for the regression lines were 0.64 (DIG) and 0.63 (24K).

vature had lower correlations among scales compared to elevation, hillshade, and IMI (Table 2). These variables are very sensitive to subtle differences in elevation so that pixel-by-pixel correspondence can fluctuate widely even though trends are similar.

When all maps were converted to a 30-m grain size, correlation trends were similar (Table 3). The relationships between DIG and 24K data were somewhat stronger, and the correlation for flow accumulation and curvature were higher for these pairs of maps. In this case, aggregation of finely-scaled pixels averaged for a 4 × 4 cell area allowed the spatial averaging of subtle differences, and the correlation were enhanced. Comparisons involving the 250K or 100K data generally were less correlated compared to data for the 7.5-m grain size. The correlation enhancement by subsampling coarse (100K and 250K) data indicates the probable value of smoothing the coarser data via stepwise resampling with bilinear interpolation so that abrupt changes in elevation between cells are not apparent.

3.3. Predicting site index and composition

Oak site index as determined from 18 plots was similarly related (R^2 = 0.63–0.64) to the DIG and 24K IMI estimate (Fig. 8). The 100K data did not show a significant relationship to site index, though the slope was in the correct direction. For the 250K data, however, statistical and visual comparisons indicate that these data seem unreliable for predicting site index for individual sites.

With the DIG and 24K data, ground estimates of percent oak composition were negatively related to IMI: the higher the moisture levels, the lower the proportion of oak (Fig. 9). Conversely, the proportion of yellow poplar and black cherry increased with increasing IMI scores (Fig. 10). Again, there was no significant relationship between IMI for the 100K data and the proportion of oak or yellow poplar and black cherry. Red maples are able to survive across a full spectrum of IMI values; although they seem most common on intermediate sites, we found no statistical relationship between IMI and the proportion of red maple.

The relationships developed allowed a GIS modeling of oak site index (Fig 11a, using DIG data only), which shows highest values in the valley bottoms and lowest values on upper south-fac-

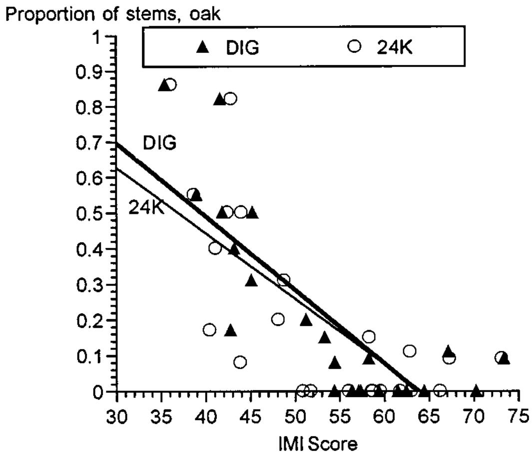

Fig. 9. Logistic regression relationship between percent composition of oaks and IMI (DIG and 24K data) for 23 plots in the Vinton Furnace Experimental Forest. P values for the relationships were 0.010 (DIG) and 0.016 (24K).

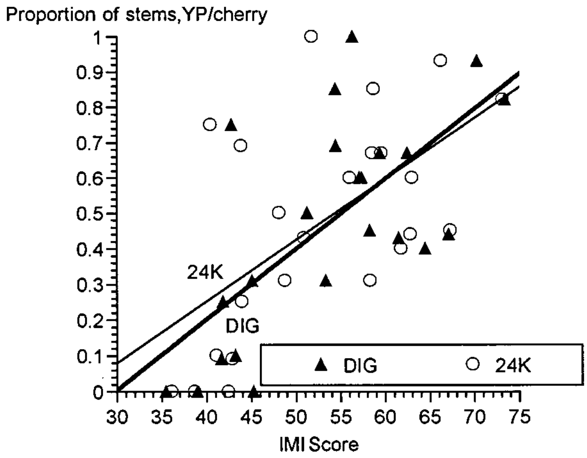

Fig. 10. Logistic regression relationship between percent composition of yellow poplar plus black cherry and IMI (DIG and 24K data) for 23 plots in the Vinton Furnace Expimental Forest; P values for the regression lines were 0.040 (DIG) and 0.083 (24K).

ing slopes and ridgetops. The map visually agrees well with data and decadal observations of the study area. According to our model, the overall average estimate for site index was 67 feet (20.4 m) at base age 50.

The logistic regression-derived map of percent oak composition for DIG data shows oak to be concentrated in relatively small, dry locations where site indexes are lowest (Fig. 11b). Conversely, quite large portions of the study area are projected to have, in the next forest, very low proportions of oak. A comparison of this model's projection of percent oak with that of an independent data set of 24 plots from the northern portion of the study area yielded a linear regression R^2 of 0.70, thereby validating the reasonableness of model results.

Because the regressions for yellow poplar plus black cherry were in the opposite direction from the oak regressions (Figs. 9–10), the mapped proportions of stems in yellow poplar plus black cherry are inverse to that of oak (Fig. 11c). They are concentrated in the more moist areas on the map. On the basis of the independent data set as well as many field observations in cutover areas, the maps project reasonable estimates of the composition of the primary species that has occurred or will occur following disruption (through natural or human-induced effects) of the current oak-dominated canopy. According to our regression results, if this disruption would occur over the entire Vinton Furnace Experimental Forest, one could expect an overall proportion of 34% oak and 34% yellow poplar and black cherry in the next forest. The remainder undoubtedly would be primarily red maple. Of course, management activities could change the successional pathways predicted here if they significantly altered the overstory or understory structure, using various site modifications, fire, or other treatments. The predictive maps shown here relate strictly to natural regeneration without human modifications after canopy removal.

4. Discussion

4.1. DEM evaluation

As expected, there was a general decrease in the quality of the results as the source data became more coarse. Estimates of slope angles, aspects, and locations of specific ridges and valleys were not reliable with 250K data. Thus, the 250K data are not recommended for predicting future composition at a detailed (*e.g.*, ridge to ridge) scale. However, the DIG and 24K data were reliable for this application. The reliability of the 100K data is ambiguous. On the basis of correlation and visual analysis, 100K data seem to be closely corre-

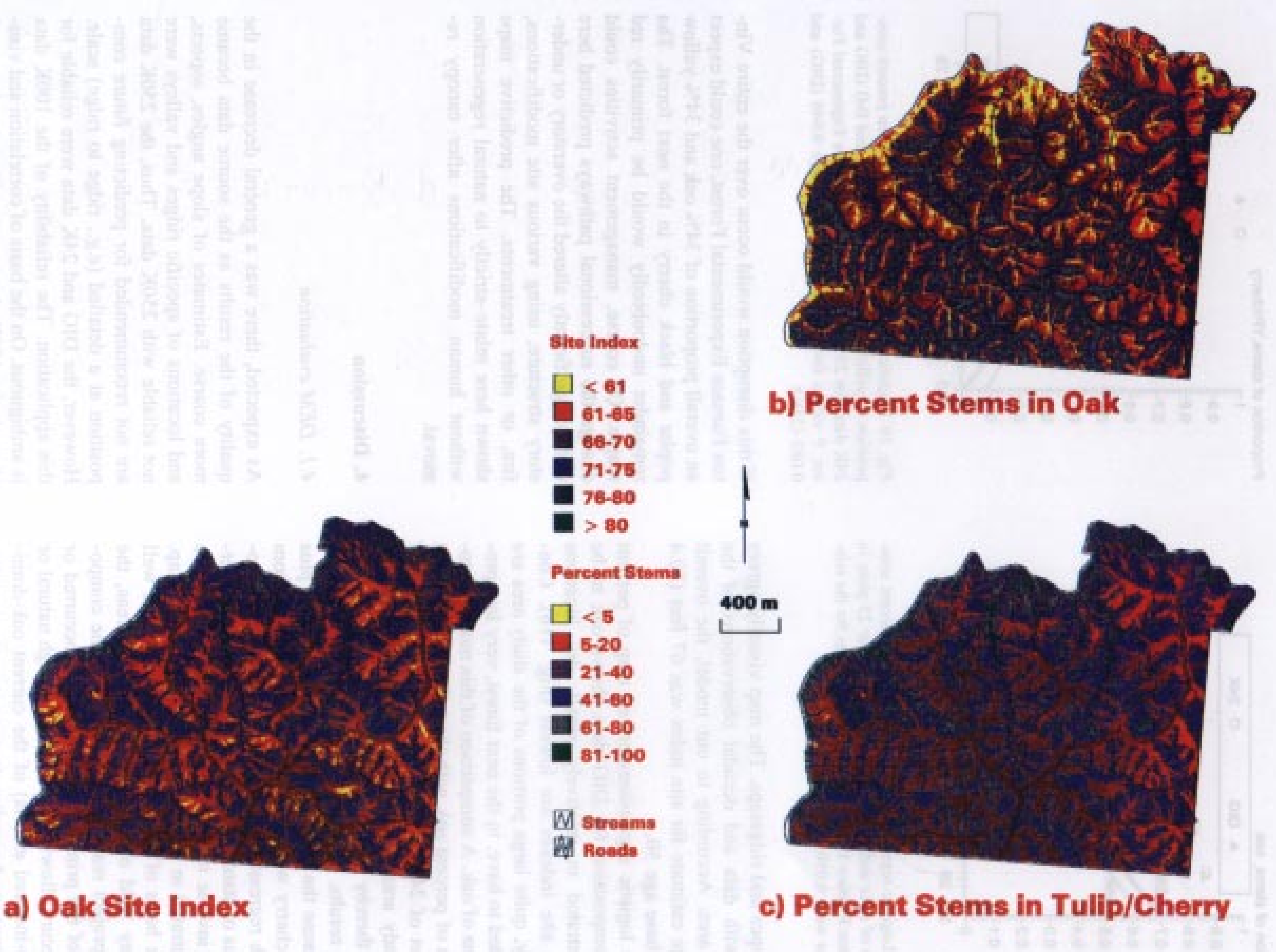

Fig. 11. GIS model outputs for the Vinton Furnace Experimental Forest (DIG data only): a) estimated site index for oaks, b) probable oak composition of the next forest, following breakup or disturbance on the present canopy, and c) probable yellow poplar plus black cherry composition of the next forest.

lated to the DIG and 24K data (Table 2, Figs. 5–6), so that one would expect the IMI to be fairly reliable. However, regressions of site index and percent composition were not significant for 100K data, unlike those for the DIG or 24K data (Figs. 8–10). Further assessments of the 100K DLG data are needed before this application can be recommended for detailed analysis and prediction. It may be that IMI differences between 100K and finer scales are especially large only for that portion of the experimental forest where the field plots were located. However, we are confident that the 100K data can provide sufficient specific topographic information for calculating the IMI at a relatively coarse resolution over large areas. The 100K DLG data soon will be available for the entire country so that statewide or even larger regional assessments will be possible.

4.2. Integrated Moisture Index

This GIS procedure produced a realistic distribution map of the IMI. In addition to the site index and tree composition presented here, the IMI can be related to many ecological processes which are related to water availability across landscapes. Increasing experience with IMI has shown it to be a valuable integrator of ecosystem function. For example, IMI classes are being used to stratify a landscape-level experimental design assessing the effect of fire on mixed-oak forest communities (Iverson *et al.* 1996). The effects of fire on understory, overstory, soil nutrients and pH, regeneration, and animal distribution are being assessed by moisture regime. Preburn analyses show IMI to be correlated, often the *most* correlated variable, to understory vegetation patterns (Iverson *et al.* 1996) and species richness (S. Sutherland, personal communication), litter depth (T. Hutchinson, personal communication), soil pH and nitrates (R. Boerner, personal communication), and the distributions for several bird species (R. Dettmers, personal communication).

4.3. Site index

Field estimates of site index historically have been problematic because of difficulties in obtaining adequate, free-to-grow trees for estimating height growth over 50 years without disturbances (Monserud 1984; Berguson *et al.* 1994). The method presented here, when properly calibrated, may be as good as or even better than field methods, because it is repeatable and consistent over time and over large areas. It is especially useful for making relative assessments of site-specific productivity potentials across landscapes within a management unit. Unlike traditional measures of site index, it is not affected by disturbances in the canopy (*e.g.*, ice storms) which can artificially reduce estimates. For measures of site quality, this effect is advantageous unless the site's potential has been altered significantly by a disturbance.

4.4. Composition

Reasonable estimates of proportions of oak or yellow poplar plus black cherry were mapped via the GIS regression model used here (Fig. 11b, c). Future stands dominated by oaks will be concentrated in low-site index areas (low IMI scores) where competition from more mesic and tolerant species will be minimized and oak regeneration can proceed. If a high level of oak was the desired future condition, management activities could be concentrated on those areas with intermediate IMI scores, *i.e.*, where oak regeneration was quite low naturally, but where fire or group selection cuts could shift the balance in favor of oaks. Limited management resources could thus be targeted where they will do the most good.

The value of the IMI for predicting future composition has a strong basis in the physiology, anatomy, and ecology of mixed oak communities. Oaks are relatively more tolerant of moisture stress because of the morphological and anatomical characteristics of oak leaves and xylem, as well as the carbon allocation patterns that favor root growth. These characteristics allow for better growth and a competitive advantage under moisture-stressed conditions (Rogers 1990; Hodges and Gardiner 1993).

Poor oak regeneration on sites of relatively high oak site index most often is due to a slow juvenile growth rate of oak seedlings under a closed canopy and their inability to respond quickly to release after canopy disturbance. Although white oak seedlings may live up to 90 years in the understory (Rogers 1990), they are slow to acclimate to changed conditions and unable to take full advantage after release on good sites. Oaks are therefore at a competitive disadvantage with the shade-tolerant red maple as advanced regeneration proceeds under the current oak-dominated canopies, which typically have low light penetration. At the other extreme, oak also does not compete well in full sunlight relative to intolerant species such as yellow poplar and black cherry.

Yellow poplar and black cherry were concentrated in the mesic sites with high oak site-index values (Fig. 11a, c). If the area were to undergo a severe windstorm or harvest, or if left to proceed to old-age mortality, we would expect the patterns of distribution shown in Figure 11c for yellow poplar and black cherry. Both species are intolerant to shade but have high growth rates in full sunlight (Beck 1990; Marquis 1990). On land of site index 75 feet or higher in the southern Appalachians, yellow poplar has faster height growth up to 50 years of age than any of its associates except white pine. It also expresses dominance well and may form nearly pure stands on good sites. Both species grow best in moderately moist, well-drained, and loose-textured soils, on north and east aspects and lower slopes, in sheltered coves, and on gentle, concave slopes (Beck 1990; Marquis 1990). These are precisely the locations with high IMI scores and, consequently, high concentrations of yellow poplar plus black cherry (Figs. 5a and 11c).

We did not find a significant linear relationship between red maple and IMI, as red maples were found fairly consistently over a wide range of IMI. Red maple is one of the most abundant and widespread trees in eastern North America (Hutnick and Yawney 1961), and probably can thrive on a wider range of soil types, textures, moisture, pH, and elevation than any other forest species in North America (Hepting 1971; Golet *et al.* 1993). It is expanding in dominance throughout its range and is able to increase following disturbances such as disease, windthrow, and harvesting (Bowersox and Ward 1972; Good and Good 1972). These patterns also are apparent from this study; though field observations tended to reveal a slightly greater preponderance of red maple in the compositional mix when site index was intermediate, *e.g.*, after cutting, red maple will dominate so long as sites are not too dry (oak) or too mesic (yellow poplar and black cherry). Also, red maple is highly susceptible to fire damage.

Finally, we have shown that the integrated moisture index (IMI) can be simply derived in a GIS from readily-available topographic data (DEM) and soils maps. The index itself requires no field assessments or current vegetation maps. It is time-invariant and is consistent between areas to be assessed. It is, however, simply an index that needs to be related to site-specific conditions for the ecosystem characteristics of interest. The IMI has been related to site productivity (site index) and to species composition in Ohio. It has also proven useful for predicting various ecosystem attributes such as understory vegetation patterns, species richness, soil pH and nitrates, and bird species distributions. We anticipate that the index will perform well in a variety of ecological applications, though it must be calibrated to the specific location and application in question. As a general index, it may not be optimized for any particular application, but can be expected to perform well in those applications where moisture is a key driving variable to the ecological pattern or process. The use of the integrated moisture index is recommended as a site attribute for analyzing and modeling ecosystems where moisture is limiting.

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