Development of an Integrated Moisture Index for Predicting Species Composition

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Abstract

A geographic information system (GIS) approach was used to develop an Integrated Moisture Index (IMI), which was used to predict species composition for Ohio forests. Several landscape features (a slope-aspect shading index, cumulative flow of water downslope, curvature of the landscape, and the water-holding capacity of the soil) were derived from elevation and soils data to create the IMI. From IMI values for forest land harvested in the past 30 years, we estimated the percentage composition of two major forest types in the region as well as the prominence of many understory species and several bird species. This approach can be used to better manage forest resources and to predict how the resource will change in the future under various forms of ecosystem management.

1. Introduction

It has been known for some time that the distribution and growth of trees in the Eastern United States are correlated with local topography and soils, but the relationships have been difficult to quantify and map (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 *(Liriodendron tulipifera)* 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 mostly related to the soil water reservoir. Slope, aspect, position, and effective soil depth were the main 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 is a site that has a prevailing water table within 2 m of the surface where ground water would be available for tree growth (Loucks 1962). Host *et al.* (1987) also reported that forest successional pathways in Michigan were strongly related to topographic and edaphic conditions, again largely due to variations in moisture availability.

The above-described relationships indicate that geographic information system (GIS) technology may be ideally suited to model landscapes for moisture level. Digital elevation models (DEM) (U.S. Geological Survey 1987) have been very useful in deriving topographic features associated with landscape processes (Jenson and Dominque 1988, Skidmore 1990, Twery *et al.* 1991, Mitasova *et al.* 1995). Digital elevation data also have been used in combination with remotely sensed and other data to derive maps of forest composition and biomass (Iverson *et al.* 1994).

In this study, our objectives were to: 1. develop a model predicting an Integrated Moisture Index (IMI) based on DEM and soils data, 2. use the IMI to estimate species composition across landscapes, and 3. use canonical correspondence analysis to further understand species-environment relationships.

2. Methodology

2.1 Study Area

The study area for the development and testing of these objectives was the Raccoon Ecological Management Area, in Vinton County, southeast Ohio, USA. The area lies within the Unglaciated Allegheny Plateau and has a mature topography 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 funaces in the region. Since then, the forests have reverted to oak-dominated canopy trees and have been the site of extensive research on cutting practices, and uneven-age and even-age silviculture for oak-hickory forests (e.g., Hilt 1985).

The 6880-ha forest is owned by Mead Paper Corporation and is co-managed as a research forested landscape with the USDA Forest Service. The primary data used in the study came from the Vinton Furnace Experimental Forest and the Arch Rock Study Area within the management area. Four other sites in Vinton and Lawrence Counties also were evaluated for understory composition (Watch Rock, Young's Branch, Blugrass, and Sharp's Creek). These five sites are being thoroughly assessed ecologically through a large ecosystem management project on introducing prescribed fire to enhance fire-adapted communities in southern Ohio.

The area is typical of upland forests which are mostly a complex mosaic of oak-hickory and mixed-oak communities (ranging from drier to more mesic conditions), with some oak--yellow poplar and mixed mesophytic communities in the ravines and other mesic landscape positions (Beatley and Bartley 1959). The oak-hickory (especially chestnut oak *(Quercus prinus))* community is indicative of locations with low soil moisture during parts of the year, whereas yellow poplar and especially the yellow buckeye (*Aesculus octandra)* and beech (*Fagus grandifolia*) are indicative of locations requiring constant and relatively high soil moisture levels. These complex mosaics are primarily affected by the overlying complexities in topography and soils.

2.2 Development of IMI

The IMI was developed to integrate GIS-derived topographic features of the landscape into one variable that can be treated statistically. The resulting IMI can be used to predict composition of various organisms, including trees, understory species, birds, and herptiles. If there is minimal variation in disturbance history and soil fertility among upland sites, the main driver to plant (and some animal) distributions is related to moisture availability. Moisture levels will be higher where direct solar radiation is minimized, in lower positions on slopes or in depressions; and in soils of suitable depth, texture, and organic matter content.

IMI is modeled here as a function of:
solar radiation potential, or hillshade (40% of model weight) +
flow accumulation of water downslope (30%) +
total available water capacity of soil (20%) +
curvature of the landscape (10%).

Maps of hillshade, water flow, and curvature were created with DEM data at a resolution of 7.5 m and were generated from digitized contours of U.S. Geological Survey 7.5 minute topographic maps (Fig. 1). The objective was to create realistic surfaces related to moisture conditions across the landscape. To capture the effects of differential solar radiation due to variation in slope and aspect, and to create a hillshade map with increasing scores equivalent to increasing moisture content, a solar altitude of 45 degrees and a solar azimuth of 22 degrees (NNE) was selected. To map water flow, a grid was created that shows the accumulated flow of water to each cell as water moves downslope; ridgetops would have a flow accumulation of only 1 while the valley bottoms would have maximum accumulation. Curvature was mapped by calculating the curvature (i.e., convexity or concavity) at each cell center -- increasing scores were equated to increasing moisture content (increasing concavity).

To map estimated total available water capacity, soil series were digitized (originally mapped at a scale of 1:15,840 by the USDA Soil Conservation Service). Soil map units were converted to estimates of soil depth (A plus B horizons) and available water capacity (per unit depth), which were used to calculate a measure of total available water capacity.

Each of the above four factors -- hillshade, flow accumulation, curvature, and total water-holding capacity -- were then scored from 0 to 100 to facilitate calculation of the Integrated Moisture Index. After numerous iterations associated with on-site visits and field experience, the weights selected for use in the GIS model for the IMI were hillshade (40%), flow accumulation (30%), total water-holding capacity (20%), and curvature (10%). The final IMI score then potentially could range from 0 to 100, with increasing scores indicating increasing moisture levels for plant growth.

2.3 Applications of IMI

2.3.1 Predicting Composition

Percentage of composition of oaks (mostly white oak (*Quercus alba*), chestnut oak, scarlet oak (*Q. coccinea*), black oak (*Q. velutina*), and northern red oak (*Q. rubra*)), red maple (*Acer rubrum*), yellow poplar, black cherry (*Prunus serotina*), and several other minor species was calculated for trees (> 10cm dbh) in 23 plots that were naturally regenerated after clearcutting in the 1960s. Average IMI scores were obtained for each plot (using the zonalstats function in Arc/Info Grid), and were regressed against the percentage of composition of oaks, red maples, and yellow poplar plus black cherry. Yellow poplar and black cherry were combined, as were the oaks, because of their close association with each other in the field.

The linear regression analysis of IMI with field plot estimates was then used to convert the 0 to 100 IMI scores to GIS-modeled estimates of %oak or %yellow poplar + black cherry. No attempt was made to model composition of red maple because the IMI-maple regression r^2 value approached zero.

2.3.2 IMI Related to Understory Vegetation

To better understand the relationship of IMI and understory vegetation, field quadrat data were gathered and analyzed using canonical correspondence analysis (ter Braak and

Prentice 1988). Frequency of each species was recorded for sixteen 2- x 1- m quadrats within each of six replications for three IMI classes (dry, intermediate, and moist) on five sites in southern Ohio -- a total of 90 plots. Field work was accomplished during August and early September 1994. These data comprised the 'species data' for canonical correspondence analysis, as performed in CANOCO (ter Braak 1992).

Each plot was precisely located on the GIS using differentially corrected global positioning system (GPS) technology. Estimates of IMI and its components (hillshade, flow accumulation, and total soil water-holding capacity) were obtained from the GIS for each plot location. Elevation and northings also were obtained using the GPS. In addition, field measurements of slope were obtained for each plot location, as were soil samples for laboratory analysis of pH, NO_3, NH_4, and proportion of sand, silt, and clay. These data comprised the 'environmental data' in CANOCO.

Canonical correspondence analysis is a technique to derive optimally a linear combination of environmental variables that best explains the species data in such a way as to maximally disperse the species scores. This technique is gaining popularity for exploring species-environment interactions. With CANOCO, it was possible to generate triplots, where (1) environmental variables, (2) individual species, and (3) field plots could be graphed in two dimensions to visualize relationships among them. Environmental variables are delimited as arrows with length related to correlation strength and direction related to correlation to species, plots, and other environmental variables. With the plotting program, CANODRAW (Smilauer 1992), many graphic representations of the data can be generated.

2.3.3. IMI Related to Other Organismal Distributions

Because of the ecosystem management study funded by the USDA Forest Service in southern Ohio, a large amount of other biological data is being collected. The IMI is being used as a stratifier to set up the sampling locations and as a variable for post-data collection analysis and modeling. For example, data are being collected on bird locations, bird nest locations, telemetry locations of the timber rattlesnake, overstory trees, regenerating tree seedlings and saplings, soil microbiota and chemistry, and various insect collection locations. These data are being, or will be, related to IMI as well.

3. Results and Discussion

3.1 IMI Generation

The IMI was derived from four variables: water flow accumulation, hillshade, curvature, and soil water-holding capacity (Fig. 1). The highly dissected nature of the area is readily apparent from the water flow map (Fig. 1a), which is a result of simply counting the number of cells contributing water downslope to each cell. The map shows the road and trail network following the ridgelines (which have low scores because few cells will have water flowing to them) and the many small streams with higher scores because of water flowing downslope to them. The hillshade map readily shows a moisture gradient from SSW slopes to NNW slopes (Fig. 1b). The curvature map generally captures small coves and depressions with higher scores, and small knolls with lower scores (Fig. 1c). Finally, the total available water capacity map -- the product of soil depth (A plus B horizons) and available water capacity through the solum -- shows higher scores in the valleys where the soil is deeper and often siltier (Fig. 1d).

The resulting model of IMI (Fig. 2a) reveals a general pattern of low scores (drier conditions) at the ridgetops and south-southwest facing slopes, especially when the soils are shallow. The deep soils and high flow accumulation along the Elk Fork (the northern boundary of the study area) are apparent with the highest IMI scores. Equally apparent is the extremely heterogeneous nature of the landscape -- within any 20-ha area, for example, one can find nearly the entire range of IMI scores.

3.2 Predicting Future Tree Composition

The ground estimates of the percentage of oak composition were negatively related to IMI: the higher the moisture levels, the lower the proportion of oak (Fig. 3). Conversely, the proportion of yellow poplar and black cherry increased with increasing IMI scores (Fig. 3). Red maples are able to survive across a full spectrum of IMI values, and, although they seem to be most common in the intermediate sites, no statistical relationship was uncovered between IMI and proportion of maple.

A regression-derived map of %oak composition showed oak concentrated in relatively small locations where the lowest site indexes occur (Fig. 2b). The mapped proportions of stems in yellow poplar plus black cherry are inverse to that of oak (Fig. 2c). They are concentrated in the moister areas on the map. Field observations in cutover areas confirm that the maps project reasonable estimates of the main species composition that has occurred or will occur following the disruption (through natural or human-induced effects) of the current oak-dominated canopy. According to our regression-derived maps, if this disruption would occur over the entire Vinton Furnace Experimental Forest, one could expect an overall proportion of 36% oak and 32% yellow poplar or black cherry in the next forest.

3.3 IMI Related to Understory Vegetation

CANOCO analysis of 12 environmental variables (IMI, hillshade, flow accumulation, soil water-holding capacity, soil nitrate, soil ammonium, pH, percent clay, sand and silt, elevation, and slope) for 62 species at one site (Arch Rock, in Vinton County) showed a very close relationship between the X axis and IMI (Fig. 4). The derived IMI variable best explains the species data as visualized by the IMI line being placed right next to the first principal axis. Other variables linked to the X axis include hillshade, water-holding capacity, pH, elevation (negatively), and soil nitrate. The lengths of the arrows also indicate that the relationship is strongest with the IMI variable. The X axis can thus be considered a moisture gradient from dry (left) to moist. 'Envelopes' simply drawn around all the plots classed as dry, intermediate, and moist also show the trend of dry to moist along the X axis. Species associated with particularly dry plots include CARTO (*Carya tomentosa*), QUVE (*Quercus velutina*), VAPA (*Vaccinium palidum*), and POST (*Porteranthus stipulatus*), while the moist species include ACSA (*Acer saccharum*), OSMCL (*Osmunda claytonia*), and GEMA (*Geranium maculatum*). Species in the intermediate zone could include some species specific to intermediate moisture, butmore often include generalist species found across the moisture gradient (e.g., ACRU, *Acer rubrum*; SMRO, *Smilax rotundifolia*; and DENU, *Desmodium nudiflorum*). This trend can be clearly seen in a plot of N2 diversity of some species in the same ordination space (Fig. 5), where the larger values (higher frequencies) are found with species near the origin of the axis.

When all five sites are included in the analysis, the plot gets considerably busier because we are dealing with 90 plots, but the general trends are the same (Fig. 6). IMI and hillshade are closely associated with the X axis that can thus be assumed to be a moisture gradient. The species described for Arch Rock also appear in similar positions in the ordination space. When the site centroids are plotted, they fall out with Arch Rock (ARC) and Watch Rock (WAT) on the bottom with a negative Y-axis score, and the other three sites with a positive score. This trend is related to latitude (northing), which is the most closely associated variable with the Y axis: WAT and ARC are northerly sites, while Young's Branch (YOU) is 50 km south, followed by the remaining sites that are 15 km farther south. We do not know if there is a climatic effect over this relatively short north-south distance, but it is possible; more likely it is an associated regional pattern of one or more geomorphologic variables.

The main conclusion of the CANOCO analysis is that the major environmental factor associated with the distribution of species within a site and among several sites is moisture availability, and that IMI does an excellent job of capturing this gradient.

3.4. IMI Related to Other Organismal Distributions

Preliminary analyses of bird distributions and the capacity to model their distributions across a landscape are yielding promising results. Using the IMI, curvature, and slope, Randy Dettmers has successfully modeled suitable habitat for acadian flycatcher (*Empidonax virescens*), worm-eating warbler (*Helmitheros vermivorus*), and hooded warbler (*Wilsonia citrina*) (Dettmers, personal communication). For example, more than 90% of acadian flycatchers were found in ravine bottoms with high IMI and concave curvature, while the worm-eating warbler was more closely associated with lower IMI classes farther upslope from the ravines.

Similarly, preliminary analyses of overstory tree data show definite trends with IMI. Species, such as chestnut oak (*Quercus prinus*) and scarlet oak (*Q. coccinia*), are closely tied to low IMI scores, while other overstory trees, such as sugar maple (*Acer saccharum*), are much more common on high IMI sites (Dan Yaussy, personal communication).

4. Opportunities for Use of IMI

The GIS was used successfully to prepare a realistic distribution map of IMI. The IMI can be related to many ecological processes occurring on landscapes, including distribution of several organism types as presented here, but also for general estimates of ecosystem productivity, heterogeneity, resilience and sustainability. The IMI is a valuable integrator of ecosystem function. The IMI is being used as a stratification variable in a landscape-level experimental design assessing the effect of fire on mixed-oak forest communities. It is being used to assess the effects of fire on herbaceous, overstory, regeneration, and animal distribution by moisture regime. The IMI is highly related to the distribution of many herbaceous species in the initial pre-burn assessments from this study. IMI will be tested in a major assessment of landscape relationships to sugar maple decline in northern Pennsylvania (S. Stout, personal communication).

The IMI also has management implications. It can be used as a tool for managing wildfire. Fuel loading and flammability are likely to be strongly related to IMI. Herbaceous and woody vegetation on sites with different IMI values will also respond differently to prescribed burning. IMI also has implications for developing silvicultural prescriptions. Regeneration will respond differently to the same silvicultural practice when applied to sites with different IMI values. Thus, the IMI provides a tool for the ecologist to build relationships with landscape processes and for the resource manager to ensure that management practices are suited to the sites involved.

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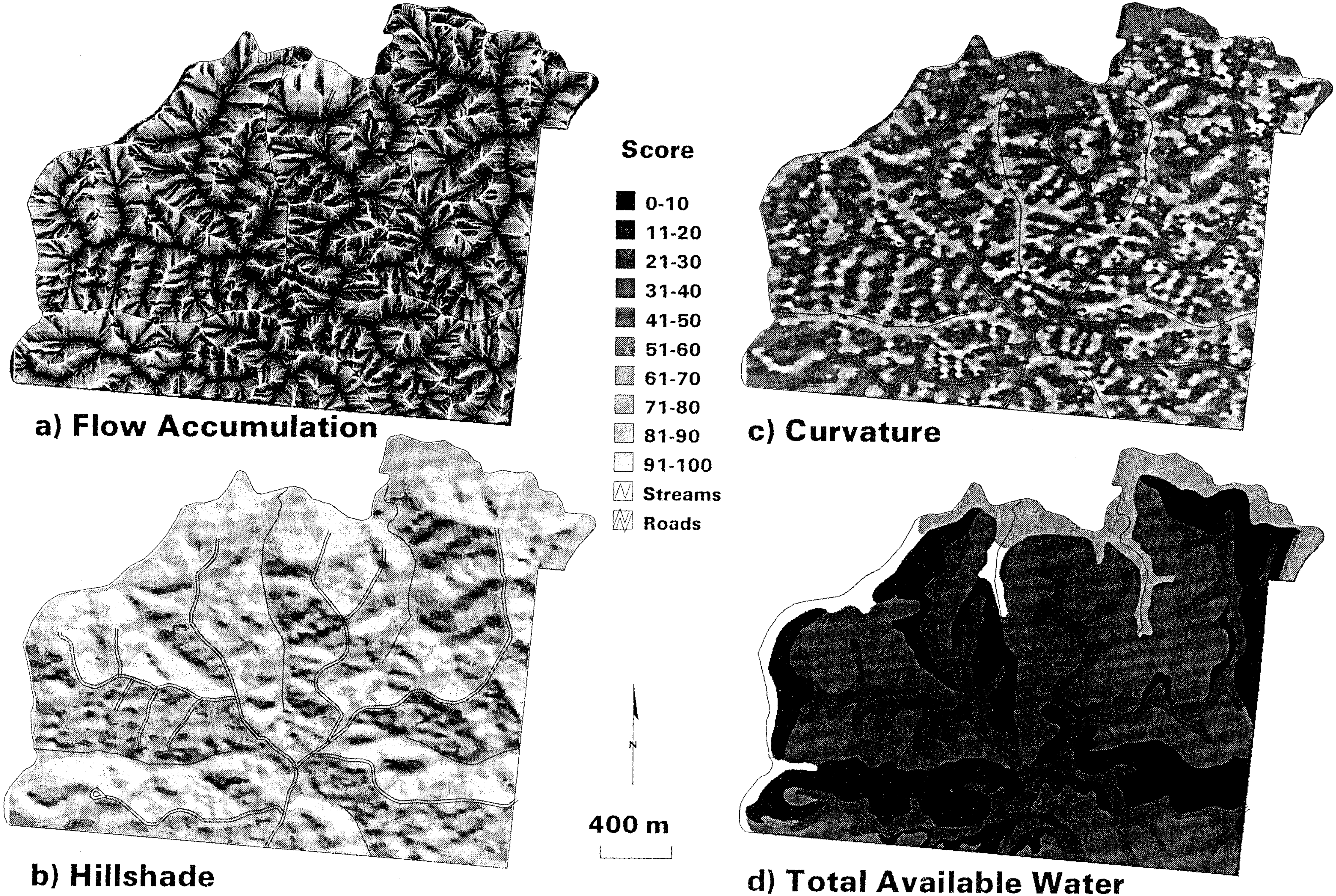
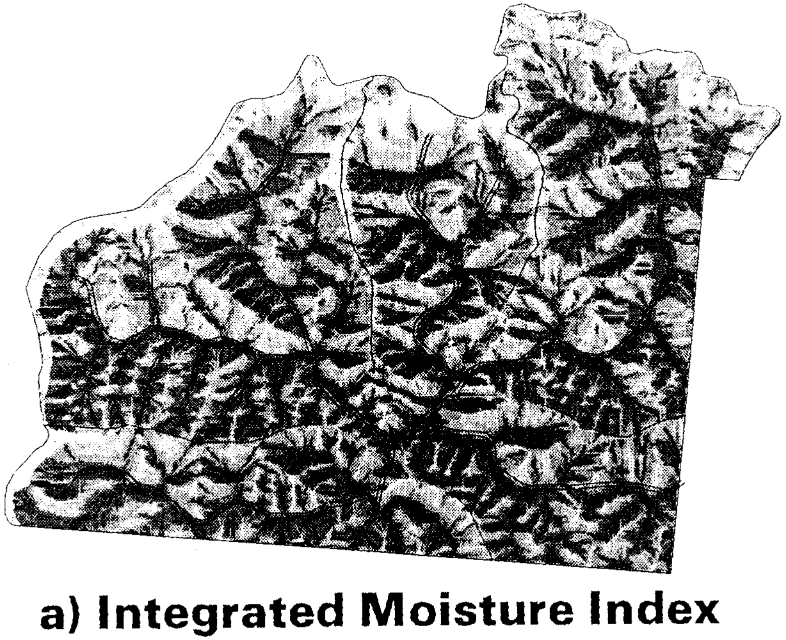


Figure 1. Maps indicating 0-100 scores for: a) flow accumulation, b) hillshade, c) curvature, and d) total water holding capacity for the Vinton Furnace Experimental Forest.



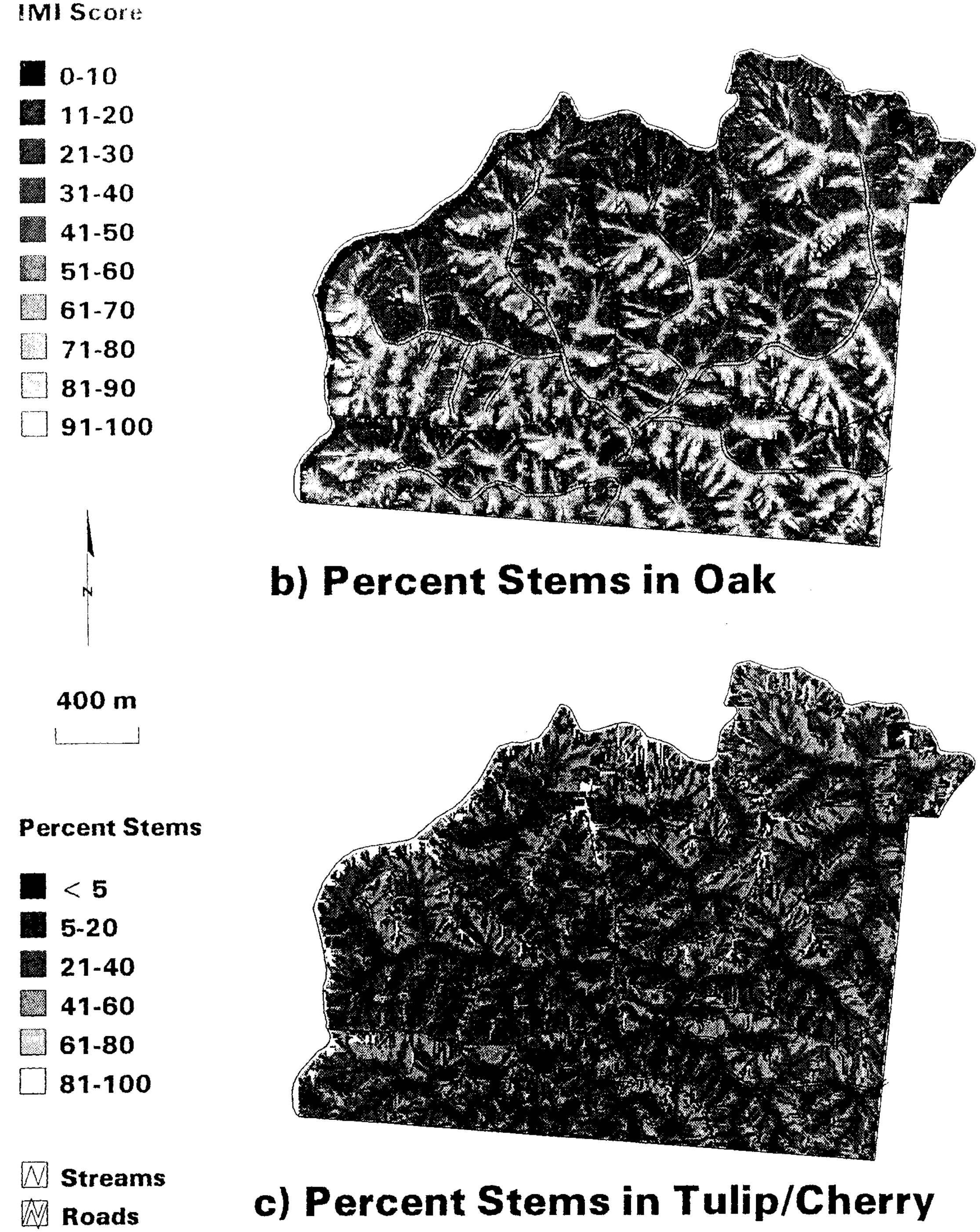


Figure 2. GIS model outputs for the Vinton Furnace Experimental Forest: a) Integrated Moisture Index, b) probable oak composition of the next forest, following breakup or disturbance of the present canopy, and c) probable yellow poplar plus black cherry composition of the next forest.

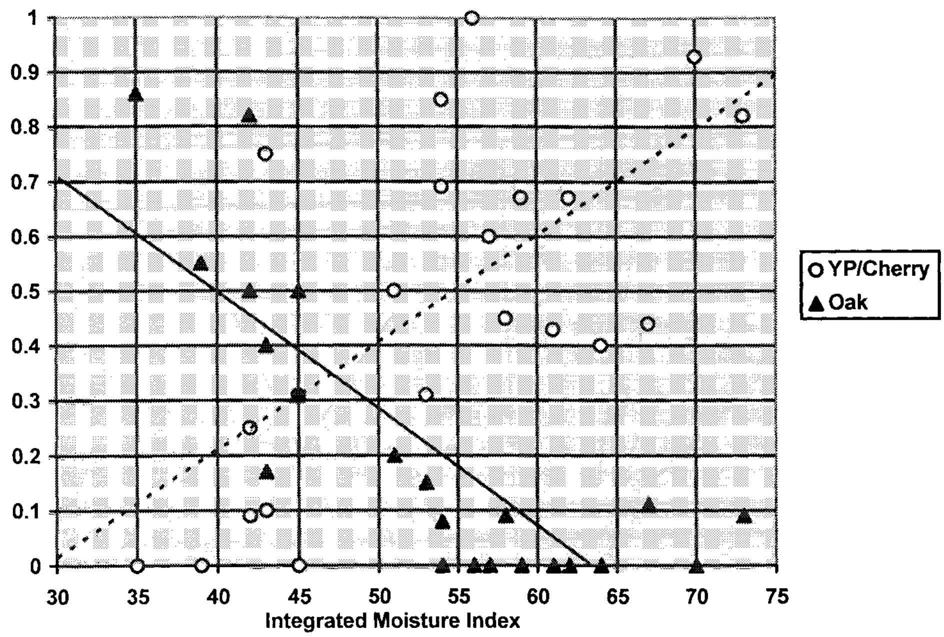


Figure 3. Linear regression relationship between IMI and percent composition of yellow poplar plus black cherry and of oaks for 23 plots in the Vinton Furnace Experimental Forest. R^2 values for the regression lines were 0.46 and 0.64 for yellow poplar and oaks, respectively.

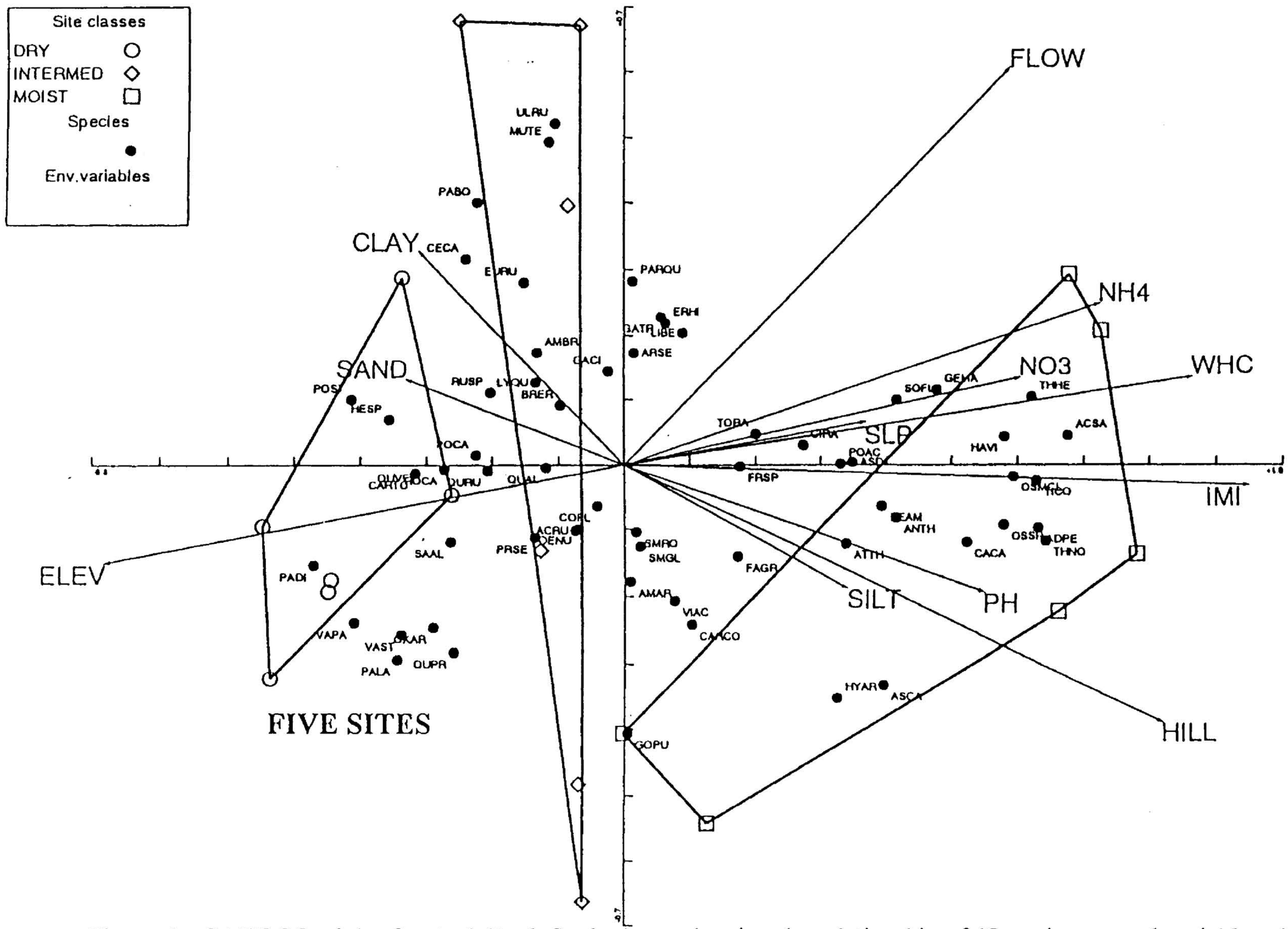


Figure 4. CANOCO triplot for Arch Rock Study Area, showing the relationship of 12 environmental variables, 18 plots, and 62 species in ordination space. Names for selected major species are given in the text (code consists of 2 letters of genus, 2-3 letters of species name).

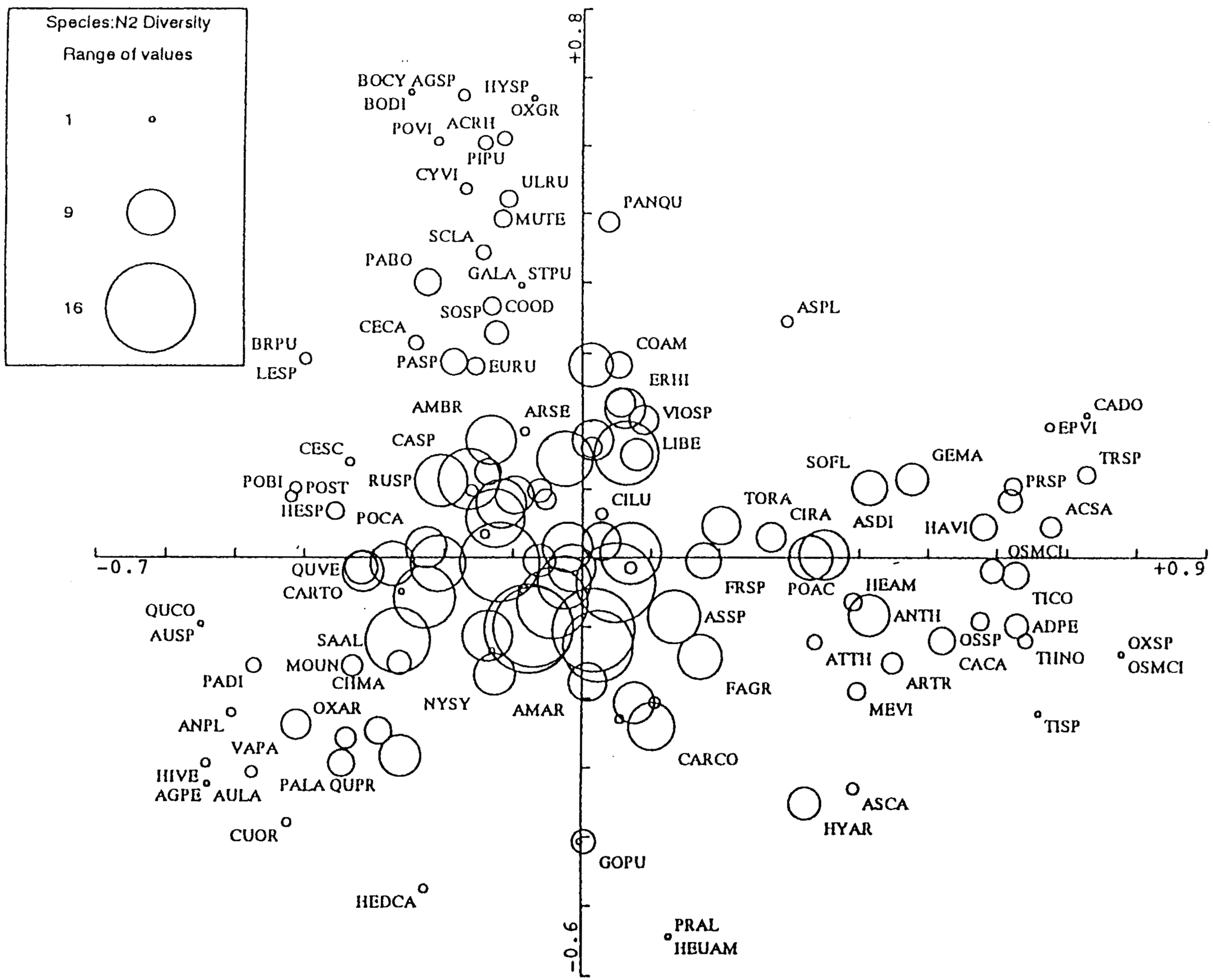


Figure 5. Plot of N2 species diversity at Arch Rock, showing specific nature of moist and dry species, and the more generalist nature of the intermediate moisture species.

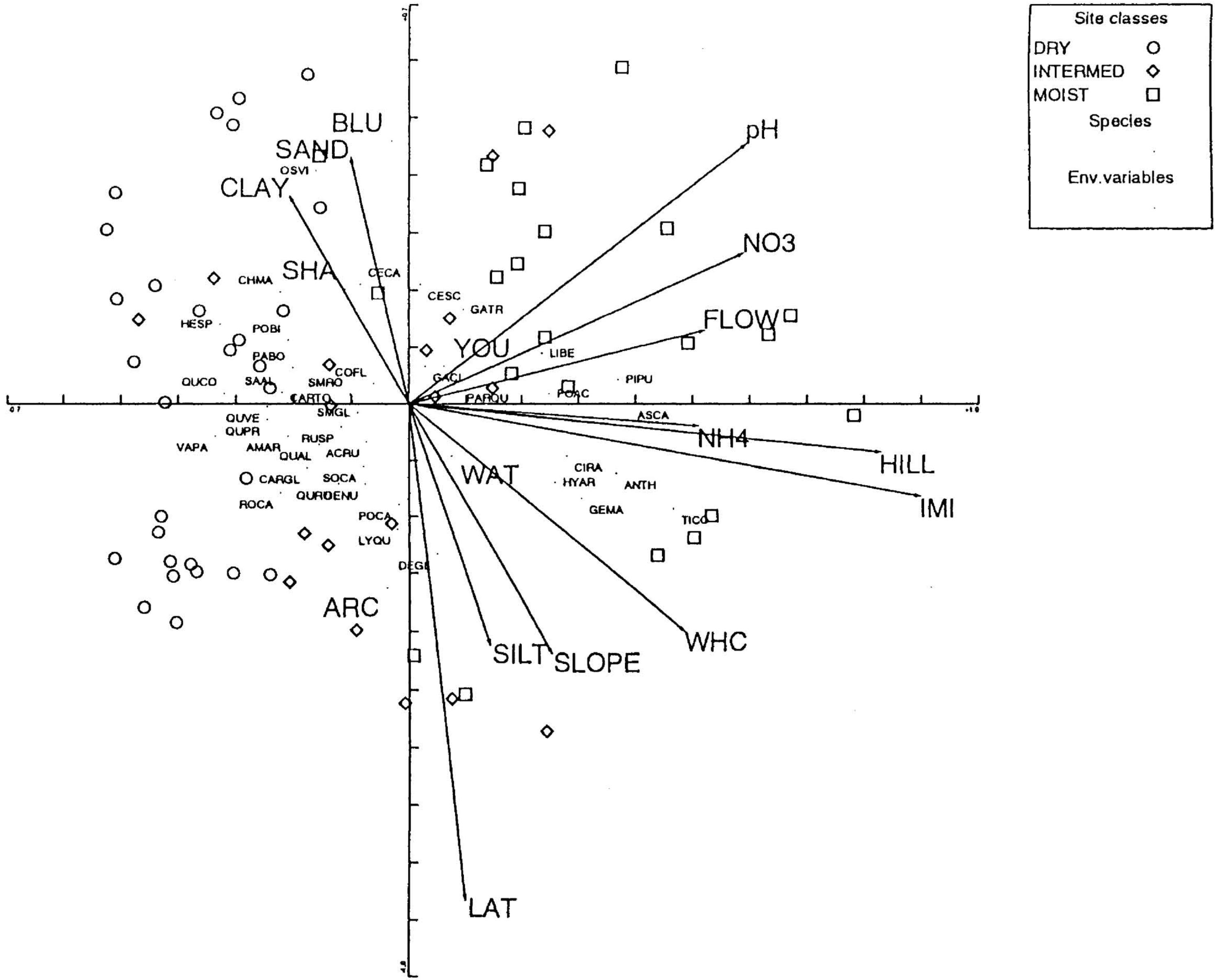


Figure 6. CANOCO triplot for all five study areas (BLU, SHA, YOU, WAT, and ARC), showing the relationship of 12 environmental variables, 90 plots, and 40 dominant species in ordination space.

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