# A COMPARISON OF MOISTURE SCALARS AND WATER BUDGET METHODS TO ASSESS VEGETATION-SITE RELATIONSHIPS

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*Abstract:* Quantification of vegetation-site relationships is often required in biogeographic research. Methods linking species to particular sites typically assess evaporative demand and soil moisture availability at the site, though methods differ in how these factors are assessed. This study compares three approaches—a water-budget approach, and field-based and map-based moisture scalars—in their ability to predict the occurrence of a single species, American beech (*Fagus grandifolia*), observed in 102, 0.04 ha plots in SE Ohio. Actual evapotranspiration and deficit provided results superior to field-based and map-based scalars. Map-based techniques are potentially limited at fine spatial scales, due to the large discrepancy between observed topographic variables, and those modeled with 7.5-minute elevation grids. The study concludes that a water budget approach is applicable to a wide range of studies exploring vegetation-site linkages. It has advantages of being objective in its computation, and applicable at a wide range of spatial scales. Perhaps most importantly with regard to global change research is the dynamic nature of the method: a site's classification will change concurrently with changes in climate. [Key words: water budget, TRMI, IMI, beech.]

## INTRODUCTION

That certain plant species tend to occur in particular settings is an observation made by even the most casual of observers. For instance, in the Appalachian Mountains, American elm (*Ulmus americana*) and sycamore (*Platanus occidentalis*) characteristically occur on bottomlands, whereas chestnut oak (*Quercus prinus*) and pitch pine (*Pinus rigida*) are more common on upper slopes and ridges. Although biotic interactions and disturbance influence species' occurrence in the landscape, in large part plants are responding to available moisture and energy at a particular site. These factors in turn are affected by precipitation, temperature, soil water-holding capacity, and topography (Burns and Honkala, 1990; Barbour and Billings, 2000).

Biogeographers often need to quantify species-environment relationships to understand the distribution of organisms, and to interpret patterns of species diversity, at both coarse and fine spatial scales. This need to quantify species-environment relationships is especially important for two aspects of global change research. First is the interest in projecting how species will respond to future climate change. For example, Iverson and Prasad (2001) used climatic and edaphic variables to model suitable habitat at the county level for 80 tree species in the eastern United States. Potential changes in their abundance were then evaluated by

*Physical Geography*, 2002, **23**, 3, pp. 245-258.

swapping current climate variables with those obtained from doubled $CO_2$ scenarios of general circulation models. A second application related to global change involves an assessment of vegetation changes that have occurred since Euro-American settlement. In this case, the locations of "witness trees" from Public Land Surveys are compared to present-day species settings (Cowell, 1995; Abrams and McCay, 1996; Abrams, 1998; Dyer, 2001). A change in species-site associations may indicate changes in the abiotic environment, biotic interactions, or disturbance regimes experienced at the study site. Accurate quantification of present-day species-environment relationships is critical then, to uncover both historic and potential future changes in vegetation patterns.

Methods aimed at establishing species-environment relationships usually compare species occurrence at particular sites with the moisture conditions of those sites. Moisture conditions are typically evaluated by assessing evaporative demand and soil moisture availability at the site, although methods differ in how these factors are assessed. The different approaches can be categorized as field-based moisture scalars, map-based moisture scalars, or water budget techniques.

The computation of field-based scalars requires the on-site measurement of factors assumed to influence radiation load and soil moisture drainage. These include aspect, topographic position (e.g., valley bottom to ridge), and slope configuration (e.g., concave, convex; e.g., Peet, 1981; Parker, 1982; Vankat, 1982; Allen et al., 1991). Additionally, some authors have utilized published tables to estimate radiation at a site from its aspect and latitude (e.g., Wentworth, 1981; Parker, 1989; Allen et al., 1991). The various radiation and soil moisture variables are assigned relative weightings to create an overall "moisture" (or "radiation") index for the site. Other authors have created nomograms showing species position in the landscape based on the site's elevation and topographic setting (e.g., Whittaker, 1956; Kessell, 1979). A shortcoming of field-based scalars is the subjective nature involved in categorizing some of the parameters (e.g., "lower slope" vs. "midslope" positions), or in assigning relative weightings to the data (such as slope and aspect) measured in the field. Additionally, since the scalar is based solely on topography, the final classification of a site is "static"—a site's moisture index will not change even if climate changes. This is an important limitation for global change applications.

Map-based techniques attempt to expedite the process of computing moisture scalars, by obtaining measurements such as aspect, topographic position, and slope configuration from maps instead of field measurements (e.g., Skidmore, 1990; Cowell, 1995; Blaszczynski, 1997; Iverson et al., 1997). The appeal of this approach likely will increase with the continued development in GIS technologies. However, map-based approaches are subject to the same limitations as the field-based scalars: subjectivity in categorization, and a static site classification. In addition, map-based approaches experience limitations related to cartographic generalization and map resolution. As the difference between scale of observation and map scale increases, these limitations become more critical.

The third approach, the water budget, has demonstrated ability in defining broad-scale vegetation types based on solar energy and available moisture (Mather and Yoshioka, 1968; Stephenson 1990). Moreover, Stephenson (1998) argued that the water budget is applicable at a wide variety of scales for predicting vegetation

**Fig. 1.** Location of Athens County within Ohio.

types. As an example, he was able to categorize forest types from lower to upper treeline in the Sierra Nevada using two variables—actual evapotranspiration (evaporative water loss from a site), and deficit (evaporative demand not met by available water). One advantage of a water budget approach over using field- or map-based scalars for linking species to sites is that it is more objective in its computation. Additionally, the variables assumed to influence vegetation at a site—evaporative demand and moisture availability—are directly assessed; the variables therefore are more biologically meaningful than a single index value (Stephenson, 1998). Finally, and perhaps most importantly in terms of global change research, the water budget is dynamic; a site's classification will change concurrently with climate.

## OBJECTIVES

The purpose of this study is to compare the three approaches in their ability to predict the occurrence of a single species at a fine spatial scale. American beech (*Fagus grandifolia*) was selected as the target species because it is a late-successional, mesic species (Burns and Honkala, 1990), and therefore was hypothesized to be sensitive to moisture differences between sites. Beech has also been the subject of numerous global change studies, including those exploring potential consequences of climatic warming (e.g., Davis and Zabinski, 1992), and those examining vegetation responses since the last glaciation (e.g., Davis et al., 1986). Finally, previous research indicated a dramatic decrease in beech abundance in SE Ohio since settlement in the early 1800s (Dyer, 2001).

For each study site, representative field-based and map-based moisture indices were derived, and a water budget computed. The field-based index selected was the Topographic Relative Moisture Index (TRMI) (Parker, 1982). The TRMI is a scalar index of four parameters: topographic position, slope configuration, slope steepness, and slope aspect. Values range from 0 (xeric) to 60 (mesic). The Topographic Potential Moisture Index (TPMI) (Parker, 1980) is virtually identical to the TRMI, but

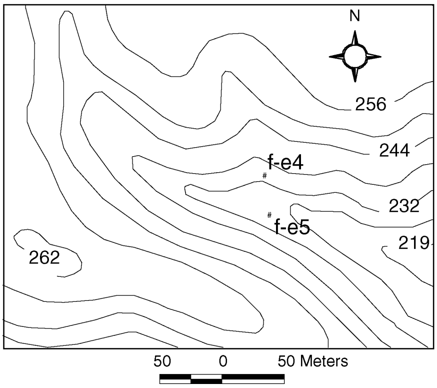

**Fig. 2.** Section of topographic map indicating dissected nature of the study area. Elevation in meters. Quadrats f-e4 and f-e5 are 23 m apart, and their respective water budgets are shown in Figure 3.

includes soil depth in its derivation (range: 0 to 70). Both indices were computed for this study.

The map-based scalar selected was the Integrated Moisture Index (IMI; Iverson et al., 1997). The IMI is derived from digital elevation models (DEMs), and incorporates hillshade (combining effects of aspect, slope steepness, and topographic position), flow accumulation (controlled largely by topographic position), and curvature (i.e., slope configuration). The index ranges from 0 (xeric) to 100 (hydric). Available water-holding capacity (AWC), from published soil maps, can also be incorporated into the IMI; the IMI with AWC also ranges from 0 to 100 (Iverson et al., 1997). Both indices (with and without AWC) were computed for this study.

## METHOD

### *Study Area*

Study sites are all located in Athens County, Ohio (39° N, 82° W, elevation 210 m; Fig. 1). The region is strongly dissected (Fig. 2), and is situated within the unglaciated Allegheny Plateau physiographic province. Upland soils are derived from sandstone, siltstone, shale, and limestone (Lucht et al., 1985). Climatically, the area is at the poleward edge of Köppen's humid temperate (Cfa) climate type; mean annual temperature is 11°C, and mean annual precipitation is 101 cm (NCDC, 2002b). Braun (1950) included the area in a Low Hills Belt of the Mixed Mesophytic Forest Region; the dominant land cover today is second-growth forest, though the area was less than 20% forested early in the 20th century (Dyer, 2001).

Study sites were located on public lands (Wayne National Forest, Strouds Run State Park, Fox Lake Wildlife Area), in areas that 1939 aerial photographs revealed to be closed-canopy forest. Subsequent air photos indicate that these areas have remained forested; thus all stands were well over 60 years old when sampling was performed in November 2001. The three study areas were all within 30 km of each other.

### *Field Sampling Procedures*

Two transects were established in each of the three study areas, situated to fall within mature forest and to encompass a wide range of topographic variability. Transects were divided into 30 m sections, and a 0.04 ha circular quadrat was randomly located within each section. A total of 102 quadrats was established, with a minimum of 30 in each study area. Within each quadrat, the number and diameter at breast height of all beech trees (>25 cm DBH) were recorded. Plot location was noted with a GPS, and slope and aspect were measured with a Brunton pocket transit. Slope configuration was noted as concave, concave/straight, straight, convex/straight, or convex, and topographic position was recorded as valley bottom, lower slope, middle slope, upper slope, or ridge top. Soil depth (to a maximum of 100 cm) was determined by inserting a steel rod. Soil texture of the upper 15 cm was determined by feel.

### *Digital Elevation Models*

The accuracy of map-based techniques obviously depends on the quality of the underlying map. In addition to map-based moisture scalars, the water-budget approach (discussed in the next section) also utilizes a digital elevation model. Therefore, a comparison was made between two digital elevation products, one grid-based, the other vector-based. Both represent the finest resolution elevation products widely available from the U.S. Geological Survey (USGS). Digital Elevation Models (DEMs) consist of a raster grid of regularly spaced (30 m) elevation values, derived from and corresponding to the USGS 7.5-minute 1:24,000-scale topographic quadrangle maps. Digital Line Graphs (DLGs) are vector files that include topographic relief; in essence these are digitized contours from the USGS 7.5-minute quadrangles.

Since calculation of both the IMI and the water budget requires a grid-based elevation model, the DLG needed to be converted. Using ArcView GIS (v. 3.2), the DLG was converted to a TIN (Triangulated Irregular Network), which represents terrain data as a set of non-overlapping triangles. The TIN was then converted to a grid with a 7.5 m resolution. The 30 m DEM was also converted to a 7.5 m resolution grid in ArcView, by first resampling to 15 m, then 7.5 m using bilinear interpolation. Hereafter, the two grids are referred to as the TIN-Grid and DEM, respectively. The accuracy of both grids was assessed by comparing slope and aspect values derived for each, with actual slope and aspect values measured in the field.

### *Calculating the Water Budget*

Calculation of a water budget requires estimates of moisture supply (precipitation), soil moisture storage, and moisture demand (potential evapotranspiration). Because of the proximity of all the study sites, normal monthly precipitation values for Athens (NCDC, 2002b) were used for all sites. Field-measured soil depth and texture were used to estimate available water-holding capacity (AWC); field-capacity values (as a proportion of soil depth) were obtained from ASCE (1990), with supplemental values from Ratliff et al. (1983) and Sanden (2002). These texture-dependent values were multiplied by soil depth to determine AWC for each site.

Potential evapotranspiration was estimated for each site using the Turc formula (Turc, 1961, in ASCE, 1990). This method was chosen because it requires only average temperature and solar radiation as input variables, and provides good estimates of both seasonal and peak evapotranspiration in humid climates (ASCE, 1990). Normal monthly temperature values for Athens (NCDC, 2002b) were used for all sites. Monthly values of global radiation were computed for each GPS'd site based on its latitude and topographic setting, using the Solar Analyst extension within ArcView (Fu and Rich, 2000). Solar Analyst generates an upward-looking hemispherical viewshed for specified locations on a DEM. The hemispherical viewsheds are used to calculate the insolation for each location, accounting for site latitude, elevation, aspect, shadows cast by surrounding topography, seasonal shifts in solar angle, and atmospheric attenuation (Fu and Rich, 2000). The Solar Analyst allows the option of specifying field-measured values of slope and aspect for the study sites; insolation was computed using both observed values of slope and aspect, as well as modeled values from the terrain grids. Monthly atmospheric diffusivity was adjusted in Solar Analyst based on cloudiness data for Columbus, Ohio (NCDC, 2002a), approximately 100 km from Athens. Monthly values were calculated by weighting the mean number of clear (20% diffusivity), partly cloudy (40%), or cloudy (60%) days. Monthly transmittivity values were set so that diffusivity and transmittivity summed to 100%.

Once values of potential evapotranspiration, precipitation, and soil moisture storage were obtained, actual evapotranspiration, deficit, and surplus were computed for each site (Mather, 1974; Fig. 3). Daily computations were performed to arrive at a single monthly value (corresponding to the last day of each month). Evapotranspiration was assumed to decline linearly with soil moisture content, since the rate of evapotranspiration decreases as the soil dries (Mather, 1974).

Aside from the option of using observed aspect and slope to calculate insolation, soil depth and texture (to compute AWC) are the only field-based variables serving as input for calculation of the water budget. To assess the effectiveness of actual evapotranspiration (AET) and deficit to account for species abundance using only published data sources, the procedures outlined above also were performed using AWC derived from soil surveys. To estimate AWC, the soil survey of Athens County (Lucht et al., 1985) was digitized, and the average depth of A and B horizons for each soil type was determined. A weighted average for water holding capacity for the combined A and B horizons was then computed; for soil complexes,

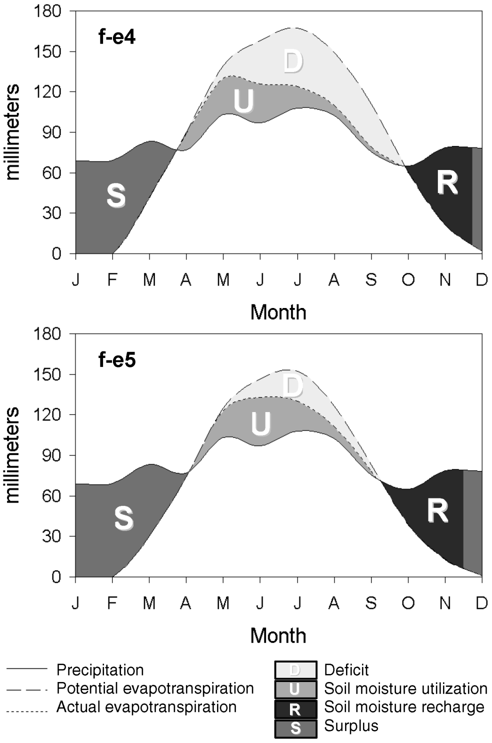

**Fig. 3.** Water budgets for two adjacent quadrats. Quadrat f-e4 is on a 22° slope, aspect is 128°, soil depth is 70 cm, texture is silty clay; annual actual evapotranspiration is 783 mm, annual deficit is 156 mm. Quadrat f-e5 is on a 23° slope, aspect is 19°, soil depth is 90 cm, texture is silty clay; annual actual evapotranspiration is 732 mm, annual deficit is 99 mm.

area-weighted values were calculated. These values are the same used for calculation of the IMI (with AWC; Iverson et al., 1997).

### *Statistical Analysis*

To identify which elevation model (TIN-Grid or DEM) most accurately represented actual topography, Pearson correlation coefficients were computed between observed and modeled values of slope and aspect. Contingency table analysis (Dyer, 2001) was performed to determine if beech demonstrated an association with observed or modeled aspect. Least-squares linear regression was performed to determine which moisture index (TRMI, TPMI, IMI, or AET and deficit) accounted for the greatest variability in beech basal area per plot. Statistical analyses were performed using SAS Version 6 (SAS, 1990).

**Table 1.** Regression Analysis Results for Statistically Significant ($p < .05$) Models[a]

| Independent variables | $R^2$ | Adjusted $R^2$ |
|---|---|---|
| AET & deficit<br>(field values of slope, aspect, AWC) | .27 | .26 |
| AET & deficit<br>(TIN-Grid slope and aspect, soil survey AWC) | .19 | .17 |
| IMI (without AWC)<br>(TIN-Grid) | .10 | .09 |
| IMI (with AWC)<br>(TIN-Grid) | .09 | .08 |

[a] Dependent variable is beech basal area ($dm^2$) per plot.

## RESULTS

### *Comparison of Elevation Models*

Values of aspect derived from both the DEM and TIN-Grid correlated highly with observed values ($r$ = .87 and .95, respectively), though both models performed poorly in capturing slope ($r$ = .17 and .18, respectively). Moreover, the difference between a site's modeled aspect or slope and the observed value was often pronounced. The average difference between modeled and observed aspect was 32° for the DEM, and 20° for the TIN-Grid. The average difference between modeled and observed slope was 9° for the DEM, and 27° for the TIN-Grid. Contingency table analysis indicated that beech showed no association with a particular aspect using either field data or the TIN-Grid; a positive association with northeast-facing slopes resulted with the DEM, however.

### *Comparison of Moisture Indices*

Table 1 provides results of the regression analysis to determine which moisture index accounted for the greatest variability in beech dominance. The dependent variable is beech basal area ($dm^2$) per plot. Only statistically significant models ($p <$ .05) are presented. No model using DEM-derived topography was statistically significant. The TRMI and TPMI models, which rely solely on field measurements, were not statistically significant.

Results suggest that the water budget approach is superior to representative map-based and field-based scalars in accounting for species dominance within these SE Ohio sites. Actual evapotranspiration and deficit, computed using field measurements of slope, aspect, and AWC, explained 27% of the variance in beech dominance (Table 1). Figure 4 is a scatter plot of this relationship, and indicates that beech is less dominant on sites with increasing moisture deficit. Using modeled values of slope, aspect, and AWC, actual evapotranspiration and deficit only account for 19% of the variance in beech dominance, though this is still superior to either

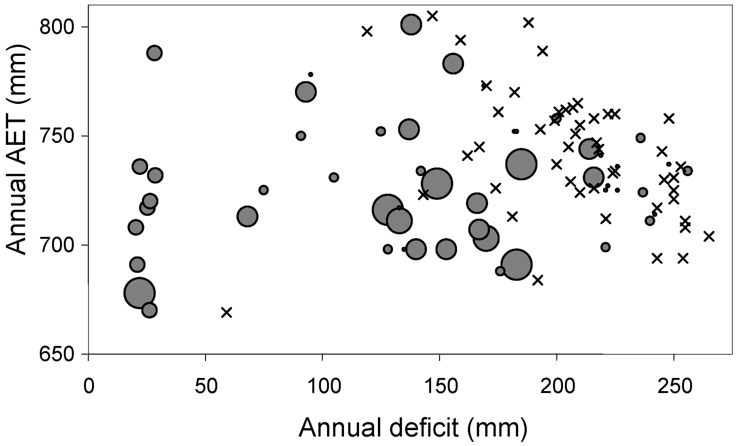

**Fig. 4.** Scatter plot of annual actual evapotranspiration versus deficit, computed using field values of slope, aspect, and AWC. Size of circle reflects plot's beech basal area. "X" indicates plot with no beech.

IMI model (with or without AWC), both of which also were computed using only published data sources for topography and soils (Table 1). The inclusion of AWC from soil surveys offered no improvement to the IMI's ability to explain beech dominance (Table 1).

## DISCUSSION

### Water Budget Versus Field-Based and Map-Based Scalars

The water budget approach offered greater explanatory power compared to the other methods of quantifying species-site relationships. While these findings are based on predicting basal area of a single species, it seems reasonable to assume that a water budget approach would be effective with other species as well; ongoing research is evaluating this assumption.

In addition to the greater explanatory power observed in this study, the water budget approach offers several advantages. Although other indices account for moisture demand and availability, the water budget approach offers a direct assessment of water use and soil moisture storage. All indices rely on topographic variables such as aspect or slope steepness, but AET and deficit are more biologically meaningful predictors than a single scalar obtained with other moisture indices. More importantly, water budget variables are not static; actual evapotranspiration and deficit calculated for a site will change with a change in precipitation or temperature, whereas other moisture index scalars computed for the site would not.

Since it utilizes a monthly time-step, the water budget approach is also more dynamic temporally in its derivation compared to other methods. Precipitation obviously may vary seasonally, but radiation, which drives moisture demand, is especially variable throughout the year. For instance, if sites were ranked based on total insolation, these relative rankings could change throughout the year because of changing sun angles and day lengths. Other studies have used radiation look-up tables based on a site's aspect and latitude (e.g., Wentworth, 1981; Parker, 1989; Allen et al., 1991). The method outlined in this paper would seem to assess more readily a site's intra-annual radiation load, and offer advantages over using proximate variables (such as aspect) to infer insolation differences.

As with map-based indices, a site's water budget variables can be computed without any field-based measurements (though in this study, model performance declined). This ability is attractive given those situations when field work is prohibitive or impossible. For example, many witness trees from the original Public Land Surveys are no longer standing, though a researcher may wish to assess species-site relationships of the presettlement forest (e.g., Cowell, 1995; Abrams and McCay, 1996; Abrams, 1998; Dyer, 2001). In this case, not only might the spatial extent of the study preclude extensive field reconnaissance, but measurements of slope and aspect at the precise witness tree location may not be possible. Before relying on a particular topographic model to assess species-site relationships, however, the researcher should attempt to assess its accuracy. For instance, in the present study, the strength of the relationship between species occurrence and aspect was dependent on the topographic model used. Issues of map resolution become increasingly critical at fine scales of analysis.

### *Spatial Resolution*

Water budget variables have demonstrated ability to discriminate vegetation types, from continental to regional scales (Mather and Yoshioka, 1968; Stephenson, 1990, 1998). This study has shown that AET and deficit also are able to account for observed variance of a single tree species, and at a very fine spatial scale. Of course, as the "grain" becomes finer, the number of variables influencing a species distribution increases (Meentemeyer and Box, 1987). In predicting the occurrence of a species within a particular plot in a larger stand, stochastic effects such as local dispersal, soil nutrient levels, canopy gaps, and site history may obscure climatic controls. It is not surprising then that the two climatic variables only accounted for 27% of the variance in beech dominance. An analogy to this outcome can be found in the application of ordination to plot data. There are two general approaches to ordination, differing in whether or not the presumed environmental control is specified *a priori*. With indirect gradient analysis, samples are arranged based solely on species abundances in the different plots; the dominant environmental gradients controlling species abundance are then inferred from the resulting arrangement of sites. With direct gradient analysis, however, ordering of samples is constrained to be linear combinations of measured environmental variables (ter Braak, 1995), such as the site's AET and deficit as in the present study. Explanatory power using direct gradient analysis is typically no higher than 25% to 30% of variance explained by indirect gradient analysis. Given the myriad of variables potentially controlling the abundance of beech in a specific plot, the ability of AET and deficit to account for 27% of the variance is significant.

### *Beech Distribution*

The initial hypothesis that beech would be sensitive to moisture differences between sites, and therefore serve as an ideal target species for this study, was not the case. Perhaps owing to the fact that SE Ohio is near the center of beech's geographic range, beech had wide ecological amplitude within the study areas, occurring in sheltered, mesic sites, as well as on ridge tops with chestnut oak. Higher explanatory power may have resulted, therefore, if a more sensitive species had been selected to model.

Previous research (Dyer, 2001) concluded that in the presettlement forest of SE Ohio, beech was positively associated with valleys, and negatively associated with ridge settings. In addition, it was noted that the abundance of beech had declined dramatically in Athens County over the past 200 years, from 10.2% of all witness trees to 3.6% of forest trees today (Dyer, 2001), perhaps due to poor dispersal following land clearing (cf. Smith et al., 1993; Simard and Bouchard, 1996). The results of this study suggest that although less abundant, beech may be occurring in a broader array of topographic settings today compared to the presettlement forest. Relatedly, in an old-growth remnant in Belmont County, Ohio, approximately 125 km NE of the study areas, beech had the highest basal area of all trees on a NW-facing slope, and exhibited slightly lower dominance on a SSW-facing slope. Beech saplings, however, were much more abundant on the SSW-facing site (McCarthy et al., 2001). McCarthy et al. (2001) concluded that fire frequencies were not greater before Euro-American settlement; it appears, however, that a change in some environmental factor(s) is allowing beech to expand into a greater diversity of topographic settings compared to the presettlement forest. This apparent expansion of beech into more diverse ecological settings is a potential subject for future research.

## CONCLUSIONS

The water budget approach to quantifying species-site relationships offers several advantages to established field-based and map-based moisture scalars. Calculation of the water budget is much more objective, insuring replication between studies; the researcher is not called upon to discriminate between "lower slope" or "midslope" positions in the field, for example, nor to decide on breakpoints for converting AWC from a ratio to an interval scale. The water budget can be applied at any spatial scale, and can be computed strictly using published data sources; results of this study suggest that at fine scales, inclusion of observed soil texture, depth, slope and aspect, improve model results, largely owing to the coarse resolution of currently available digital terrain models. In terms of global change research, the water budget approach offers the additional benefit of being a "dynamic" model; unlike other moisture indices, derived values are dependent upon temperature and precipitation, and therefore will change as climate changes. One recognized limitation to the water budget approach, compared to the field-based and map-based scalars, is that it does not factor in soil moisture drainage from upslope; soil moisture storage is dependent only upon soil properties of the particular site. Ongoing research will seek to incorporate an objectively measured topographic index (e.g., Kirkby, 1975; McNab, 1993) into the methodology. Despite this limitation, the superior performance of the water budget approach suggests the technique has applicability to a wide range of studies exploring vegetation-site linkages.

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