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RESEARCH ARTICLE

Assessing topographic patterns in moisture use and stress using a water balance approach

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Abstract Through its control on soil moisture patterns, topography's role in influencing forest composition is widely recognized. This study addresses shortcomings in traditional moisture indices by employing a water balance approach, incorporating topographic and edaphic variability to assess fine-scale moisture demand and moisture availability. Using GIS and readily available data, evapotranspiration and moisture stress are modeled at a fine spatial scale at two study areas in the US (Ohio and North Carolina). Model results are compared to field-based soil moisture measurements throughout the growing season. A strong topographic pattern of moisture utilization and demand is uncovered, with highest rates of evapotranspiration found on south-facing slopes, followed by ridges, valleys, and north-facing slopes. South-facing slopes and ridges also experience highest moisture deficit. Overall higher rates of evapotranspiration are observed at the Ohio site, though deficit is slightly lower. Based on a comparison between modeled and measured soil moisture, utilization and recharge trends were captured well in terms of both magnitude and timing. Topographically controlled drainage patterns appear to have little influence on soil moisture patterns during the growing season. In addition to its ability to accurately capture patterns of soil moisture in both high-relief and moderate-relief environments, a water balance approach offers numerous advantages over traditional moisture indices. It assesses moisture availability and utilization in absolute terms, using readily available data and widely used GIS software. Results are directly comparable across sites, and although output is created at a fine-scale, the method is applicable for larger geographic areas. Since it incorporates topography, available water capacity, and climatic variables, the model is able to directly assess the potential response of vegetation to climate change.

Keywords Water budget · Evapotranspiration · Soil moisture · Solar radiation · Species-environment relationships · Climate change · Topography · Deciduous forests · Coweeta · Ohio

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Introduction

A long tradition of gradient analysis in community ecology acknowledges topographic influences on forest composition, due in large part to topographically controlled variation in soil moisture (e.g., Whittaker 1956; Hack and Goodlet 1960). In addition to influencing composition, topographically controlled variations in microclimate affect patterns of species richness, plant establishment, productivity, nutrient cycling, pedogenesis, and forest flammability

(Lookingbill and Urban 2004). Thus knowledge of variations in moisture demand and moisture availability within the landscape is essential to gain an understanding of the spatial variation in ecological processes, and to assess ecosystem responses to altered climatic conditions.

In order to model species-environment relationships, biogeographers and forest ecologists historically have characterized sites based on their topographic setting, since high resolution soil moisture data are lacking for most areas. One approach to characterize species-environment relationships is the use of nomograms, which show species position in the landscape based on the site's elevation and topographic setting (e.g., Whittaker 1956; Kessell 1979). More often, factors assumed to influence moisture availability and evaporative demand are assigned relative weightings to create a single index value for the site (e.g., Peet 1981; Wentworth 1981; Parker 1982, 1989; Vankat 1982; Allen et al. 1991; Iverson et al. 1997). Factors assumed to influence radiation load and soil moisture drainage include latitude, aspect, topographic position (e.g., valley bottom to ridge), and slope configuration (e.g., concave, convex).

Despite their long history, the use of site indices to characterize species-environment relationships has several shortcomings. Firstly, the variables selected (e.g., slope, aspect, "hillshade") are not necessarily biologically significant, but instead serve as easily measured surrogates or "proxies" for factors which plants are responding to directly (Stephenson 1998; Urban et al. 2000; Lookingbill and Urban 2005). Secondly, many of the indices involve a subjective characterization of the site (e.g., assigning sites to categories based on slope position or the degree of slope curvature; Parker 1982; Iverson et al. 1997). The resultant index value for the site depends not only on the user, therefore, but more importantly it is relative to other sites in the study area. Index values are not necessarily directly comparable with values derived for other study areas. Thirdly, although many indices, such as the open-ended wetness index (which factors in a site's slope and contributing area; Beven and Kirkby 1979), *correlate* with patterns of soil moisture, the derived values do not provide an indication of the *amount* of soil moisture at any particular site.

Numerous studies have indicated that certain topographic settings are wetter than others (e.g., Helvey et al. 1972; Zaslavsky and Sinai 1981) but by-and-large, moisture indices are unable to assess moisture differences between topographic sites in absolute terms. "How much more moisture is available at a north-facing cove site compared to a ridge top?" remains an unanswered question. Finally, since moisture indices are based solely on topography, the final classification of a site is "static," and will remain fixed even if climate changes. Although temperature and precipitation may change, other variables critical for determining moisture demand and availability at a site (such as topography or soil water-holding capacity) will not. A moisture index that takes this into account will be more useful in investigations of the potential response of vegetation to climate change. Given the topographic heterogeneity and resultant habitat diversity of mountainous areas, it is plausible that certain species may be able to shift to new topographic "refugia" (McLachlan et al. 2005; Pearson 2006) within a landscape, and not be forced to migrate hundreds of kilometers poleward in the face of climate change (Dyer 1995). "What will a site's moisture status be if temperature increases by 5°C and precipitation decreases by 10%?" represents a type of scenario that traditional topography-based moisture indices cannot assess.

This study seeks to address these shortcomings in traditional moisture indices by employing a water balance approach, incorporating topographic and edaphic variability to assess fine-scale moisture demand and moisture availability. A water balance approach directly assesses evaporative demand and moisture availability, which plants respond to across all geographic scales. A water balance approach has demonstrated ability in defining broad-scale vegetation types (e.g., deciduous forest, tallgrass prairie; Mather and Yoshioka 1968; Stephenson 1990; Frank and Inouye 1994), in categorizing forest types within a montane environment (Stephenson 1998), and in predicting the occurrence of a single species within a forest stand (Dyer 2002). Water balance variables have also been used to successfully capture patterns in productivity (Rosenzweig 1968), decomposition (Dyer et al. 1990), species richness (Currie 1991), and the delineation of species ranges (Manogaran 1975).

Components of a water balance approach include potential evapotranspiration (PET), a measure of moisture demand, which is the amount of water that can be evaporated and transpired from a vegetated surface if water is not a limiting factor. Actual evapotranspiration (AET) accounts for water availability, and the difference between PET and AET is deficit. When PET exceeds precipitation, water demand is met in part through soil moisture utilization (drawing from soil storage). The maximum amount of water that can be held in storage is dependent on the site's available water capacity (AWC), which in turn is dependent on soil depth and texture. Precipitation in excess of PET results in soil moisture recharge, and any remaining excess becomes surplus, lost from the site by subsurface drainage (Mather 1974).

Given the availability of high resolution climate, soils, and elevation data for many regions, it is now possible to apply well-established methods to model the water balance within areas of moderate- to high-relief. The approach offers numerous advantages over traditional indices: moisture demand and availability at a site are quantified in absolute terms (millimeters of water), not a relative index. The application of the approach does not involve subjective categorization of topographic variables, so that results should be uniform between users. More importantly, the absolute and uniform nature of the approach insures that results are directly comparable between any study areas. Since the approach incorporates climate data in addition to elevation and soils, it lends itself to exploring ecosystem response to climate change. The approach utilizes a monthly time-step, allowing the user to investigate ecosystem responses to monthly, annual, or seasonal (e.g., May–June) climatic variables (Frank and Inouye 1994; Dyer 2004). Finally, the approach utilizes data that are readily available for many areas, using a single "out-of-the-box" GIS program; models were created using "ModelBuilder" in ArcGIS 9.2 (ESRI 2006) and can be run without any additional programming knowledge. Models and user's guides are available for download (http://oak.cats.ohiou.edu/~dyer/).

The objective of this study is to develop a fine-scale assessment of monthly moisture demand, utilization, and stress, for two forested study areas in the eastern US, one with high topographic relief, one with moderate-relief. Results will be validated by comparing modeled soil moisture with soil moisture measured at a network of sensors installed along a range of topographic settings.

Study areas and field instrumentation

In order to validate the water balance approach, it was necessary to apply the model to sites with continuously monitored soil moisture. In this way, modeled soil storage could be compared with soil moisture measured in the field. Two sites were selected, a North Carolina site with steep relief (elevation range 675–1,490 m, within the Blue Ridge Mountains, USA), and an Ohio site with moderate-relief (elevation range 675–980 m, located in the Allegheny Plateau, USA; see Fig. 1). The two sites are approximately 500 km apart.

The North Carolina site (35.05°N 83.45°W) is situated in the Appalachian oak section of the Mesophytic forest region (Dyer 2006), and is part of the Coweeta Long-Term Ecological Research Site. Upland soils are derived from granite, mica schists, and gneisses (Day and Monk 1974). Climate is humid subtropical (Köppen's Cfa); average annual precipitation is 1,826 mm and average annual temperature is 13°C, with a July maximum of 22°C and January minimum of 3°C (NCDC 2002). Continuous soil moisture measurements were obtained for nine plots (Coweeta LTER 2008), covering a range of topographic settings (Fig. 2a). These measurements were sampled at 30–60 cm depth using a Campbell

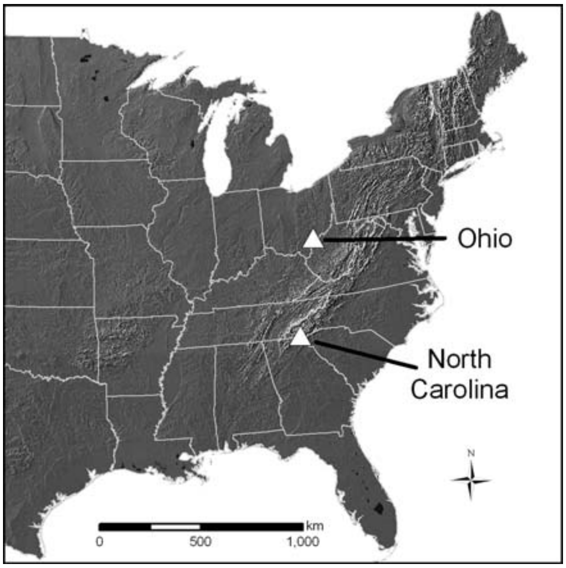

Fig. 1 Location of the Ohio and North Carolina study areas in the eastern United States. Shaded relief map from Thelin and Pike (Thelin and Pike 1991)

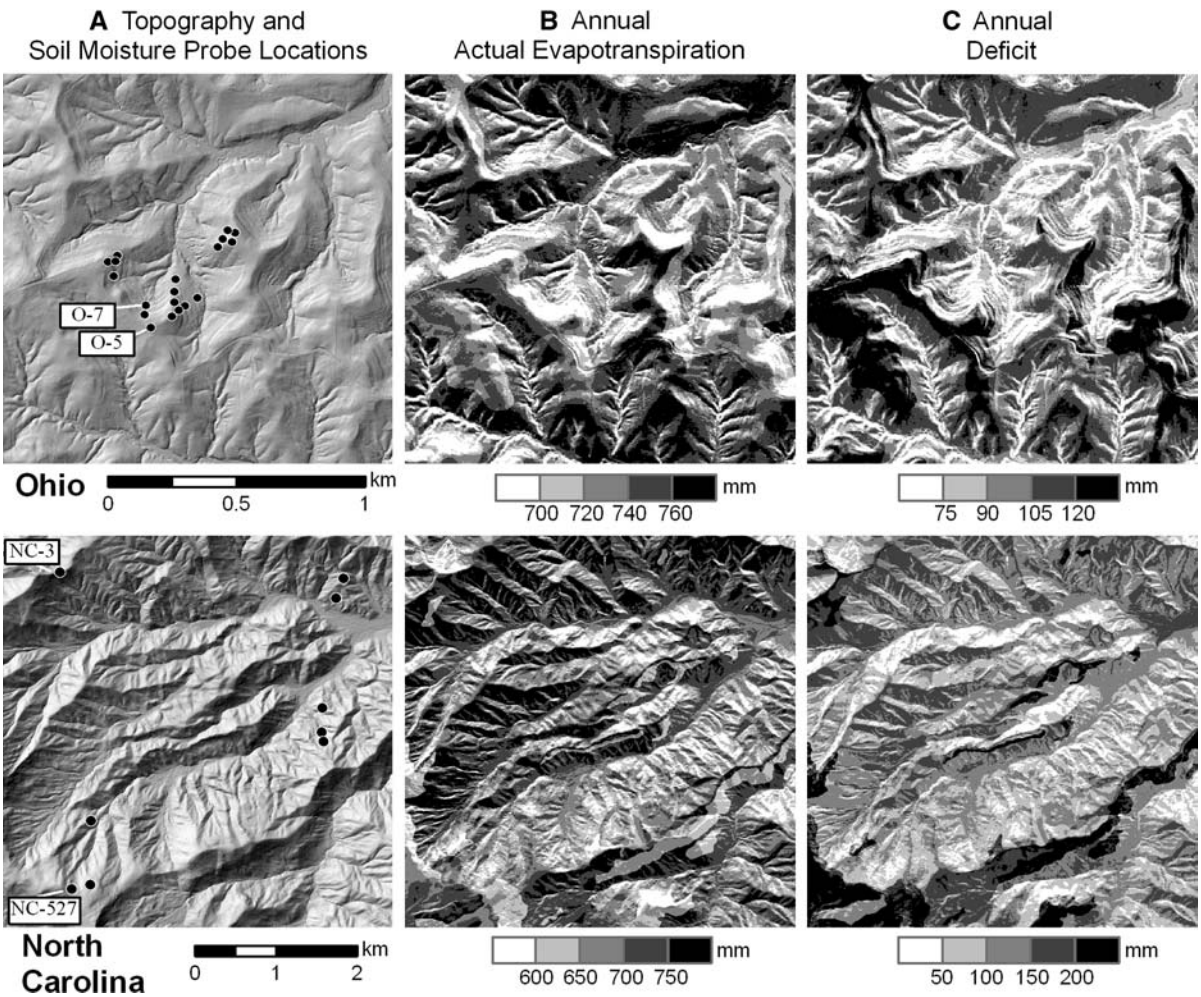

Fig. 2 Ohio and North Carolina study areas (see Fig. 1), showing **a** topography and location of soil moisture probes (note difference in scale between the two study areas), **b** Annual actual evapotranspiration, and **c** Annual deficit. Note the topographic pattern of (**a**) reflected in the maps of AET and deficit

Scientific CS615 Water Content Reflectometer and CR10 data logger. Probes measure the dielectric constant of the soil to determine volumetric water content to within ±2% (Campbell Scientific 1996). For five of the sites, soil moisture values represent the average of two probes installed along the upper and lower boundary of 20 × 40 m plots; plot corners were recorded via differential GPS, and soil probe locations were located within a 10 × 10 m grid established within the study plots (B. Kloeppel, research scientist, personal communication, February 2008). The other four sites have a single soil moisture probe, whose location was established with differential GPS. For all nine sites, hourly readings were averaged to obtain an average monthly soil moisture value. Monthly temperature, precipitation, and solar radiation were also obtained for the North Carolina site (Coweeta LTER 2008) to serve as input for the water balance model; these climate data were recorded within a 5 km radius of each of the soil probes. All data were for the year 2000.

The Ohio site (39.27°N 81.96°W) also is within the Mesophytic forest region (Dyer 2006). Upland soils are derived from sandstone, siltstone, shale, and limestone (Lucht et al. 1985). Climate is humid continental (Köppen's Dfa); average annual precipitation is 1,006 mm and average annual temperature is 11°C, with a July maximum of 23°C and January minimum of −2°C (NCDC 2002). Nineteen soil moisture probes were installed at 50 cm depth along several topographic transects (ridge to lower slope, along common contour lines on convex, concave and straight slopes; Fig. 2a); soil texture was determined at time of installation. ECH_2O EC-5 sensors, in combination with Em-50 data loggers, were used to measure the dielectric constant of the soil in order to find its volumetric water content with ±2% accuracy (Decagon Devices 2006). Hourly soil moisture measurements were averaged to obtain a monthly value. Probe locations were established via differential GPS. For computing the water balance, temperature and precipitation were recorded on-site within a 500 m radius of each soil probe, and solar radiation was obtained for a site 14 km away (Scalia Laboratory 2008). All data were for the year 2007.

Methods

Data needs for performing a water balance are few: a digital elevation model (DEM), soil available water capacity (AWC), and monthly temperature, precipitation, and solar radiation. These data are readily available for many locations, so the method is applicable in many areas. For example, in the US, soil water-holding capacity is available from digitized soil surveys (1:12,000–1:63,360 mapping scales; NRCS 2008), and gridded data are available for monthly climate (~800 m resolution, Daly et al. 2002), elevation (~10 m resolution, USGS 2008), and solar radiation (10 km resolution, NREL 2008). The resolution and spatial extent of these data sets means that the analysis can be performed at a very fine spatial scale, yet the approach is applicable over large geographic areas. As discussed in the previous section, solar radiation and climatic data measured on-site were available and used for both study sites. A fine-scale DEM was available for each site (North Carolina: 3.5 m resolution, USGS 2008; Ohio: 0.7 m resolution, OGRIP 2008). Compared to field measurements, the average difference in slope computed from the DEMs was 3° for each study area; average difference in aspect was 7° for the North Carolina site, and 14° for the Ohio site. (Slope and aspect were reported for five of the nine North Carolina sites.) Available water capacity in the top 100 cm of soil was obtained for each site from NRCS (2008). In temperate deciduous forests, 95% of roots occur within the top 100 cm (Gale and Grigal 1987; Jackson et al. 1996); soil probes were installed at the approximate midpoint of this depth. At soil moisture probe sites, AWC ranged from 85 to 150 mm for the Ohio site, and 83–204 mm for the North Carolina site; median values were 107 and 128 mm, respectively.

A key component of a water balance approach is the calculation of potential evapotranspiration (PET) at each site. There are approximately 50 different methods of computing potential evapotranspiration (Lu et al. 2005), although for this application it was essential to select a method that provided monthly estimates of PET using readily available data.

Methods of modeling PET include surface-dependent approaches, which generally include vegetation and soil characteristics, and reference-surface methods, which model PET for a "reference crop" (such as grass or alfalfa) but do not directly include vegetation parameters (Fisher et al. 2005); these reference-surface methods are typically either temperature- or radiation-based. In the present study, a reference-surface approach was adopted for a number of reasons.

One reason for selecting a reference-surface approach is the lack of sufficient information to apply "correction factors" to account for PET differences between forests and reference crops. Some authors conclude that evapotranspiration rates are higher for reference crops (e.g., Shuttleworth 1993), while other conclude they are higher for forests (e.g., Lu et al. 2003). Vörösmarty et al. (1998) concluded that the use of methods incorporating vegetation characteristics such as leaf conductance and canopy resistance did not significantly improve estimates of PET. Fisher et al. (2005) also concluded that a simple radiation-based model may be preferable to more complex surface-dependent methods. Since an objective of this approach is to facilitate regional-scale investigations, it is desirable to select an approach that requires fewest input variables (Lu et al. 2005). In addition to issues of data availability and model parsimony, another reason for selecting a reference-surface method was the interest in assessing spatial patterns of moisture "potential," irrespective of the current vegetation. This ability is especially important for modeling the potential vegetation response to climate change; assuming that a reorganization of vegetation patterns may occur, where might "suitable" sites exist within the landscape? Finally, since the focus is on topographically controlled variability between sites, it was necessary to select a radiation-based method of estimating PET. Incident solar radiation varies significantly with topographic position. In the northern hemisphere, for example, south-facing slopes may receive over 1.5× the incident radiation as north-facing slopes (Gates 1980). The Turc method of estimating PET meets all of these criteria (Turc 1961, in ASCE 1990).

The American Society of Civil Engineers (ASCE 1990) ranked the Turc method second behind The Penman-Monteith approach (which requires estimates of temperature, radiation, wind speed, humidity, and leaf area index) based on its ability to predict evapotranspiration at various lysimeter sites. The Turc method slightly overestimated annual evapotranspiration in humid environments as recorded by lysimeters, but accurately estimated evapotranspiration for the peak month. Amatya et al. (1995) concluded that compared to the Penman-Monteith approach, the Turc method provided the best estimate of annual, monthly, and peak summer PET at three sites in North Carolina. Lu et al. (2005) concluded that since it was developed for warm, humid climates, the Turc method would be expected to perform well in the southeastern USA. Due to its proven ability to accurately estimate evapotranspiration and its relative ease of computation across the study area, the Turc method was selected to compute evapotranspiration in this study:

$$\mathrm{PET} = 0.013\left[\frac{T}{(T+15)}\right](R_s + 50) \quad (1)$$

where PET = monthly potential evapotranspiration in mm, T = normal monthly temperature in °C, and R_s = monthly global radiation received at the earth's surface, in cal cm^{-2}. For drier conditions (relative humidity <50%), a relative humidity term is included in the Turc equation (ASCE 1990). Although its estimates of potential evapotranspiration are more accurate in humid climates (ASCE 1990), the Turc method has been shown to be comparable to other estimates of PET in a range of climate types throughout the US (Federer et al. 1996; Vörösmarty et al. 1998).

ArcGIS (v. 9.2) software includes a "Solar Radiation" toolset which estimates global solar radiation at any time of year for either a point or for an entire DEM, based on its latitude (ESRI 2006). The only atmospheric parameters required for Solar Radiation are the diffuse proportion, and atmospheric transmittivity (the proportion of solar radiation outside the atmosphere that reaches the surface). Since additional factors, such as surface reflectance or altitude, may affect incident solar radiation at a site, monthly estimates of diffuse proportion and transmittivity (hereafter, D and T) were parameterized using actual solar radiation values measured at each study site. First, Solar Radiation was performed for a single point coinciding with the site at which solar radiation values were collected; a "flat site" was specified, since solar collectors are horizontal. All combinations of D and T were implemented in 0.1 increments, ranging from $D = 0.2$ to 0.7, and $T = 0.3$ to 0.7, which are typical for the eastern US (NREL 2008). Monthly radiation estimates using the "best" D–T combination were within 5% of measured values, with annual estimates of global solar radiation within 1% of measured values for both sites. These best monthly D–T values then served as Solar Radiation parameters run on the entire DEM; in this mode, the program accounts for slope, aspect, and shadows cast by surrounding topography in computing incident radiation for each grid cell within the study area.

Once monthly radiation was computed, water balance models were performed to estimate PET, soil moisture storage, AET, soil moisture deficit, and soil moisture surplus for every grid cell within the DEM. (Cell size is 3.5 m for the North Carolina study area, 0.7 m for Ohio.) Soil moisture utilization was computed using a daily time-step, with the monthly value of soil storage corresponding to the last day of each month. Soil moisture availability was assumed to decline linearly as the soil dries (e.g., only 50% of soil moisture need can be obtained when the soil is at 50% of field capacity; Mather 1974).

In order to validate the model, estimates of modeled soil storage were compared to soil moisture measured in the field using the soil moisture probes. To facilitate comparison of the two, each was converted to "percent full" measurements. Monthly storage values were computed as percent of available water capacity; measured soil moisture values were converted to "percent plant available water" (PAW) after estimating field capacity (FC) and the permanent wilting point (PWP) for each probe site:

$$\mathrm{PAW} = 100 \times \left[\frac{(\mathrm{VWC} - \mathrm{PWP})}{(\mathrm{FC} - \mathrm{PWP})}\right] \quad (2)$$

where VWC is the average monthly volumetric water content at each probe site (T. Martin, D. Devices, personal communication, February 2008). To compute field capacity and permanent wilting point for each site, daily soil moisture values were plotted out for the entire period of record. For each probe, soil moisture values approached an upper asymptote during the non-growing season, and a lower asymptote late in the growing season. This is the typical pattern throughout the Appalachians, with maximum soil moisture following winter recharge, and minima following the summer soil moisture utilization period (Helvey and Patric 1988). Field capacity can be identified with fair certainty in these humid environments; in the present study identification of the permanent wilting point was facilitated by drought conditions that each study area experienced; monthly PDSI (Palmer Drought Severity Index, NCDC 2008) values were in the "moderate" or "severe drought" category throughout the summer and fall months for both North Carolina (2000) and Ohio (2007) sites. Comparisons between modeled soil storage and measured soil moisture are performed for the period of soil moisture utilization, beginning and ending when both measured and modeled values for all sites was 100%, April–December. In temperate deciduous forests, this is likely the critical period in terms of vegetation response to soil moisture patterns.

Within the model, soil moisture supply at a site is comprised of precipitation and soil moisture storage. Drainage from upslope may be hypothesized to be an important contributor to a site's moisture supply. If this were the case, the modeled soil moisture should be underestimated for lower slope positions or cove sites, compared to ridges or convex sites, for example. To evaluate this possibility, stepwise regression (SAS 2004) was used to uncover any relationships between the differences in sites' measured versus modeled soil moisture, and GIS-derived variables describing the sites' topographic setting. These variables included slope, aspect, curvature, profile curvature, plan curvature, upslope area, topographic wetness index, distance to divide, elevation difference to divide, distance to peak, elevation difference to peak, and landform category (e.g., ridge, valley, slope).

Results

Patterns of moisture utilization and deficit

An advantage of this modeling approach is its ability to represent patterns of moisture stress and moisture availability across broad areas (see Fig. 2b, c). For both the North Carolina and Ohio study areas, a strong topographic pattern is seen in annual evapotranspiration and annual deficit (cf. Fig. 2a; see Table 1). Due to their sheltered topographic settings, coves and valleys experience reduced rates of AET, with higher rates of AET observed on ridges and especially on slopes with southerly aspects (Fig. 2b; Table 1). Ridges and especially southerly slopes experience highest moisture stresses (Fig. 2c; Table 1). North-facing slopes experience lowest rates of both AET and deficit.

A second advantage of the approach is the direct comparability of results across study areas, since all values are in millimeters of water. Although the data are from different years (2000 for North Carolina, 2007 for Ohio), it can be seen that the Ohio site experiences higher annual AET rates (median

Table 1 Average, minimum, and maximum values of annual AET and deficit by topographic position, for the North Carolina and Ohio study areas, as shown in Fig. 2b, c. Landform categories defined according to the Topographic Position Index (NOAA 2008)

		Actual evapotranspiration (mm)			Deficit (mm)		
Study site	Landform	Avg	Min	Max	Avg	Min	Max
NorthCarolina	Ridge	688	329	812	135	0	326
	SE-S-SW slopes	740	449	821	165	4	327
	NW-N-NE slopes	634	311	790	77	0	271
	Valley	678	200	823	105	0	310
Ohio	Ridge	735	534	788	109	19	158
	SE-S-SW slopes	758	518	801	116	31	157
	NW-N-NE slopes	701	467	770	74	1	135
	Valley	720	375	800	82	1	148

value = 738 mm) compared to the North Carolina site (median value = 693 mm). Higher rates of AET are also observed when comparing sites by landform position (Table 1). Higher AET rates at the Ohio site can be attributed to its lower elevation (~260 m) and resultant warmer summer temperatures (June–August 2007 average = 24.5°C) compared to the North Carolina site (~970 m, June–August 2000 average temperature = 22.0°C). Due to its lower latitude, higher elevation, and steeper slopes, however, some North Carolina sites experience potentially higher irradiation, which is reflected in higher deficit values on south-facing slopes compared to the Ohio sites (Table 1). Overall, the North Carolina study area has slightly higher annual deficit (median value = 121 mm) compared to the Ohio study area (median value = 101 mm).

An examination of monthly water balances for individual sites further reveals the fine-scale pattern in moisture availability and moisture stress (Fig. 3). A pair of North Carolina sites (NC-3 and NC-527, approximately 3.9 km apart) are located on a ridge and upper slope, respectively, whereas two Ohio sites (O-5 and O-7, situated 90 m apart along the same topographic transect) are situated on a ridge and in a cove, respectively (see Fig. 2a; additional site descriptors are given in Fig. 3). Despite the close proximity of each pair, striking differences are observed between the sites. Annual PET at NC-3 is 926 and 656 mm at NC-527 (29% less than NC-3). Soil moisture deficit represents 19% of PET at NC-3 (175 mm), and 12% of PET at NC-527 (78 mm). Annual surplus is 39% of total precipitation at NC-3, and 53% at NC-527 (463 and 645 mm, respectively).

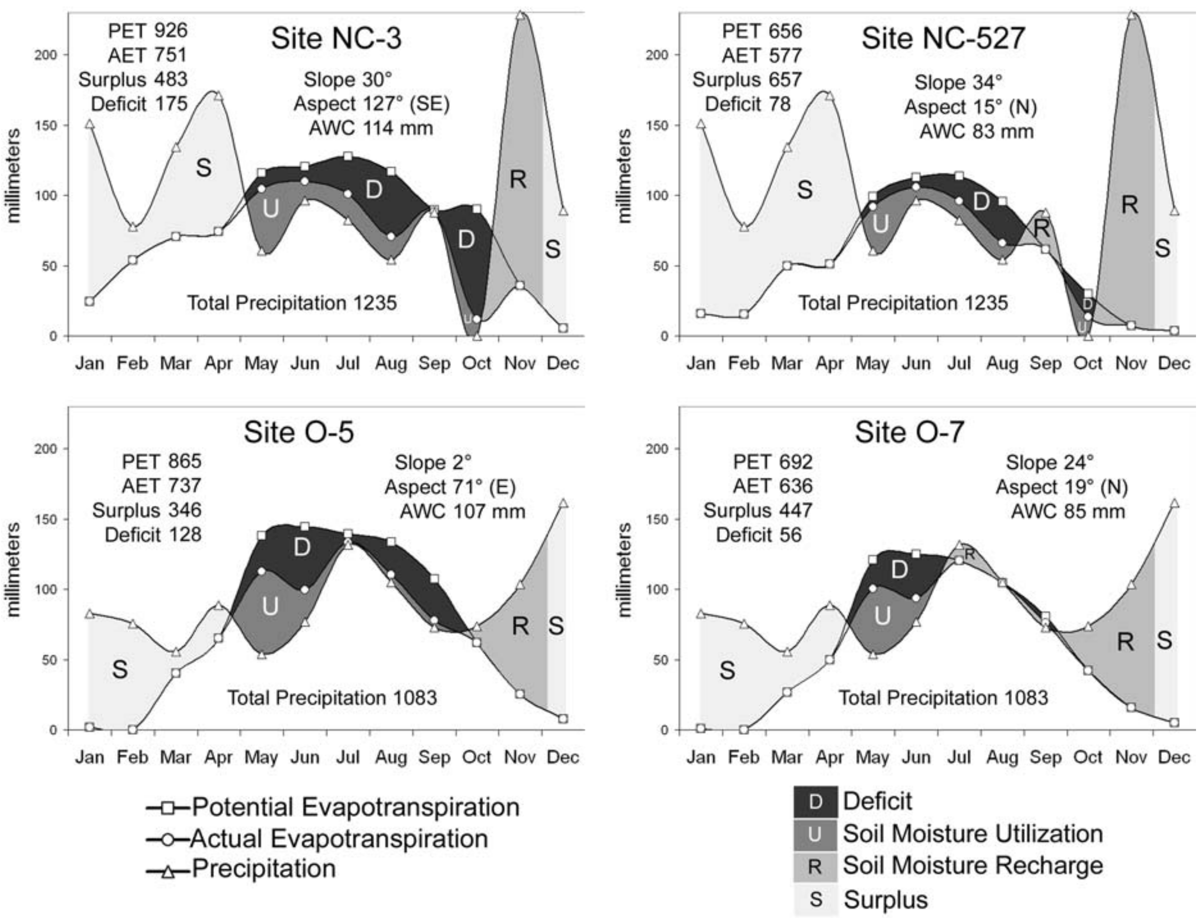

Fig. 3 Annual water balances for a pair of sites in the North Carolina (NC) and Ohio (O) study areas. See Fig. 2A for location of four sites. NC-3 and NC-527 are approximately 3.9 km apart, O-5 and O-7 are approximately 90 m apart. Annual values of PET, AET, Surplus, Deficit, and Total Precipitation are in millimeters

For the Ohio sites, PET of O-7 (692 mm) is just 80% of PET at O-5 (865 mm). Soil moisture deficit represents 15% of PET at O-5 (128 mm), and only 8% of PET at O-7 (56 mm). Finally, annual surplus is 32% of total precipitation at O-5, and 41% at O-7 (346 and 447 mm, respectively).

Comparison to soil moisture measurements

In terms of both magnitude and timing, soil moisture utilization and recharge trends were captured well by the model (Fig. 4). For the nine North Carolina sites, Pearson correlation coefficients between monthly Storage and Plant Available Water ranged from 0.92 to 0.97 ($P < 0.001$), with an average correlation coefficient of 0.94. Correlation coefficients between modeled and measured soil moisture were reduced somewhat due to the way that monthly precipitation is accounted for with each. Although soil storage was modeled with a daily time-step (the monthly value represents the last day of the month), monthly precipitation was distributed evenly across each day. In contrast, although measured soil moisture values were averaged to obtain a monthly value, soil probe readings reflect individual precipitation events. For example, compared to modeled soil moisture, lower measured values were observed in July and September at the North Carolina sites (Fig. 4). In both months, at least three-quarters of the monthly precipitation fell during the last 10 days, so soil moisture probes were reading drier conditions throughout most of the month.

For the Ohio sites, this issue regarding the distribution of monthly precipitation was more pronounced: for each month from May to November, most of the month's precipitation (61–100%, average 75%) fell during the second half of the month. The result is that the soil probes were often responding to precipitation that fell at the end of the previous month. Although the measured and modeled soil moisture curves are similar (Fig. 4), the measured monthly values lag behind the modeled values by one month from May to November. Accounting for this lag effect, Pearson correlation coefficients were significant ($P < 0.05$) for 17 of the 19 Ohio sites; correlation coefficients ranged from 0.75 to 0.98, with an average correlation coefficient of 0.90.

Differences between modeled and measured soil moisture could be attributed to the topographic configuration of the sites, since drainage does not contribute to a site's soil moisture supply in the model. However, visual inspection revealed no discernible pattern between topographic setting and model error, and stepwise regression between variables describing a site's topographic setting and its measured versus modeled soil moisture difference revealed no statistical relationship.

Discussion

In the humid forested study areas, patterns of soil moisture were captured using a radiation-based approach to modeling moisture demand, and assuming evapotranspiration declines linearly with soil moisture content. It is noteworthy that soil moisture patterns were driven more by topographically controlled variations in radiation, and not by

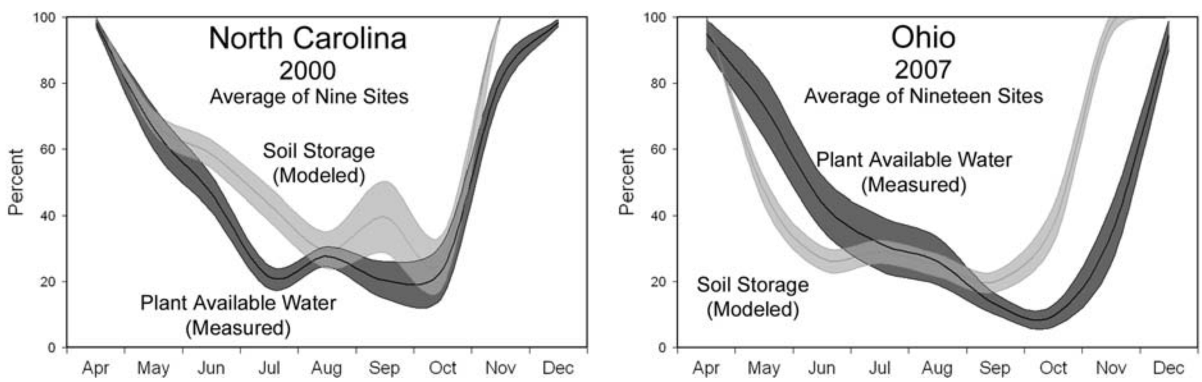

Fig. 4 Average values of measured Plant Available Water and modeled Soil Storage for nine sites in the North Carolina study area, and 19 sites in the Ohio study area, throughout the soil-utilization season. *Shaded areas* represent ± ½ standard deviation

topographically controlled variations in drainage. In the present model, moisture supply at an individual site is comprised of precipitation and soil moisture storage. Given the long-recognized relationship between topographic configuration and soil moisture drainage, it was anticipated that discrepancies between measured and modeled values could be attributed to augmentation of soil moisture at certain sites due to drainage from upslope; as the soil moisture utilization period progresses, drainage patterns would result in measured soil moisture being higher than modeled values on lower slope versus ridges, or on concave versus convex sites. However, no such relationship emerged between a site's topographic setting and the difference in its measured versus modeled soil moisture.

There are two likely explanations as to why no relationship emerged between a site's topographic setting, and differences between measured soil moisture and soil moisture modeled using radiation and AWC. The first factor has to do with the depth of the soil moisture probes (30–60 cm at the North Carolina sites, 50 cm at the Ohio sites). Numerous studies have reported that topographic control on soil moisture decreases with increased depth (Yeakley et al. 1998; Florinsky et al. 2002; Lookingbill and Urban 2004). Yeakley et al. (1998) attribute this observation to the higher clay content, lower macroporosity and lower hydraulic conductivity deeper in the soil profile, as well as the longer percolation times following precipitation events. The result is that topographically controlled patterns in soil moisture seem to be restricted to the upper 20–30 cm of the profile.

The second factor as to why no relationship emerged between a site's topographic setting and differences between measured and modeled soil moisture is the period of study: patterns of soil moisture at both sites were investigated during the soil moisture utilization period, when soil moisture was below field capacity. Western et al. (2002) conclude that terrain indices are unable to account for a significant proportion of variation in soil moisture as a catchment dries, since there is insufficient moisture content for flow to occur over significant distances. The relatively minor role topography plays in explaining moisture patterns when soils are below field capacity has been observed in a number of other studies (Western and Blöschl 1999; Chamran et al. 2002; Park and van de Giesen 2004). And yet it is during the growing season, when sites are experiencing moisture deficit, that patterns of soil moisture would be expected to be most critical in segregating species within the landscape. Given the inherent difficulties in modeling soil moisture drainage, it is noteworthy that the present model is able to capture soil moisture patterns while only incorporating AWC and topographically controlled moisture demand. The inclusion of topographic augmentation of available water into the model via upslope drainage is not warranted, at least if a goal is to model soil moisture patterns during the growing season. Under typical conditions, however, soils would be expected to be at field capacity throughout most of the non-growing season.

Since differences in moisture demand are largely responsible for fine-scale moisture patterns, an accurate assessment of radiation differences within the study area is critical. A strength of this approach is its ability to accurately model radiation. Although calibration is required to establish the diffuse proportion and transmittivity parameters for the Solar Radiation toolset, ultimately very accurate estimates are possible. Numerous other approaches estimate incident solar radiation-based on a site's slope, aspect, and latitude (e.g., McCune and Keon 2002; Pierce et al. 2005; McCune 2007), but these often represent "clear sky" estimates. Especially in humid environments, the diffuse proportion and transmittivity parameters can be significantly different than clear sky conditions. Since these conditions vary spatially and temporally, parameterizing them for a particular study area is important. Additionally, with this approach a site's computed radiation value is used to directly assess moisture demand, rather than serving as an index of moisture demand.

Conclusions

A water balance approach was able to accurately capture patterns of soil moisture in both high-relief and moderate-relief forested environments of the eastern US. The approach utilizes established relationships to quantify the biologically meaningful variables of moisture demand, availability, and stress at a very fine spatial scale. However, since it relies on widely available data (monthly temperature, precipitation, radiation, and digital maps of AWC and elevation), the approach is applicable for large geographic areas. Potential applications of the approach might include the modeling of species distributions, fire behavior, productivity and decomposition rates, and nutrient cycling. In the present study, the validation procedure required modeling moisture demand and availability for a particular year with available soil moisture data; depending on the aims of other studies, longer-term climatic data could also be employed (e.g., monthly temperature and precipitation normals, average monthly values of global radiation). Furthermore, the current water balance approach executes with a monthly time-step for reasons of model tractability. Depending on the needs of a particular study, temporal resolution could be improved with the incorporation of daily values of temperature, precipitation, and solar radiation (including daily estimates of diffuse proportion and transmittivity parameters).

A goal of this study was to model patterns of moisture "potential," irrespective of current vegetation at a site. In this regard, the approach shares the aims of other moisture indices (e.g., Parker 1982; Iverson et al. 1997). Even though some factors that may influence moisture conditions at a site (e.g., rainfall intensity, canopy interception, infiltration rates) were ignored, the model was able to capture both the magnitude and timing of soil moisture at various locations with different site conditions. Values obtained between pairs of sites in both study areas illustrate the significant differences that may be observed over short distances within a topographically diverse landscape. The water balance approach offers significant improvements over other moisture indices, including its ability to quantify moisture conditions at a site in both relative and absolute terms (millimeters of water), and its ability to produce values directly comparable across studies. Since the approach includes climatic variables, the model is able to directly assess the potential response of vegetation to climate change.

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