A GIS-Based Water Balance Tool to Quantify Ecological Variation in Complex Terrain

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Abstract

Environmental gradients have long-interested physical geographers, and a number of indices have been developed to characterize variation in soil moisture conditions within a landscape. A water balance approach has the advantage of providing researchers the ability to quantify moisture availability and demand in a biologically-meaningful manner. An ArcGIS tool is presented, that computes a complete monthly water balance for each pixel within a digital elevation model, using data layers that are readily-available nationwide. Moisture availability is a function of precipitation and soil available water capacity, whereas moisture demand (potential evapotranspiration) is determined by temperature and topographically-controlled radiation load. Model improvements incorporate the interactive effects between temperature and radiation throughout the day. An overview of the model, which is available as a free download *(http://www.ohio.edu/people/dyer/)*, is presented, as well as guidelines for parameterizing ArcGIS's Solar Radiation toolset. Monthly diffuse proportion and transmittivity values for the toolset were determined for the eastern U.S. An application of the model in complex terrain demonstrates the utility of the model, using composition and growth-rate data from forest plots in southeastern Ohio. Finally, a field-based relative index of moisture demand is presented, that captures topographic relationships informed by the GIS-based model.

1. Conceptual overview

A water balance approach assesses inter-annual variation in moisture demand and moisture availability across a landscape. **Moisture Demand, or Potential Evapotranspiration (PET)**, is governed by temperature and radiation load, and can be estimated using the Turc equation:

$$PET_{monthly} = 0.013 \times \left[\frac{Temperature_{monthly}}{(Temperature_{monthly} + 15)}\right] \times (Global\ Radiation_{monthly} + 50)$$

Where PET is in mm, Temperature in °C, and Radiation in cal cm^{-2}. Therefore modeling *Moisture Demand* requires monthly climate grids (temperature) and a Digital Elevation Model (DEM) for a study area, since a site's radiation load varies according to slope and aspect, as well as time of year, latitude, and atmospheric conditions [*see Fig. 3.1*]. One can assume that the temperature of a nearby weather station is characteristic for the entire study area, or use an existing gridded temperature grid such as PRISM.

Moisture Availability is dependent on precipitation, and soil moisture storage. Additional moisture derived from upslope drainage is not considered because (1) our ability to model subsurface flow is not as straightforward as our conceptual model suggests [*see Fig. 5.1*], and (2) subsurface flow does not occur if soils are not saturated. During much of the growing season, soil moisture is likely to be below field capacity; if soil moisture is at field capacity then plants are not experiencing moisture deficit, so upslope augmentation is irrelevant. As with Moisture Demand, modeling *Moisture Availability* requires grids of monthly climate (precipitation), as well as soil available water capacity (AWC) for a study area. Digital soil maps are available for many locations from the Natural Resources Conservation Service (NRCS).

2. Radiation drives moisture demand

Using the ArcGIS Solar Radiation toolset

ArcGIS provides a "Solar Radiation" toolset that can compute monthly values of total (global) radiation for each pixel in a DEM, based on slope, aspect, topographic shading, latitude, and time of year. The user must specify two atmospheric parameters: the **diffuse proportion** of global radiation, and **transmittivity** (the proportion of solar radiation outside the atmosphere that reaches the surface). The toolset's default values for these parameters are 0.3 and 0.5, respectively. These values can assume a wide range of values, however. In the eastern US, I have observed 21 different combinations, with monthly values of diffuse proportion between 0.2 – 0.7, and transmittivity values between 0.3 – 0.7. Misspecifying these values can have profound effects on radiation estimates. Since additional factors, such as surface reflectance or altitude, may affect radiation at a site, I adopt the approach of adjusting the two values to best approximate a "known" radiation value. For example, from the National Solar Radiation Database it is possible to determine monthly radiation estimates for a number of sites. Using these sites, I derived monthly estimates of the diffuse proportion and transmittivity, which can then be used for any site in the eastern U.S.

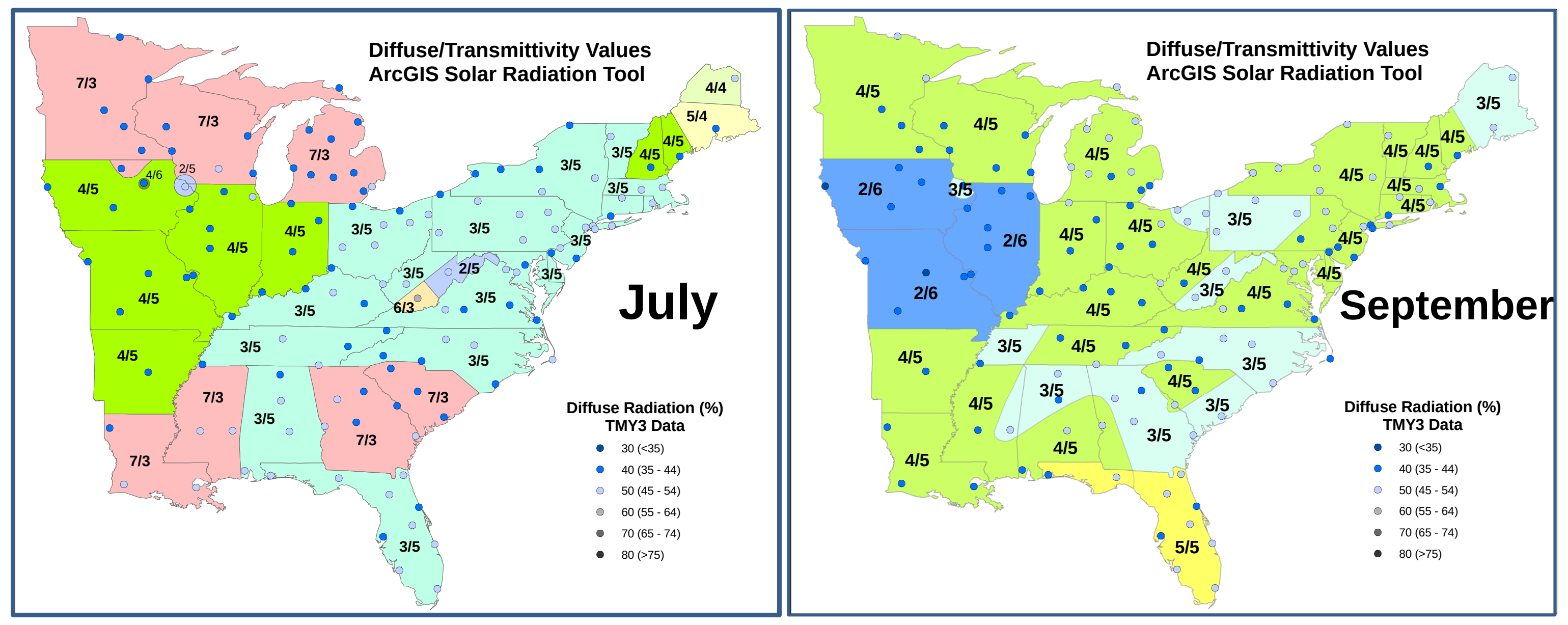


Figure 2.1. Suggested monthly Diffuse Proportion and Transmittivity values for ArcGIS's Solar Radiation toolset (default values are 0.3 and 0.5). Parameterization was based on a "brute-force best-fit" approach, matching reported values for National Solar Radiation Database Class I sites (shown). Note the NSRDB-reported Diffuse Percent, and the corresponding best Diffuse Proportion value for the Solar Radiation toolset.

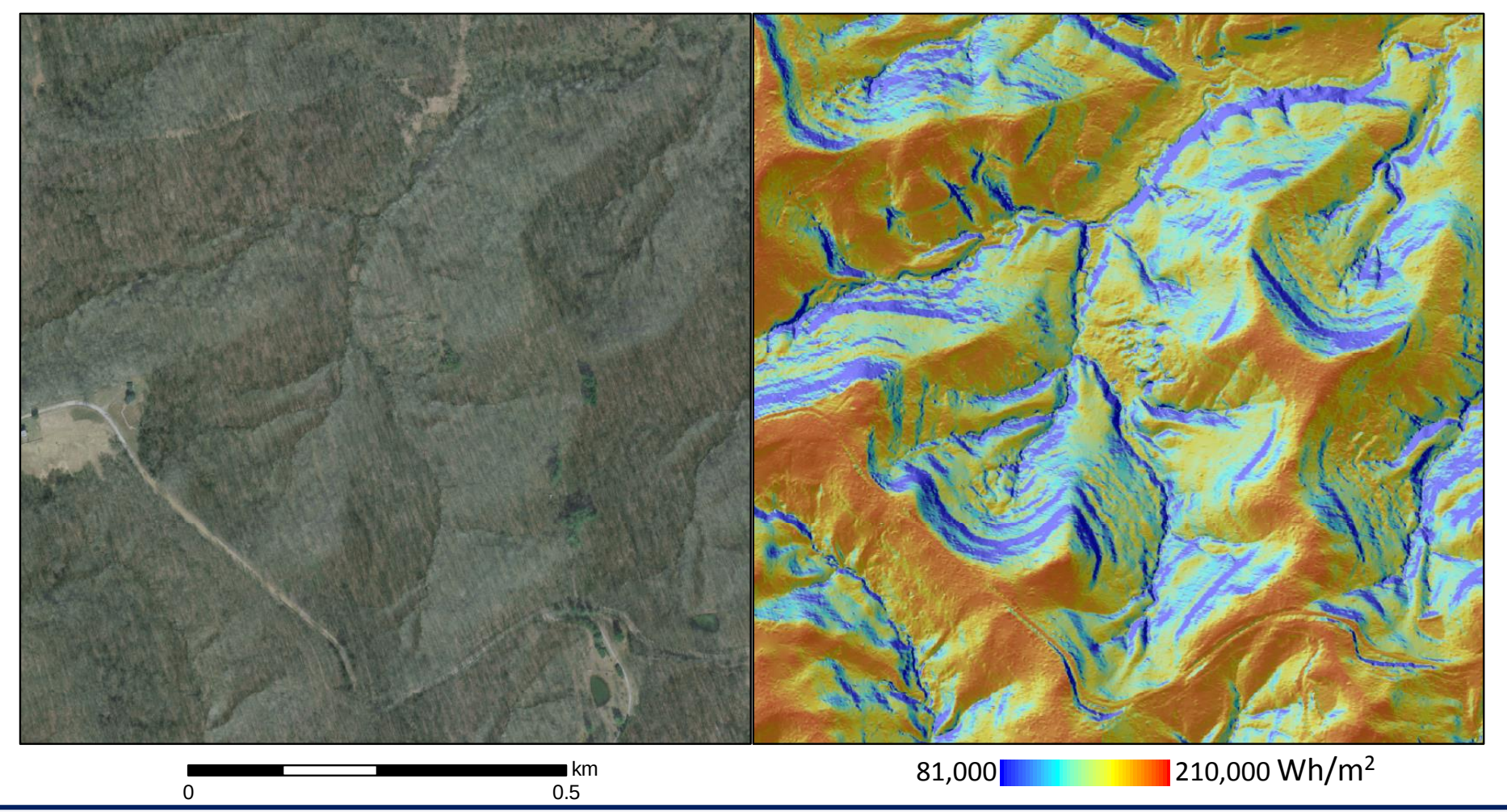


Figure 2.2. July radiation estimated for a southeastern Ohio site.

3. How does moisture ***demand*** vary throughout the growing season?

Moisture Demand (PET) is governed by temperature and radiation. But by using a monthly time-step, diurnal variations in temperature are not considered. The result is that maximum PET occurs on southern exposures, since that is where maximum insolation occurs (and PET is symmetrical about the N-S axis). To overcome this, the Water Balance toolset employs "adjustment coefficients" that either increase or decrease PET based on topographic position. These coefficients were derived by computing two separate *daily* water balances throughout the growing season for four sites [Williamsport PA (41°N), Elkins WV (39°N), Beckley WV (37°N), Asheville NC (35°N)]; one daily run used average hourly temperatures, the other used a daily mean temperature each hour. Differences between the two grids were noted based on topographic position, and adjustment coefficients developed.

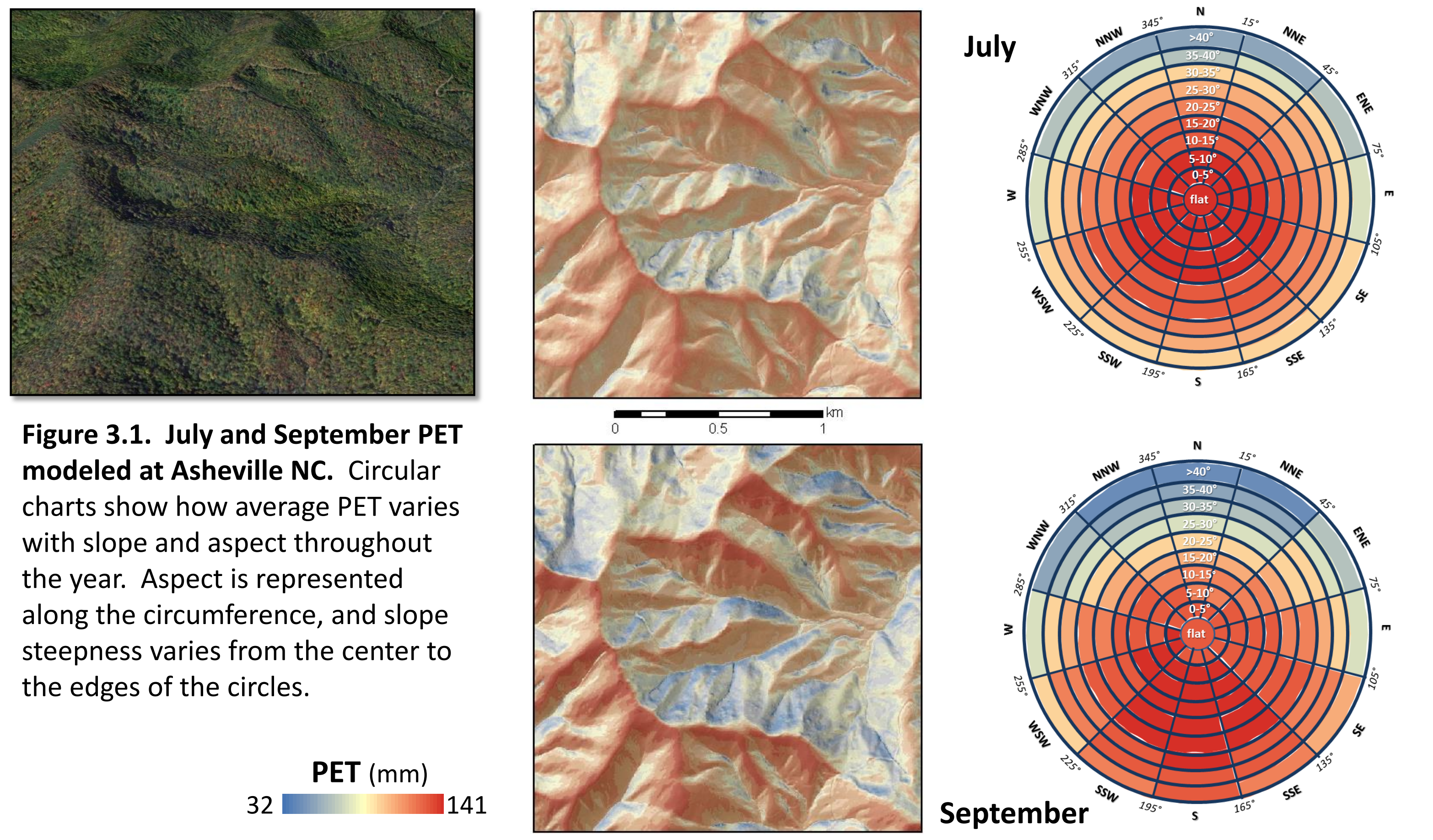


Figure 3.1. July and September PET modeled at Asheville NC. Circular charts show how average PET varies with slope and aspect throughout the year. Aspect is represented along the circumference, and slope steepness varies from the center to the edges of the circles.

4. Mapping moisture ***stress***

If monthly precipitation is insufficient to meet a site's moisture demand (PET), plants utilize soil moisture storage. The amount of available soil moisture is determined by the Available Water Capacity grid, and depends on soil depth and texture; before the start of the growing season, soils are at field capacity. Soil moisture utilization is computed using a daily time-step in the model, and soil moisture availability declines 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). If there is insufficient available moisture to meet demand, Actual Evapotranspiration (AET) will be less than Potential Evapotranspiration (PET). **Deficit** is the difference between PET and AET – the amount of water that plants "come up short."

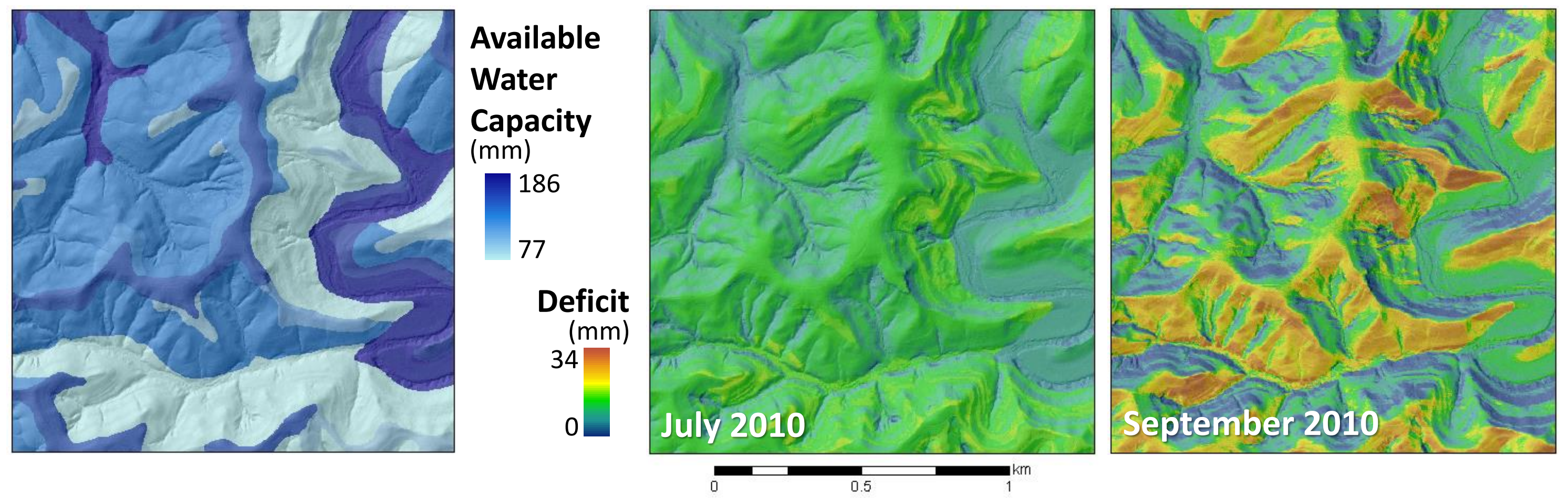


Figure 4.1. Available Water Capacity (top 1 meter of soil) and Monthly Deficit grids for the Raccoon Ecological Management Area in southeastern Ohio.

5. How well does the tool capture soil moisture patterns?

Continuously-monitored soil moisture data were obtained for a site in the Blue Ridge Mountains of North Carolina, and in the Unglaciated Allegheny Plateau in Ohio. These data were compared to modeled values of soil storage from the Water Balance tool. To facilitate comparison, both data sets were converted to "percent full" measurements. In terms of both magnitude and timing, soil moisture utilization and recharge trends were captured well by the Water Balance model.

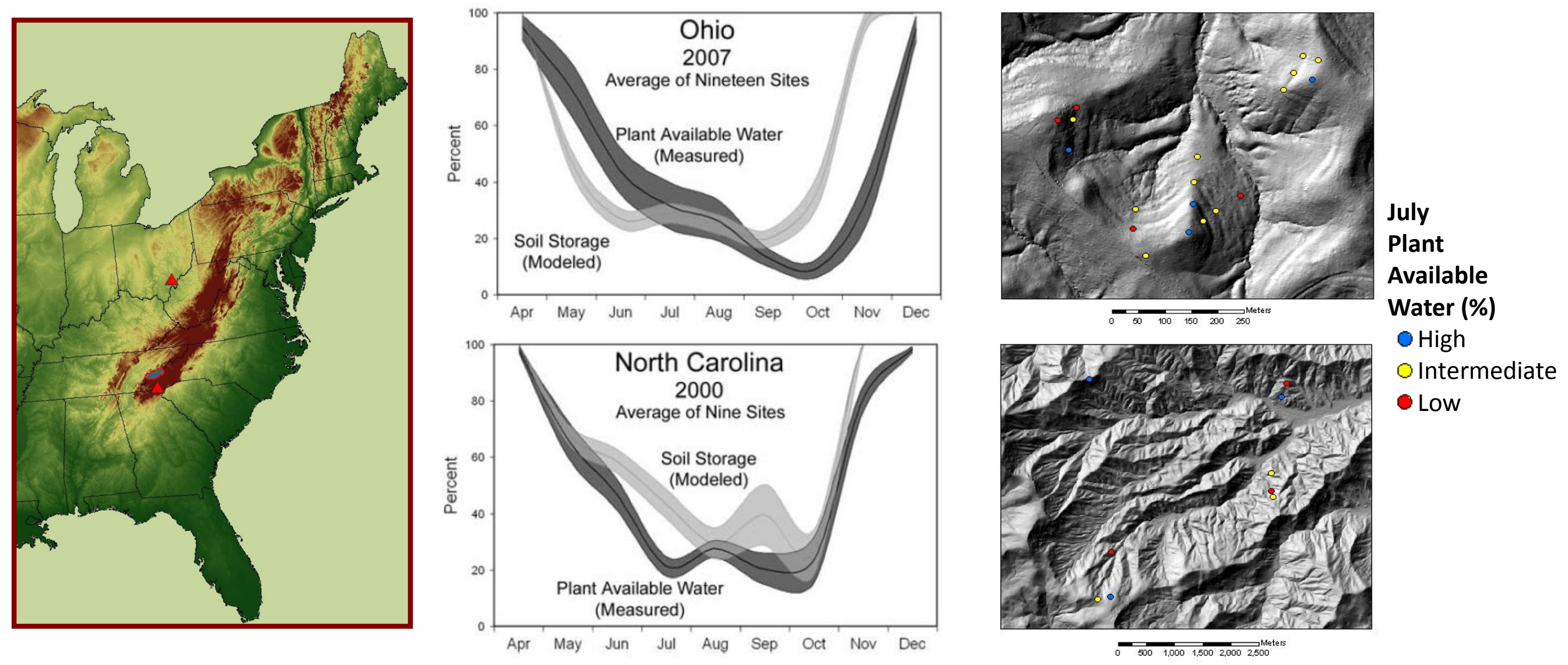


Figure 5.1. Average values of measured Plant Available Water and modeled Soil Storage throughout the soil-utilization season. Shaded areas represent ±½ standard deviation. *Figures on the right*: Patterns of *monitored* soil moisture indicate that topographically-controlled drainage is more complex than might be expected. At both study sites, several "ridge top" probes recorded higher soil moisture than probes situated downslope. This observation calls into question our ability to accurately model soil drainage during the growing season.

6. An application of the water balance tool

(collaboration with Alexander Anning, Environmental and Plant Biology, Ohio University

As part of a study examining prescribed burning and thinning treatments on forest dynamics, tree cores were extracted from 348 canopy trees, comprising five species (tulip poplar, white, black, and chestnut oaks, hickory species) across four treatment units (control, thin, burn, thin+burn) in southeastern Ohio. Ring-widths of the two cores from each tree were averaged together to obtain a single value for that tree, and converted to basal area increment (BAI), the net increase in total cross-sectional stem area of tree. Since the focus of the study was on tree response to management treatments, five-year BAI values were computed to filter out the high frequency variations in radial growth due to climate. The approximate location of each tree was captured with a GPS receiver, and then imported into GIS. A buffer with a 10-meter radius around each tree was used to extract modeled water balance variables. Even though initial results examined five-year BAI values against water balance variables from a single year, tulip poplar seemed to be very sensitive to topographically controlled microclimate. A negative relationship between growth and deficit in the control plots was observed in the two years analyzed, even though both experienced more rainfall than normal in the growing season (583 mm): 2003 (834 mm), and 2010 (732 mm). An "interactive effect" is also evident when examining growth vs. moisture demand (PET) and availability (Deficit). Interestingly, this microclimatic link between growth and microclimatic variables breaks down in the treatment plots, as tree growth responds more directly to the treatment and/or release from competition.

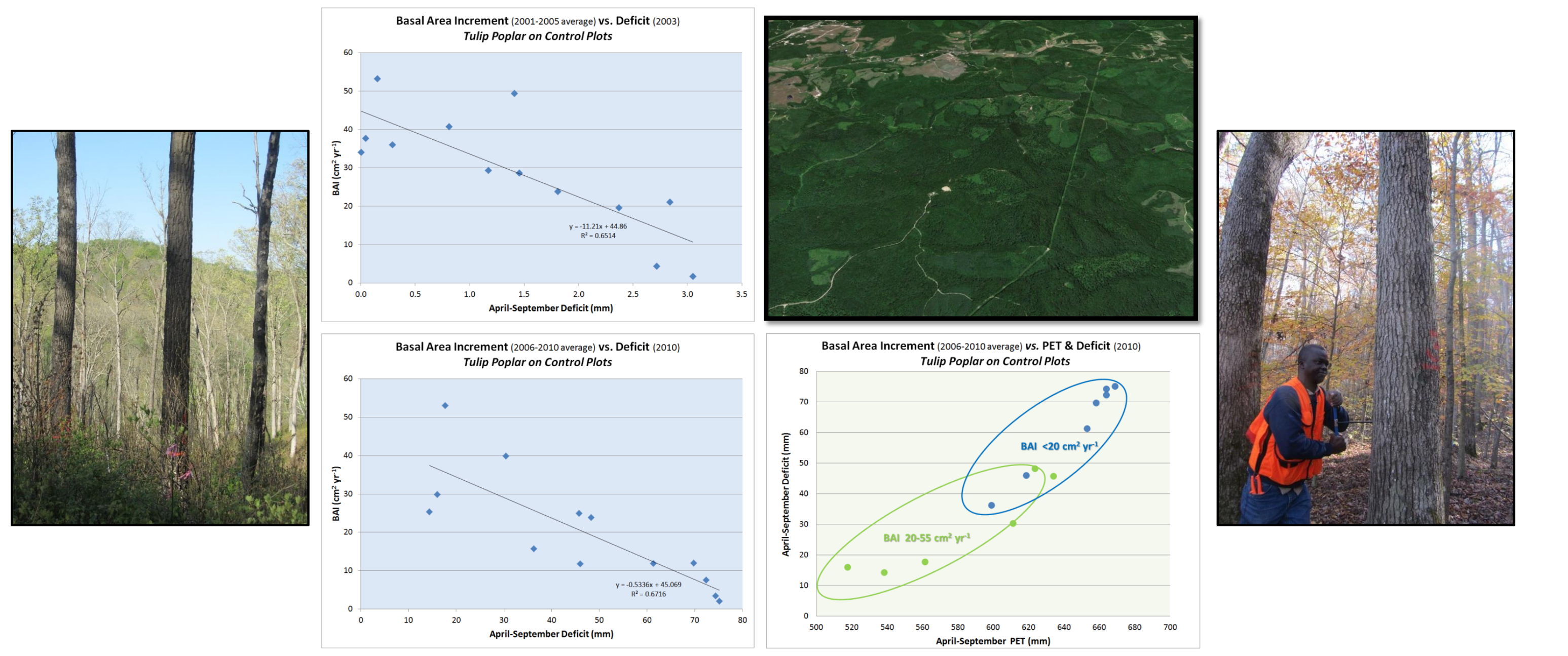


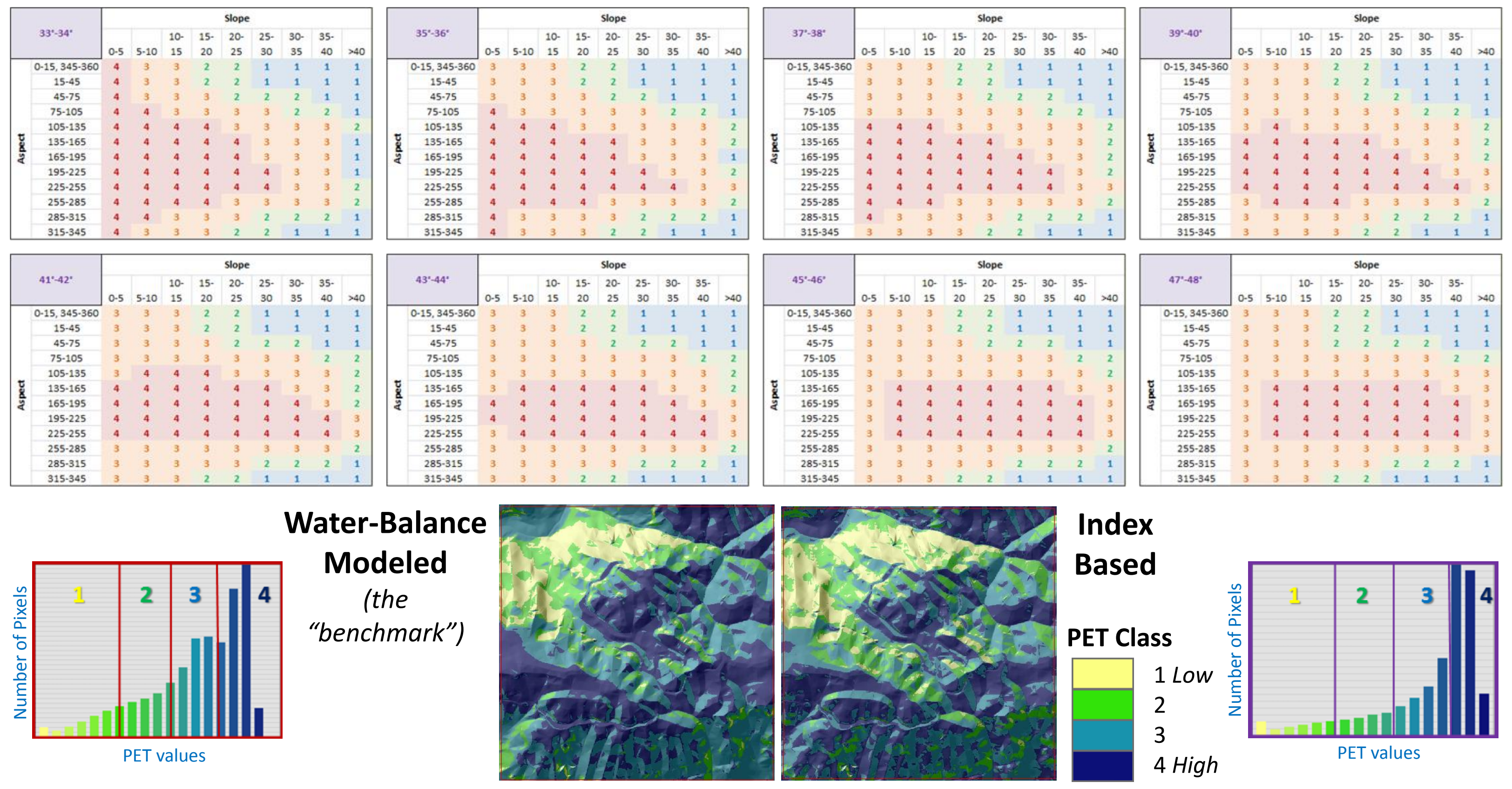
Figure 6.1. Growth of individual tulip poplar trees is linked to water balance variables at the site

7. What if I don't "do" GIS?

(collaboration with Gaurav Sinha, Geography, Ohio University)

The GIS-based Water Balance tool offers numerous advantages in its ability to define patterns of moisture demand and availability; it assesses moisture utilization in absolute terms at fine resolution but large spatial extents, and since it incorporates temperature and precipitation in addition to topography and soil available water capacity, the model is able to evaluate responses to changing climate. There are instances, however, when researchers may want a quick assessment of moisture demand based on field measurements. In these situations, the Water Balance model is able to inform our ability to quantify the interactive roles of slope, aspect, and latitude.

Direct, "clear sky" solar radiation can be estimated for any location based on its slope, aspect, latitude, hour angle, declination, and date. Using such a "theoretical" equation, we derived clear-sky direct radiation for all possible combinations of slope (0-60°) and aspect, for 2° latitudinal bands (32°-48°N). Using the Turc equation, radiation values were used to derive PET, and these theoretical results were compared against those of the Water Balance model for four sites [Williamsport PA (41°N), Elkins WV (39°N), Beckley WV (37°N), Asheville NC (35°N)]. Since the Water Balance approach accounts for direct and diffuse radiation, and incorporates atmospheric conditions and surrounding topography, there were notable differences between the "theoretical" and "modeled" PET. However, using mean and standard deviation "break points" with this comparative approach, it was possible to capture 4 PET classes for the growing season (April-September) based only on slope, aspect, and latitude of the site. Using these "PET Index" charts enables the user to quickly assess seasonal moisture demand at a site, without more-involved GIS analysis.



33°-34°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	4	3	3	2	2	1	1	1	1
15-45	4	3	3	2	2	1	1	1	1
45-75	4	3	3	3	2	2	2	1	1
75-105	4	4	3	3	3	3	2	2	1
105-135	4	4	4	4	3	3	3	3	2
135-165	4	4	4	4	4	3	3	3	1
165-195	4	4	4	4	4	3	3	3	1
195-225	4	4	4	4	4	4	3	3	1
225-255	4	4	4	4	4	4	3	3	2
255-285	4	4	4	4	3	3	3	3	2
285-315	4	4	3	3	3	2	2	2	1
315-345	4	3	3	3	2	2	1	1	1

35°-36°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	3	3	3	2	2	1	1	1	1
15-45	3	3	3	2	2	1	1	1	1
45-75	3	3	3	3	2	2	1	1	1
75-105	4	3	3	3	3	3	2	2	1
105-135	4	4	4	3	3	3	3	3	2
135-165	4	4	4	4	4	3	3	3	2
165-195	4	4	4	4	4	3	3	3	1
195-225	4	4	4	4	4	4	3	3	2
225-255	4	4	4	4	4	4	4	3	3
255-285	4	4	4	4	3	3	3	3	2
285-315	4	3	3	3	3	2	2	2	1
315-345	4	3	3	3	2	2	1	1	1

37°-38°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	3	3	3	2	2	1	1	1	1
15-45	3	3	3	2	2	1	1	1	1
45-75	3	3	3	3	2	2	2	1	1
75-105	3	3	3	3	3	3	2	2	1
105-135	4	4	4	3	3	3	3	3	2
135-165	4	4	4	4	4	3	3	3	2
165-195	4	4	4	4	4	4	3	3	2
195-225	4	4	4	4	4	4	4	3	2
225-255	4	4	4	4	4	4	4	3	3
255-285	4	4	4	3	3	3	3	3	2
285-315	4	3	3	3	3	2	2	2	1
315-345	3	3	3	3	2	2	1	1	1

39°-40°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	3	3	3	2	2	1	1	1	1
15-45	3	3	3	2	2	1	1	1	1
45-75	3	3	3	3	2	2	1	1	1
75-105	3	3	3	3	3	3	2	2	1
105-135	3	4	3	3	3	3	3	3	2
135-165	4	4	4	4	4	3	3	3	2
165-195	4	4	4	4	4	4	3	3	2
195-225	4	4	4	4	4	4	4	3	3
225-255	4	4	4	4	4	4	4	4	3
255-285	3	4	4	4	3	3	3	3	2
285-315	3	3	3	3	3	2	2	2	1
315-345	3	3	3	3	2	2	1	1	1

41°-42°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	3	3	3	2	2	1	1	1	1
15-45	3	3	3	2	2	1	1	1	1
45-75	3	3	3	3	2	2	2	1	1
75-105	3	3	3	3	3	3	3	2	2
105-135	3	4	4	4	3	3	3	3	2
135-165	4	4	4	4	4	4	3	3	2
165-195	4	4	4	4	4	4	4	3	2
195-225	4	4	4	4	4	4	4	4	3
225-255	4	4	4	4	4	4	4	4	3
255-285	3	3	3	3	3	3	3	3	2
285-315	3	3	3	3	3	2	2	2	1
315-345	3	3	3	2	2	1	1	1	1

43°-44°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	3	3	3	2	2	1	1	1	1
15-45	3	3	3	2	2	1	1	1	1
45-75	3	3	3	3	2	2	2	1	1
75-105	3	3	3	3	3	3	3	2	2
105-135	3	3	3	3	3	3	3	3	2
135-165	3	4	4	4	4	4	3	3	2
165-195	4	4	4	4	4	4	4	3	3
195-225	4	4	4	4	4	4	4	4	3
225-255	3	4	4	4	4	4	4	4	3
255-285	3	3	3	3	3	3	3	3	2
285-315	3	3	3	3	3	2	2	2	1
315-345	3	3	3	2	2	1	1	1	1

45°-46°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	3	3	3	2	2	1	1	1	1
15-45	3	3	3	2	2	1	1	1	1
45-75	3	3	3	3	2	2	2	1	1
75-105	3	3	3	3	3	3	3	2	2
105-135	3	3	3	3	3	3	3	3	2
135-165	3	4	4	4	4	4	4	3	3
165-195	3	4	4	4	4	4	4	4	3
195-225	3	4	4	4	4	4	4	4	3
225-255	3	4	4	4	4	4	4	4	3
255-285	3	3	3	3	3	3	3	3	2
285-315	3	3	3	3	3	2	2	2	1
315-345	3	3	3	2	2	1	1	1	1

47°-48°	Slope								
Aspect	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
0-15, 345-360	3	3	3	2	2	1	1	1	1
15-45	3	3	3	2	2	1	1	1	1
45-75	3	3	3	2	2	2	2	1	1
75-105	3	3	3	3	3	3	3	2	2
105-135	3	3	3	3	3	3	3	3	3
135-165	3	4	4	4	4	4	4	3	3
165-195	3	4	4	4	4	4	4	4	3
195-225	3	4	4	4	4	4	4	4	3
225-255	3	4	4	4	4	4	4	4	3
255-285	3	3	3	3	3	3	3	3	3
285-315	3	3	3	3	3	2	2	2	1
315-345	3	3	3	2	2	1	1	1	1

Figure 7.1. "PET Index" charts for assessing growing-season moisture demand at a site based on its slope, aspect, and latitude. Histograms show the distribution of PET values for the Beckley WV (37° N) study area, both modeled (left) and theoretical (right). Maps show the chart-based PET classes for a 2 x 2 km section of the Beckley study area (right), compared to PET classes derived from the GIS-based water balance model (left).