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Discussions

Effects of DEM scale on the spatial distribution of the TOPMODEL topographic wetness index and its correlations to watershed characteristics

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Abstract

Topographic wetness indices (TWIs) calculated from digital elevation models (DEMs) are meant to predict relative landscape wetness and should have predictive power for soil and vegetation attributes. While previous researchers have shown cumulative TWI distributions shift to larger values as DEM resolution decreases, there has been little work assessing how DEM scales affect TWI spatial distributions and correlations with soil and vegetation properties. We explored how various DEM resolutions (2, 5, 10, 20, 30, and 50 m) subsampled from high definition LiDAR altered the spatial distribution of TWI values and the correlations of these values with soil characteristics determined from point samples, Natural Resources Conservation Service (NRCS) soil units, depths to groundwater, and managed vegetation distributions within a first order basin in the Upper Southeastern Coastal Plain with moderate slopes, flat valleys, and several wetlands. Point-scale soil characteristics were determined by laboratory analysis of point samples collected from riparian transects and hillslope grids. DEM scale affected the spatial distribution of TWI values in ways that affect our interpretation of landscape processes. At the finest DEM resolutions, valleys disappeared as TWI values were driven by local microtopography and not basin position. Spatial distribution of TWI values most closely matched the spatial distribution of soils, depth to groundwater, and vegetation stands for the 10, 20, and 30 m resolutions. DEM resolution affected the shape and direction of relationships between soil nitrogen and carbon contents and TWI values, but TWI values provided poor prediction of soil chemistry at all resolutions.

1 Introduction

The TOPMODEL topographic wetness index and its derivatives (TWIs) are intuitively attractive to hydrologists because they elegantly encapsulate our beliefs about variable source area (VSA) behavior (Dunne and Black, 1970; Dunne et al., 1975; Hewlett and Hibbert, 1967) and the spatial variation of soil moisture. In turn, landscape position

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and soil moisture exert first order control on soil properties (e.g. texture, organic matter, chemistry) and vegetation characteristics, so we expect these characteristics to correlate with TWI values (e.g. Florinsky et al., 2002, 2004; Sariyildiz et al., 2005; Seibert et al., 2007). Under the assumption that relative wetness should be a major determinant of soil characteristics, we used both quantitative and qualitative techniques to investigate the correspondence of soil and vegetation characteristics to relative wetness as predicted by the TOPMODEL TWI calculated at fine to coarse DEM resolutions.

Previous researchers have shown that distributions of TWIs and their components are highly sensitive to scale (e.g. Zhang and Montgomery, 1994; Quinn et al., 1995; Kienzle, 2004), consistently demonstrating that TWI distributions shift to higher values as the DEM grid size increases. However, the question of how DEM resolution affects the spatial distribution of TWI values has been largely ignored. We investigated how the spatial arrangement of TWI values varied with DEM resolution. The question of appropriate DEM scale has become more critical since the advent of Light Detection and Ranging (LiDAR) data now makes high-resolution DEMs an easy choice when LiDAR is available. Our interest was in seeing how high-resolution DEMs changed our perceptions of relative landscape wetness predicted by TWI values.

The application of TWIs to explain the spatial distribution of moisture and soil and vegetation characteristics has encountered problems of several types. Efforts to determine optimal DEM resolution have found the answer depended on the terrain attribute investigated, but was generally within the range of 5–20 m (Zhang and Montgomery, 1994; Quinn et al., 1995; Kienzle, 2004). Lane et al. (2004) applied 2, 4, 8, 16, 32 and 64 m DEMs to TOPMODEL hydrologic simulations and showed that areas of saturation tended to increase, while channel definition decreased with decreasing resolution. The ability of TWIs to predict spatial patterns of soil moisture is highly dependent on geology (Güntner et al., 2004; Blyth et al., 2004) and also on the discrepancy between surface and subsurface topography (Thompson and Moore, 1996). Researchers have found that TWI values have some predictive power concerning soil and vegetation characteristics, but scatter among the relationships is high, and TWIs usually explain less than 40 % of the variation in soil and vegetation properties (e, g, Thompson and Moore, 1996; Florinsky et al., 2002; Sorenson et al., 2006; Seibert et al., 2007). The noise in these relationships is usually attributed to factors such as geology, depth to groundwater, soil characteristics unrelated to landscape position, and subsurface topography. Hwang et al. (2012), in their description of lateral hydrologic connectivity of headwater catchments using hydrologic vegetation gradient showed the relation between TWI distribution and downslope flow path length. Florinsky et al. (2004) also pointed out that a landscape must have sufficient soil moisture in order for topographically-driven lateral flow to affect soil moisture distributions significantly. These problems raise further questions about the effects of DEM scale on the spatial arrangement of wetness values and their relationship to soil and vegetation attributes.

The TOPMODEL topographic wetness index is defined as the natural log of the ratio of upslope contributing area per unit width to local slope (Beven and Kirkby, 1979). We derived TWI values from a high resolution LiDAR dataset of the Savannah River Site (SRS) subsampled to 2, 5, 10, 20, 30, and 50 m resolutions. The original LiDAR dataset featured high-accuracy ~0.877 m spatial resolution and 0.05 ft root mean square error (RMSE). Characterized by rolling topography, the landscape of the study site is comprised of permeable lithology, wide alluvial valleys, wetlands, and no shallow bedrock. Interflow does occur over an argillic sandy clay loam Bt horizon with a median conductivity of around 5 mm h^{-1}, but it is not a major hydrologic process due to short downslope travel distances (Jackson et al., 2014; Du et al., 2015). Furthermore, the depth of the A and E horizons over the Bt horizons is highly variable, ranging from as little as 0.2 to over 2 m and varying substantially over short distances, leading to a high interflow generation threshold (Du et al., 2015).

Because of these characteristics, this is an unusual landscape for evaluating the TWI concept. The TOPMODEL TWI intrinsically assumes lateral slope-parallel flow is an important process distributing water in the landscape. If interflow is not a dominant

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hydrologic process, uncertainty exists whether TWIs should be predictive of hydrologic responsiveness, soil characteristics, and vegetation characteristics. For example, in the highly infiltrative chalk geology of southern England, Blyth et al. (2004) found very little correlation between TWI values and soil wetness. This study is both an evaluation of DEM scale on the correspondence of TWI values with soil and landscape characteristics and also an evaluation of the applicability of these indices to a landscape in which interflow is not a dominant process.

The specific objectives of this study were to investigate the effects of DEM scale upon (1) spatial arrangements of TWI values, (2) the correlation of TWI values with point measurements of soil carbon and nitrogen content, (3) and the relationship between TWI values and distributions of landscape characteristics associated with relative wetness, including: Natural Resources Conservation Service (NRCS) soil maps, depths to groundwater, and vegetative cover. We randomly sampled hillslope and riparian soils on hillslope grids and riparian transects and analyzed the samples for carbon (C) and nitrogen (N) content. We then evaluated these soil characteristics against TWI values calculated at each scale to determine the degree of correlation between soil characteristics and TWI. We compared the distribution of TWI maps at various resolutions to hydric soil map units of NRCS soil series, riparian vegetation polygons, and depths to groundwater. We also evaluated the variation of TWI values along the ephemeral and intermittent stream network. These evaluations and visual inspection of the spatial arrangement of TWI values through maps reveals DEM resolution effects not shown by analyzing the aggregate distributions of TWI values.

The forested hillslopes in the study area are managed for timber production, so in this case the vegetative cover distribution does not represent climax vegetated conditions partly controlled by soil wetness, but rather incorporates past planting and management reflecting land manager perceptions of relative wetness and soil productivity as well as best management practice guidelines for leaving undisturbed vegetation around streams and wetlands. For example, pines are planted and managed on hillslopes and plateaus that are expected to be drier while unmanaged or lightly

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managed mixed hardwood forests are left on the wetter valley floors. Wetlands are left unmanaged. Thus, our tests of relative wetness are quantitative (correlations with point soil characteristics), qualitative (comparisons with mapped soil and landscape attributes), and partly sociological (comparisons with vegetation distributions whose management is dictated by human perceptions of wetness).

2 Site

The study area is a first-order intermittent stream basin measuring approximately 1 km^2 that drains into the upper Four Mile Branch at the Savannah River Site, a National Environmental Research Park, in the Sandhills of South Carolina (Fig. 1). The basin is dissected into three obvious ephemeral valleys each with a Carolina Bay depressional wetland located at the top of the valley. The extent of each of the stream reaches and their properties (ephemeral, intermittent and perennial) in the watershed were identified through frequent field observation. The Savannah River Site is located in the Upper Coastal Plain physiographic province. Most of the hillslopes are moderately sloping (2–5 %), although the hillslopes just above the valley floors often reach slopes as high as 25–30 %. The valleys are flat and hummocky, and contain hydrophytic vegetation. Prior to 1950, the site was used as agricultural land (row crops and pastures), but it was planted or reverted to forest since then. Currently, vegetation in the study area features mixed hardwood in the lowlands graduating to managed pines in the upper elevations of the basin (Kilgo and Blake, 2005).

Topsoils in the study area are primarily sand to sandy loam in texture, and they are underlain by an argillic sandy clay loam that occurs usually between 0.5 and 1.5 m below the surface. Infiltration rates are high, and Hortonian overland flow has not been observed in the forests. The upland areas of the basin feature Dothan series sand (Plinthic Kandiudults), and the lowest areas feature Pickney series sand (Cumulic Humaquepts). The upper riparian zones are mostly a complex of Vaucluse (Fragic Kanhapludults) and Ailey (Arenic Kanhapludults) series with loamy sand topsoil.

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Average monthly temperature, according to a record from 1948 to 2005 by the South Carolina Department of Natural Resources, ranges from 1.4 °C in January to 33.6 °C in July. Average annual precipitation is 1243 mm, distributed fairly evenly through the year.

3 Methods

3.1 Analysis of TWI

A 1 m (raster cell size 1 m × 1 m) LiDAR-derived DEM was resampled using ArcGIS 9.3 (ESRI Inc., Redlands, CA, USA; hereafter referred to as ArcGIS) Resample tool. The resulting raster grid sizes (i.e. resolutions) were 2, 5, 10, 20, 30 and 50 m. LiDAR data were obtained from the USDA Forest Service (USFS) in March 2009. The components of the TWI were calculated using TauDEM v. 4.6 (http://hydrology.usu.edu/taudem/taudem4.0/taudem40.html). Specific Contributing Area (CA_S) and slope ($\tan\beta$) were calculated using the "D-inf" (multiple flow direction) flow direction/slope tool in TauDEM v. 4.6. TWI was then calculated in Raster Calculator (ArcGIS), using the following equation:

$$\mathrm{TWI} = \ln(\mathrm{CA_s}/\tan\beta) \quad (1)$$

TWI was calculated in this way at each DEM resolution, and designated by its respective resolution (i.e. 2, 5, 10, 20, 30 and 50 m TWI). Maps of TWI values across the study watershed were created for each DEM resolution.

Distributions of the TWI values for the entire basin were computed using JMP 9.0.0 (SAS Institute Inc., Cary, NC, USA). Quantile metrics were used to quantify key differences among the distributions. There were over 200 000 cells in the basin at the 2 m resolution and approximately 300 cells in the basin at the 50 m resolution. Cumulative distribution plots were constructed and the minimum, maximum,

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interquartile range, and median for each resolution were calculated to quantify the effect of DEM resolution on the calculation of TWI.

3.2 Soil, vegetation, and groundwater maps

We visually compared the maps of calculated TWI values of various resolutions to the maps of NRCS-mapped soil units especially with the hydric soil types, USFS-delineated vegetation types, and also depth to groundwater using kriged well data. Soil pedology should vary across landscapes partly in response to relative wetness. For example, the NRCS soil map units in the riparian zone and depressions (wetlands) show poorly drained, frequently flooded Pickney sand, Rembert sand and Ogeechee sand units (Fig. 2a). These map units are identified as hydric sandy soil with very high hydraulic conductivity value that occupies a narrow stretch along the river section and the depressions (wetlands). The growth and management of vegetation is also partly dictated by relative wetness, distance from mapped drainage ways and wetlands, and site productivity. For example, according to the vegetation distribution, the valley floors are dominated by sweet gum and yellow poplar hardwoods (Fig. 2b).

A depth-to-groundwater map was created in several steps. First a snapshot of groundwater level was taken on 18 October 2012 from measurements of 16 wells located in and around the study basin (~ 4.7 km^2). The groundwater level was then combined with surface water level points sampled along Four Mile Creek and perennial stream branches in the LiDAR derived DEM. The combined points were interpolated by kriging to generate a water level map, which was later subtracted from DEM-generated surface topography to calculate the depth-to-groundwater map (Fig. 4a).

In order to compare the distribution of various TWI resolutions with depth to groundwater maps, we created depth to groundwater maps having corresponding horizontal grid sizes that matched with the resolutions of TWIs. The effects of resolution on TWI were evaluated based on how the distributions in TWI maps were correlated to the corresponding depth to groundwater maps. Within the hydric and streamside polygons, the distributions of each TWI resolutions were classified into five classes.

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The classifications of the TWI values were based on their quantile distribution: < 10th quantile (very low), 10th to 25th (low), 25th to 75th (medium), 75th to 90th (high), and > 90th quantile (very high). Then the effects of TWI resolutions were evaluated using the proportions of TWI classes within the area covered by hydric soil and streamside vegetation cover.

3.3 Evaluation of TWI values along the stream network across DEM resolutions

To quantify the effect of DEM resolution on the characterization of valley pixels, we defined the stream channel pixels and valley thalweg pixels (above the point of channel initiation) and assessed the variation of valley TWI values among the 2, 10, and 20 m DEMs. The stream channel of the study watershed was created using ArcHydro tool in GIS environment where the channel initiation threshold number of cells were determined by trial and error using the observed stream network (Fig. 1) as verification network. Ground inspection of the channels and valleys indicated two stream types in the study watershed: (1) an intermittent stream with a well-defined channel, and (2) ephemeral streams with evidence of fluvial scour on the valley floor, but no defined channel (Fig. 1). The intermittent stream reach measures approximately 285 m from the outlet of the watershed and the ephemeral stream reaches extend approximately 1250 m in total length in three branches. We then plotted the TWI values of all stream and valley thalweg cells in the entire network for each of the various resolutions and calculated the mean and standard deviation of TWI values along the network.

3.4 Soil sampling

Soil samples were collected from two 100 m × 100 m grids on the hillslopes, and seven transects across and perpendicular to the main intermittent stream of the study watershed (Fig. 2). The grids were established according to a 6/10 cyclic sampling pattern (Burrows, 2002), with two smaller (10 m × 10 m) but identical grids nested within each larger grid for a total of 100 sampling points per grid. The transects consisted of

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10 sampling points, spaced 8 m apart. There were a total of 270 sampling points. Each sampling point was georeferenced using an Archer (Juniper Systems Inc., Logan, UT, USA) handheld GPS unit (Hemisphere XF DGPS, Calgary, Alberta, Canada) so that the sampling points could be matched with the cells in the TWI raster.

In July 2010, a soil sample was extracted from the A horizon sampling point to a depth of 7.5 cm using a 20 lb. slide hammer and sleeves with an inner diameter of 7.5 cm. Well-mixed pulverized samples (1 mg) were analyzed for C and N concentrations using a CHN elemental analyzer (NC 2100, CE Elantech Inc., Lakewood, NJ).

3.5 Soil carbon (C) and nitrogen (N) content vs. TWI

Elemental concentrations for each sample unit were transformed to content (kg ha^{-1}) using the bulk density and weight of the organic matter. The TWI and C and N data were right-skewed and therefore were log-transformed before statistical analysis. The relationships between C and N content and TWI in each horizon were evaluated using quadratic regression equations in JMP 9.0.0 (SAS Institute Inc., Cary, NC, USA). The rationale for exploring this type of relationship was that the conditions for the chemical changes of carbon- and nitrogen-containing molecules are somewhat dependent on soil moisture in a non-linear way. For example, soil microbial respiration is slow or non-existent in very dry or very saturated conditions, but at a maximum in moist soil. Therefore, if soil metabolism is plotted along a gradient of soil moisture from dry to saturated, the best fit of the data points will likely be a curve rather than a line. Each DEM resolution of TWI was regressed against C and against N in separate analyses.

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4 Results and discussion

4.1 Cumulative distributions of TWI values

DEM resolution strongly affected the distribution of TWI values and quantiles of TWIs calculated over the study basin (Table 1). Minimum, and median TWI values were smallest at the highest resolution and increased as DEM resolution decreased. There was nearly a three-fold difference in minimums between the 2 and 50 m TWIs from 1.9 to 6.05. Median and mean of the distribution were also highly sensitive to DEM resolution, ranging from 4.95 and 5.8 at 2 m resolution up to 8.05 and 8.7 at 50 m resolution respectively. In this terrain, TWI distributions were most sensitive to DEM resolution at high resolutions (there is a large difference between the 2 and 5 m distributions) and not very sensitive at low resolutions (the 30 and 50 m distributions were very similar). In steep mountainous terrain, Zhang and Montgomery (1994) found the opposite where 30 and 90 m resolutions showed significant variation in the statistics of resulting TWI maps. This shows that mountainous watersheds need very low resolution to smooth out the surface to the point where resolutions do not make any difference. The interquartile range (IQR) and the standard deviation did not show nearly as much variation across resolutions as did the mean and median of the distributions.

4.2 Spatial distributions of TWI values – soil, vegetation, and depth to groundwater comparisons

The spatial distribution of relative wetness values (Fig. 3) were strongly affected by DEM resolution. Most striking, at the finer resolutions, valleys disappeared as the TWI values of most valley pixels were defined by the local microtopography and were insensitive to the larger drainage area flowing to the valley at that point. Thus, 2 and 5 m resolution maps produced many relatively low TWI values in the valleys, due to hummocky topography. Also, at the finer DEM resolutions, the TWI maps produced finely defined drainage pathways with thin ribbons of high TWI values that dissect the

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landscape up to the ridgetops. As a result, the valleys were not strongly contrasted from the hillslopes at the 2 m resolution (Fig. 3). As the resolution decreased, the bulk of the high TWI values shifted to the valley floors, the apparent drainage system coarsened, and high TWI values became rarer near the ridgetops. At the 20 and 30 m resolutions, the contrast between valleys and hillslopes was strong, and the threads of high TWI values closely matched the valley bottoms inferred from topography, vegetation, and depth to groundwater (Figs. 3–5). At 50 m resolution, the TWI map became very conceptual and no longer looked like a drainage system. At all resolutions, the TWI maps predicted threads of high TWI values extending far up the slopes, but neither soil nor vegetation characteristics reflected these predictions of upslope wet areas. Wilson and Gallant (2000) found similar sensitivity of other distributed landscape variables to DEM resolution. Qualitatively, the 10 to 30 m resolution TWI maps best matched our conceptualization of the watershed topography and watershed attributes such as the streamside vegetation cover, the distribution of hydric soil map units (Fig. 2) and field observations.

Depths to groundwater within the basin vary from 15 m at the northeast ridge to 0 m at the stream channels (Fig. 4a). In the 20 m TWI map, there is a clear gradient of relative wetness as one moves from the water divide regions to the valley bottom, similar to the distribution of depths to groundwater (Fig. 4). TWIs are negatively correlated to depths to groundwater and the magnitude of the correlation coefficients increase as resolution decreases (Fig. 5). At high resolution, the correlation is very poor, about −0.2, which can be attributed to the TWI variability associated with surface topographic details rather than landscape position. At low resolution, the dampening of the variability in surface topography resulted in smooth TWI gradient towards the valley as it is in depth to groundwater. The correlations at 20, 30, and 50 m resolutions are nearly constant with only slight increase between 20 and 50 m. the depth to groundwater map most closely resembled the 20 and 30 m TWI maps (see Figs. 3 and 4). This apparent optimum scale was similar to those found by Zhang and Montgomery (1994) and Kienzle (2004). However, with respect to delineating the boundaries of the three

Carolina Bay wetlands, the high resolution 2 and 5 m DEMs appeared to capture the boundaries better.

Figure 6 shows the effect of TWI resolution based on the distribution of the various wetness classes within the hydric soil and streamside management polygons. Across all resolutions, the proportion of relatively wet cells is dominant in hydric soil polygons. This is consistent with the fact that soils vary across landscape in response to relative wetness. The wet cell proportion significantly increased as the resolution coarsened (Fig. 6a). The proportion of wet cells increased from about 44 % at 2 m to 80 % at 50 m DEM. On the contrary the proportion of relatively dry cells and medium wetness decreased from 16 and 22 % at 2 m resolution to 11 and 5 % fractional areas at 50 m DEM resolution. This indicates that a relatively dry area according to high resolution TWI maps turns into a relatively wet condition in low resolution TWI maps.

The streamside vegetation polygon reflects the legacy of past forester decisions about where soil conditions are too wet for growing pine trees or the minimum allowable distance between aquatic habitat (defined streams and wetlands) and timber harvest allowed by USDA Forest Service management guidelines. The land managers at this site plant pine trees on the hillslopes where soils are drier and favorable to pine growth, and they leave hardwoods growing in the bottomlands and near streams and wetlands. Because of the riparian buffer requirements, the streamside vegetation polygons are generally wider than the hydric soil polygons and contain regions of relatively drier conditions. Figure 6b shows coarsening TWI resolution increases the proportion of wet cells and decreased the proportion of medium wetness cells. This was similar to the change observed within the hydric soil polygons, but the effect was not as strong. The proportion of wet cells increased from 24 % at 2 m resolution to about 40 % at 50 m resolution. The medium wetness condition decreased from 40 % at 2 m to about 20 % at 50 m DEM. This can be viewed as a shift of wetness in streamside polygons from moderately wet condition to wet as resolution decreased. The proportion of dry cells remained relatively constant regardless of DEM resolution.

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Variability of TWI values along the stream network decreased with decreasing DEM resolution (Fig. 7). For 2 m DEMs, TWI values ranged from 10 to 20, and displayed high variation from point to point along the longitudinal transect. Conversely, TWI values generated from the 20 m DEM varied from only about 12.8 to 16.1. At high DEM resolutions, TWIs decreased slightly as expected from the basin mouth going upstream but this relationship was not apparent at coarser resolutions. The relationship featured a negative slope of 0.002 for the 2 m resolution but nearly zero for 10 and 20 m DEMs. Contrary to the general trend of the effect of DEM resolution on median TWI values, median TWI values along the stream network increased with increasing DEM resolution. The median TWI value of 2 m DEM resolution was 16.28 and it decreased to 15.3 and 14.25 for 10 and 20 m DEM resolutions. There was no clear difference found in the calculated TWI between the intermittent and ephemeral streams.

Graphing point-scale mineral soil C and N contents against TWI values interpolated from the resident and nearest pixels, as well as against pixel TWI values, indicated that the form and direction of the relationship depended on DEM scale (Figs. 8 and 9). At the finest DEM scale of 2 m, carbon and nitrogen contents decreased with increasing TWI values, but at the coarser DEM scales of 30 and 50 m, carbon and nitrogen contents increased with increasing TWI values. Over the DEM scales of 5 to 20 m, the data suggested the hypothesized U-shaped relationship with higher carbon and nitrogen contents at the lowest and highest TWI values. In all cases, correlations between TWI and soil carbon and nitrogen contents were poor, with r^2 values substantially lower than the higher values of around 0.4 reported in the literature (e.g. Florinsky et al., 2002; Sorenson et al., 2006; Seibert et al., 2007), indicating that subsurface controls on lateral flow are substantially larger than surface topography. Welsch et al. (2001) found that TWIs explained 56 % of the variation in subsurface nitrate concentrations, by far the best reported performance for TWI prediction of landscape and soil attributes.

The finer scale sampling used in parts of the variably-spaced sampling grid resulted in multiple points located in the same pixels at the larger DEM scales (Fig. 8b). These points also indicated substantial and not surprising variability in soil chemistry over

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the scale of even 5 m pixels. This suggests that a more appropriate study design for evaluating soil characteristics relative to DEM scale would be to map out the pixels in the field at various resolutions and take composite soil samples from across each pixel to represent average conditions over the pixel. This would require pre-generating the pixels, determining the coordinates of the pixel corners, using GPS to mark these corners in the field, and then composite sampling across each pixel before conducting lab analysis. Achieving enough pixels at each scale for statistical analysis would be extremely laborious. When starting with LiDAR topography, an infinite set of pixels can be created at each resolution based on the coordinate origin of the pixel grid, so an alternative analysis would be to produce many realizations of the pixel grid for each DEM resolution and evaluate the robustness of the distributions and the relationships to point soil attributes across scales.

The TOPMODEL TWI assumes that water accumulation and routing is driven by shallow slope-parallel subsurface flow. The evaluation of landscape attributes against the spatial arrangement of TWI values at different scales suggests that the scales at which shallow subsurface processes drive soil wetness are not as fine as the scale of surface microtopography, and that the optimal scales for estimating relative wetness range from about 20 to 30 m. Furthermore, in this landscape, TWI values created with 2 and 5 m DEMs reflected fine scale microtopography that has been modified substantially by the human activities of forest clearing, agriculture, ditch digging, road building, fire line creation, and tree planting. Therefore, the fine scale surface features reflect subsurface pathways less than they would in an undisturbed watershed. The data and maps presented here suggest that the mid-scale resolutions of 20–30 m provide the closest match between shallow subsurface processes and surface topography.

We did not select this watershed specifically to test TWI values against other landscape metrics associated with soil moisture. We were already using LiDAR data to study this watershed's hydrology, and we knew from previous work that TWI distributions varied with DEM resolution, but we were surprised to find that not only did distributions change, but spatial patterns changed substantially. These spatial patterns reveal that fine scale topography may poorly predict site conditions when soil moisture is driven by much larger scale groundwater processes. Unfortunately, this watershed is managed, so vegetation distributions reflect not just landscape controls but also management decisions. Furthermore, the soils have been previously disturbed, so topsoil characteristics may partially reflect legacy effects of management. Ideally, a future study would examine the relationships between TWI distributions, vegetation distributions, and soil characteristics in relatively undisturbed watersheds varying in dominant hillslope flow pathways. Despite these limitations, this study demonstrates that DEM scale strongly affects inference generated from TWI distributions.

5 Conclusions

The spatial distribution of TWI values across the landscape, and the inference generated therefrom, is highly sensitive to DEM scale. We documented a migration of the bulk of the wettest cells from higher to lower elevation as resolution decreased and a change in the thickness and number of high TWI threads leading from the ridges to the valleys. Higher resolution DEMs mapped thinner and more numerous drainage threads while coarser resolutions mapped wider and fewer drainage threads. Essentially, valleys disappeared at the finest resolutions while the drainage network became very abstract at the coarsest 50 m resolution. The 20 and 30 m DEMs produced spatial distributions of TWI values that most closely matched the distribution of mapped soil types, the relative wetness determined from depth to groundwater maps, and the spatial distribution of forest stands managed partly on the basis of wetness and drainage networks.

Consistent with the findings of previous researchers, cumulative distributions of TWI values consistently shifted as DEM resolution changed. As DEM resolution coarsened, the median value and minimum TWI values increased and the range of predicted TWI values decreased. This was also observed by Zhang and Montgomery (1994) and

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Kienzle (2004). However, each of these studies observed different relative sensitivities of the TWI distributions to DEM scale. When evaluated in concert with previous studies, the investigation indicates the sensitivity of TWI distributions to DEM resolution depends on terrain characteristics.

The correspondence between TWIs and depths to groundwater is very sensitive to DEM resolution. The study showed that TWI and depth to groundwater are more correlated at lower resolution DEMs. Visual observation of the distribution of TWI map and its correlation with depth to groundwater map showed that the 20 and 30 m TWI maps more closely resembled the observed groundwater map of the study site. TWI distributions generated from high resolution DEMs bore no resemblance to depths to groundwater.

The distribution of TWI values in the hydric soil showed a significant increase of wetness with decreasing resolution. Even at high resolution (2 m), the TWI map identified more than 60 % of the area as very wet and wet area. The high proportion of high TWI values in the hydric soil polygons is consistent with the influence of wetness on the distribution of soil pedology. In streamside vegetation polygon wetness values showed only moderate shift of wetness with decreasing resolution. Compared to hydric soils, the effect of resolution on TWI is not sensitive in the streamside vegetation cover. This is due to the fact that streamside vegetation area extends significantly beyond the valleys; diminishing the effect of DEM resolution on the proportion of wetness classes affected by the size of drainage ways which increases with decreasing resolution. DEM resolution also affected the shape and direction of apparent relationships between soil chemistry and TWI values. At the finest (2 m) DEM resolution, both N and C contents decreased with increasing TWI values while at the coarsest (50 m) resolution, N and C contents increased with increasing TWI values. Over the intermediate DEM scales, N and C concentrations suggested U-shaped relationships with TWI, with the highest N and C contents occurring at the lowest and highest TWI values. In all cases, relationships between N and C contents and TWI were not well-defined, and variation of TWI values explained no more than 30 % of the variation in N and C contents,

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indicating that surface topography is a poor predictor of N and C accumulations in this landscape.

Prior to the advent of LiDAR, the choice of DEM resolution was largely a moot question, as the effort to create high resolution DEMs was prohibitive for most projects. Previous assessments of the effects of DEM scale on topographic indices relied on laborious photogrammatic interpretation. With available high resolution LiDAR, the creation of high resolution DEMs for this study was easy, but not necessarily beneficial, depending on the desired analysis. The results indicate that LiDAR is not a panacea for hydrologic assessments but rather raises questions about integration of different scales relevant to different watershed characteristics and processes.

These results illustrate that considerations of scale effects must be made when choosing a DEM resolution for characterizing relative soil wetness and hydrologic sensitivity. The spatial and elevational distributions of high TWI values (expected to be variable source areas) were highly sensitive to the choice of resolution, an issue that must be considered when applying the TOPMODEL TWI in modeling and land-use planning applications.

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Table 1. Quantile distribution characteristics across resolutions. Sample sizes of each resolution were: 2 m = 294 173; 5 m = 47 082; 10 m = 11 768; 20 m = 2943; 30 m = 1311; and 50 m = 474.

Statistics	2 m TWI	5 m TWI	10 m TWI	20 m TWI	30 m TWI	50 m TWI
Minimum	1.93	3.22	4.30	4.98	5.80	6.05
Median	4.95	6.22	7.08	7.60	7.89	8.07
Maximum	21.26	16.08	20.17	17.92	16.48	16.88
Range	19.32	12.86	15.87	12.93	10.68	10.83
Mean	5.82	6.60	7.61	8.15	8.47	8.73
Standard deviation	2.42	1.62	2.03	1.96	1.91	1.93
InterQuartile range	2.56	2.04	1.85	1.59	1.43	1.51

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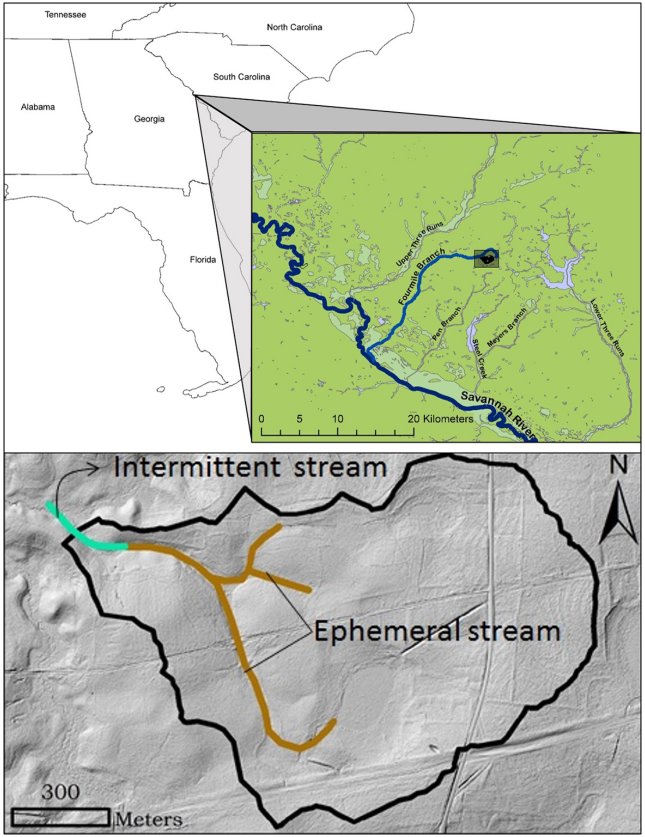

Figure 1. Above: Fourmile Branch of Savannah River in South Carolina, with the general study area shaded in inset. Below: hillshaded map of the study area. The basin boundary as delineated by hand is depicted as a solid black line. Road F runs N–S on the right side of the hillshade figure.

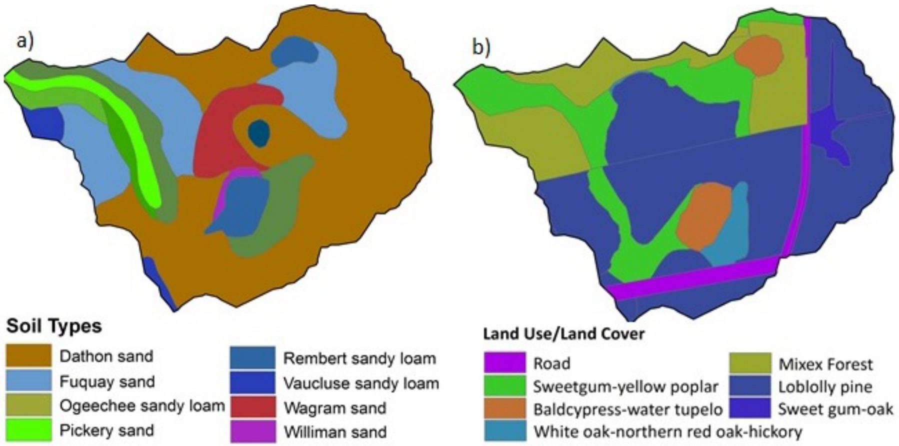

Figure 2. (a) NRCS soils map and soil C and N sampling grid. **(b)** USFS stand type map.

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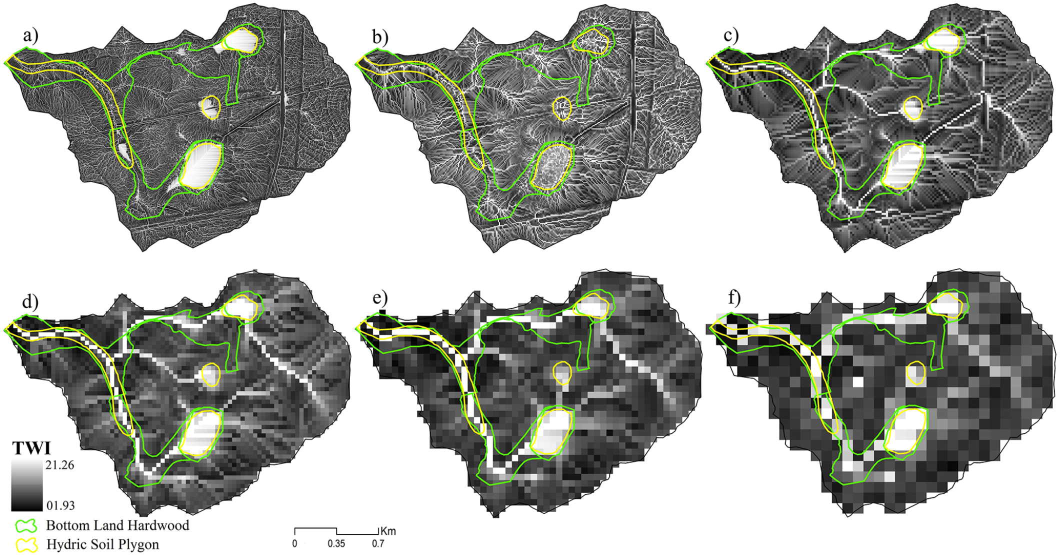

Figure 3. Spatial distribution of TWI values for **(a)** 2 m, **(b)** 5 m, **(c)** 10 m, **(d)** 20 m, **(e)** 30 m, and **(f)** 50 m DEMs. Hydric soil polygons, which consist of mainly Pickney, Rembert, and Ogeechee sand units were superimposed on TWI map. High resolution DEMs produce thin high TWI value drainage lines extending high into the watershed, nearly to the ridgelines and also produce very thin wet valleys. Coarser DEMs do not produce high TWI values only lower in the watershed. The high TWI values of the 20 m DEM look most like the distribution of wet areas identified by the depth to groundwater map, the vegetation map, and the soils map (see Figs. 4 and 2).

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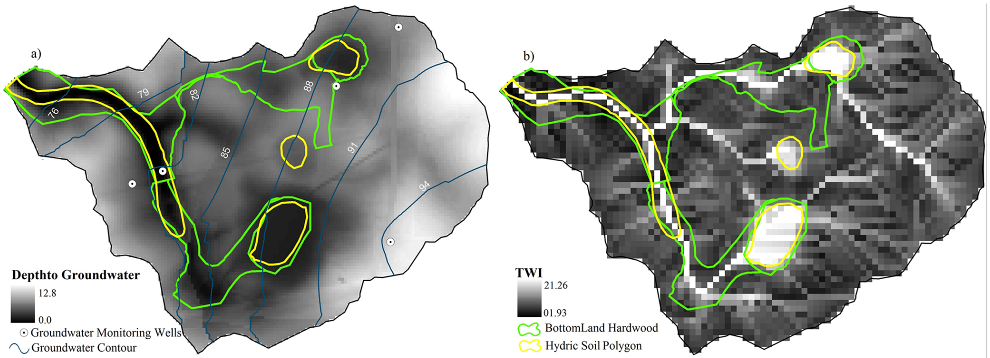

Figure 4. Depth to groundwater table **(a)** and 20 m TWI map **(b)**. Although to a much lesser extent than the higher resolution DEMs, the 20 m TWI map still produces high TWI drainage lines extending above the upper wetlands that are not corroborated by vegetation or soil indicators but are partly corroborated by the depth to groundwater map.

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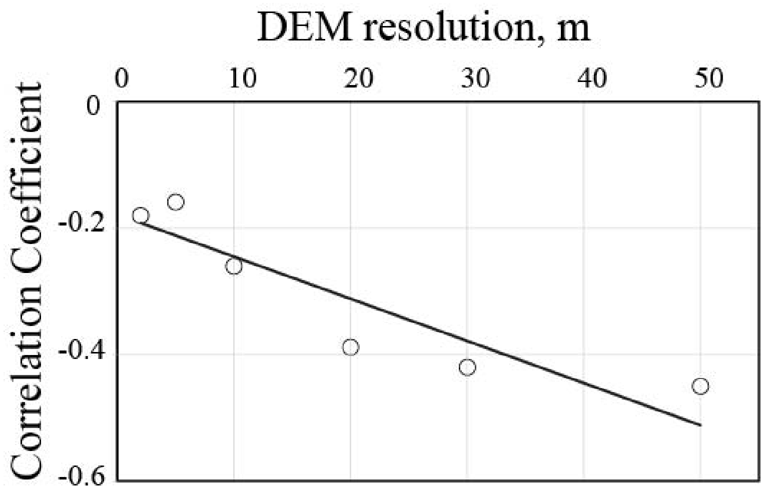

Figure 5. Correlation between spatial distribution of TWI values and depth to groundwater across the study watershed for 2, 5, 10, 20, 30, and 50 m DEM resolutions.

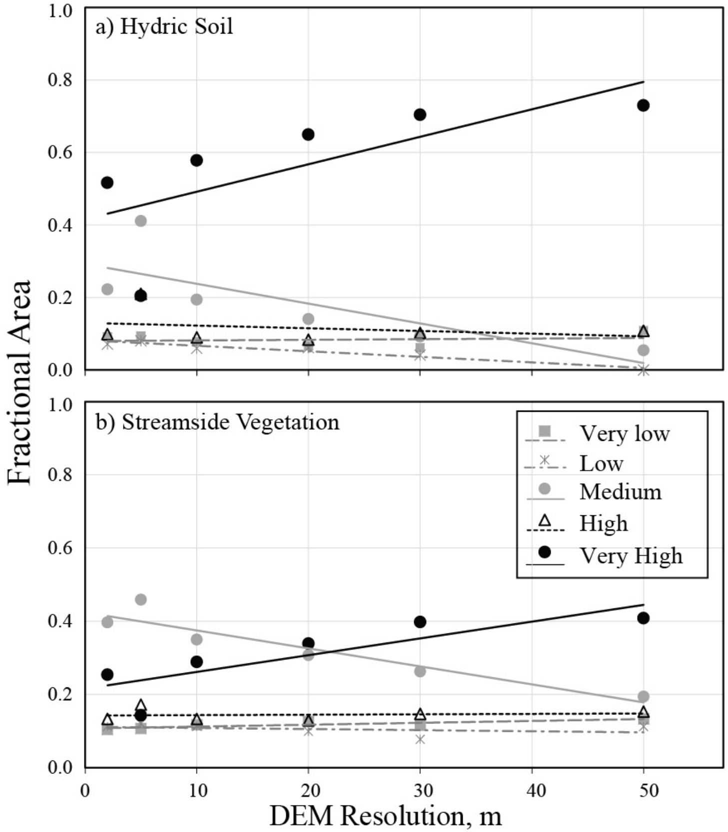

Figure 6. Fractional distribution of TWI classes in the hydric soil polygon **(a)** and streamside vegetation polygon **(b)** for 2, 5, 10, 20, 30, and 50 m DEM resolutions. For the evaluation of proportion of wetness area in the hydric soil and streamside polygons, the TWI values were classified into five wetness classes based on their quantile distribution (< 10th quantile (very low), 10th to 25th (low), 25th to 75th (medium), 75th to 90th (high), and > 90th quantile (very high).

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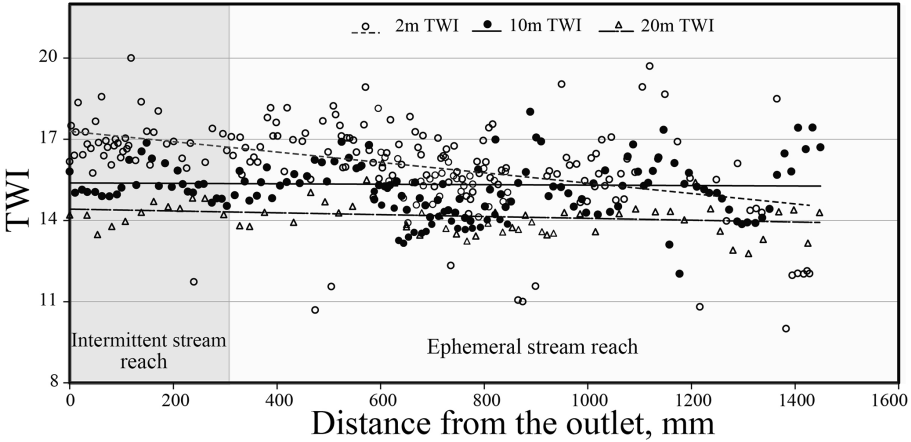

Figure 7. Variation of TWI values along the ground-truthed stream network for 2, 10, and 20 m DEM resolutions. The slope of the fitted trend lines are -2×10^{-3} for 2 m TWI, -3×10^{-4} for 10 m TWI, and -8×10^{-5} for 20 m TWI. Standard deviations of TWI values along the stream network decreased with decreasing DEM resolution and were 1.75, 0.92 and 0.32 for 2, 10, and 20 m DEM resolutions, respectively.

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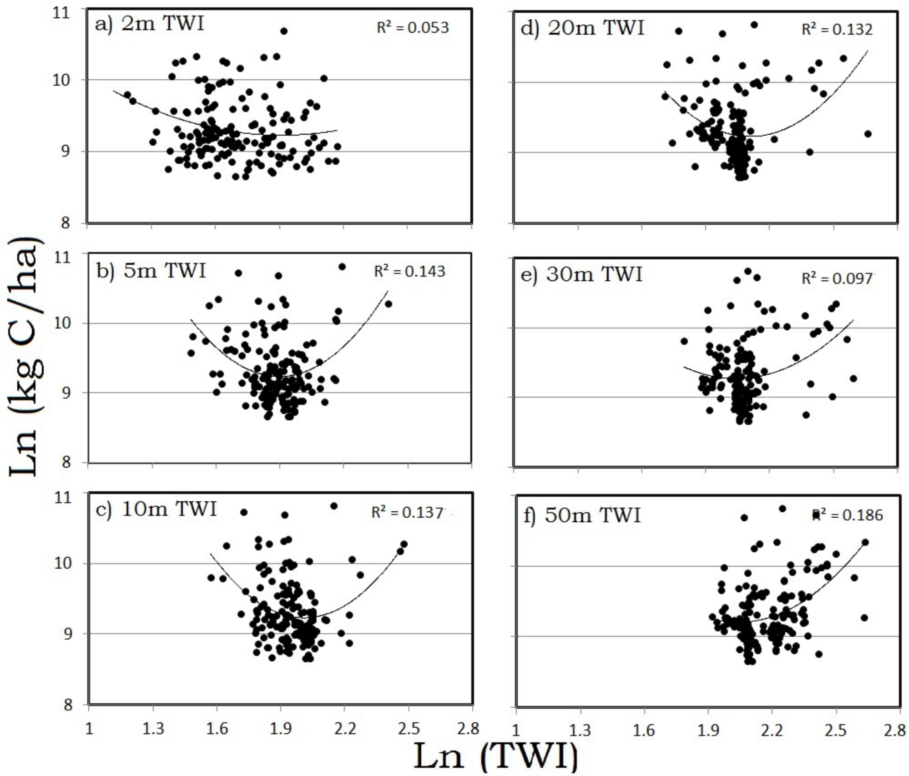

Figure 8. Natural log of carbon contents from point samples of mineral soils (0–7.5 cm depth) evaluated across TWI values interpolated from the resident pixel and the nearest adjacent pixels.

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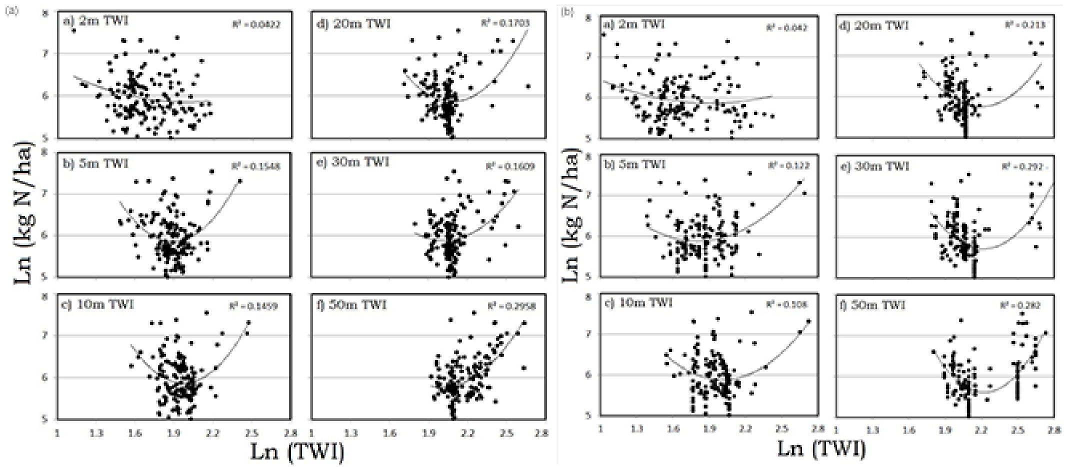

Figure 9. (a) Natural log of nitrogen contents from point samples of mineral soils (0–7.5 cm depth) evaluated across TWI values interpolated from the resident pixel and the nearest adjacent pixels. **(b)** Natural log of nitrogen contents from point samples of mineral soils (0–7.5 cm depth) evaluated across TWI values of the pixels associated with each point sample.

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