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Key Points:
- Variability of VWC was higher at the plot scale than the landscape scale
- Variability of VWC was higher in the riparian area than in the uplands at both plot and landscape scales
- Landscape-scale VWC remained correlated to terrain metrics throughout the seasonal drydown

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Nested Scales of Spatial and Temporal Variability of Soil Water Content Across a Semiarid Montane Catchment

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Abstract Topographic redistribution of water has been represented by various terrain metrics (e.g., topographic wetness index, slope, and upslope accumulated area). This type of landscape characterization has promoted the use of terrain metrics to inform how spatial patterns of soil volumetric water content (VWC) influence streamflow, ecological processes, and associated nutrient fluxes. However, evaluation of what these static terrain metrics reflect has only been accomplished in a few catchments. Additionally, previous research suggests that relationships between topographic metrics and VWC could be different across catchments through time. Here we measured VWC from snowmelt through summer drydown across a semiarid montane catchment. Using a spatially nested sampling design, we assessed the spatiotemporal variability of VWC from plot (tens of meters) to landscape scales (hundreds of meters). Variance of riparian area VWC increased as the catchment dried, while upland variance decreased, highlighting the utility of delineating distinct landscape units when considering spatial variability of moisture, rather than calculating statistics across the landscape as a whole. In contrast to previous research, we found that the relationship between VWC and topographic metrics persisted through the dry catchment state, suggesting that patterns of topographic redistribution of water during snowmelt continued to influence dry season VWC despite variability in plot scale vertical processes (e.g., evapotranspiration). Future research should focus on resolving the relationship between catchment moisture state and VWC variability as a function of wetness state, seasonality, and magnitude of precipitation, topography, and soil depth.

1. Introduction

Topography has a fundamental influence on the spatial configuration of water and energy mass balances across catchments (Beven & Kirkby, 1979; Sommer et al., 1997; Wagener et al., 2007) due to variations in slope and aspect and their influences on water redistribution, snowmelt, and evapotranspiration. The resulting spatial patterns of soil water content can influence streamflow (Atkinson & Sivapalan, 2003; Jencso & McGlynn, 2011; McGlynn & Seibert, 2003; Nippgen et al., 2011) and associated nutrient dynamics (Creed & Band, 1995; Gardner & McGlynn, 2009; McGlynn & McDonnell, 2003; Pacific et al., 2010). Metrics of landscape structure have been used to capture the influence of topography to predict the spatial variability of ecohydrologic processes (Emanuel et al., 2010; Kaiser et al., 2013) and to extrapolate point measurements to catchment scales (Duncan et al., 2013; Riveros-Iregui & McGlynn, 2009; Webster et al., 2008). Topographic indices, such as the topographic wetness index (TWI; a function of upslope accumulated area [UAA] and local slope), have often been used as metrics of water availability in these studies. However, the utility and applicability of these approaches depends on the underlying relationships between patterns of water redistribution, water storage, and topography. In addition, the scale of measurement, and if or how these relationships change across variable catchment wetness states, can also influence their applicability (Grayson et al., 1997; Nyberg, 1996; Western et al., 1999). Local or plot-scale variability (tens of meters) of soil water content could further impact our ability to extrapolate point measures (and associated uncertainty) to the landscape scale. Therefore, we suggest that determining the degree to which hydrologic patterns are reflected by terrain metrics, which hydrologic conditions support these relationships, and the magnitude of local variability, is critical to their application in scaling/predicting ecological and biogeochemical processes that are linked to vadose zone hydrology.

It is widely acknowledged that estimates of soil moisture are influenced by the scale of measurement (Western & Blöschl, 1999) and that patterns of soil moisture are typically a function of both local and nonlocal controls

(Grayson et al., 1997; Western et al., 2002). The measurements themselves are therefore a function of the measurement scale and the scale of natural variability (Western & Blöschl, 1999). Variability at the local scale can be a function of soil properties, vegetation, and microtopography, while large-scale topography typically imparts nonlocal controls and leads to landscape-scale patterns. Although it is acknowledged that local and nonlocal factors influence soil moisture across catchments and across wetness states, they remain poorly characterized and understood (Grayson et al., 1997; Lin et al., 2006; Van Meerveld & McDonnell, 2005). When catchments approach saturation (i.e., extensive near-surface groundwater), water movement generally follows topographic gradients or potentially bedrock gradients when they differ (Anderson & Burt, 1978; Freer et al., 1997). Grayson et al. (1997) refers to this period when lateral water movement dominates (e.g., nonlocal controls) as the wet-preferred state and the period when vertical processes such as evapotranspiration and vertical drainage (e.g., local controls) dominate as the dry-preferred state. This distinction would suggest that topographic wetness indices should best predict soil water content in the wet-preferred catchment state and perform poorly in the dry catchment state (Beven & Kirkby, 1979; Western et al., 1999). If the lateral movement of water controls landscape-scale patterns of saturated throughflow early in the season and vertical loss of water through evapotranspiration (ET) and drainage influence local shallow soil moisture late in the season, then these processes might result in nested scales of variability. This begs the question, is there a memory effect associated with the former (landscape-scale saturated throughflow drainage patterns) even after it is no longer a dominant process? Or, do local vertical processes become the predominant influence on local water availability?

The influence of wetness states on spatial patterns of soil moisture has received particular attention by a number of research groups, notably in the Tarrawarra Catchment, Australia (annual precipitation $\bar{x}$ = 820, slope $\bar{x}$ = 8%, e.g., Grayson & Western, 2001; Park & Van De Giesen, 2004; Western & Blöschl, 1999), the Mahurangi Catchment, New Zealand (annual precipitation $\bar{x}$ = 1,600 mm, slope $\bar{x}$ = 16%, e.g., Western et al., 2004; Wilson et al., 2003), and at the Shale Hills Critical Zone Observatory, Pennsylvania, United States (annual precipitation $\bar{x}$ = 980 mm, slope $\bar{x}$ = 25–48%, e.g, Lin et al., 2006; Takagi & Lin, 2012). This research has highlighted that the spatial variability of volumetric water content (VWC) and its change over wetness states can be highly location dependent. For example, in Shale Hills (Lin, 2011) and Tarrawarra (Western et al., 2004), the variance of VWC (defined as the sill of the variogram) increased with increasing catchment wetness, meaning that VWC was more similar across the landscape when the catchment was dry. Conversely, in the Mahurangi catchment, the VWC variance decreased with increasing catchment wetness (Western et al., 2004). These contradictions have been attributed to the scale of topographic variability across each catchment (complexity of the terrain), presence of perennial source areas, differences in soils, seasonal climatic differences, and their resulting influence on the dominant hydrologic processes at a given time (Takagi & Lin, 2012; Western et al., 2004). Overall, spatial variability in VWC appears to peak at intermediate saturation, potentially due to the bounding effects of porosity and the wilting point at either end of the range; however, this is not fully consistent across catchments.

Despite extensive research on spatial patterns of soil moisture across scales, local scale variability has received less attention. This local scale variability can be particular relevant for understanding what individual measurements across a landscape represent (see Famiglietti et al., 2008; Western et al., 1998, for extensive lists of soil moisture variability studies). We suggest that understanding how local or plot-scale variability in soil moisture changes across a landscape and across wetness states is critical to inform the application and interpretation of topographic indices.

To better understand the relative magnitudes of landscape and local/plot-scale variability in VWC and correspondence with topographic indices, we designed a nested sampling scheme at Tenderfoot Creek Experimental Forest (TCEF). TCEF is a particularly interesting location to test and expand on previous findings because it meets assumptions regarding terrain metrics, spans a greater elevation range than previous sites, and is snowmelt dominated with little summer rain input. Our sampling design allowed us to quantify plot-scale variability in seven high-density (n = 30) plots nested within a wide range of topographic positions (n = 42) that reflect landscape-scale patterns. With this experimental design, we sought to answer the following questions:

Q1: What is the relationship between soil water content and topographic indices over the course of the growing season drydown?

Q2: How does landscape variability of soil water content compare to plot-scale variability? Do the processes that control this variability change from wet to dry catchment states?

2. Methods

2.1. Site Description

TCEF is located in central Montana. Our sampling campaigns occurred in two catchments (Figure 1); upper Stringer Creek (394 ha; 2,090–2,425 m) which is an undisturbed catchment, and Spring Park Creek (SPC, 400 ha; 2,100 – 2,425 m) which contains patch cuts and thinned forest, harvested in 2000 (Hardy et al., 2006). These catchments receive average annual precipitation of 880 mm, with 70% falling as snow from October through April (Nippgen et al., 2011; Schmidt & Friede, 1996). Flathead sandstone, Wolsey shale, and granite gneiss are overlain by shallow soils (1.5 m deep, typic cryocrepts in the uplands and aquic cryobalfs in the riparian areas). Uplands are moderately sloping (average 8%) and are covered by Grouse whortleberry (*Vaccinium scoparium*) in the understory of a lodgepole pine forest (*Pinus contorta*), interspersed with subalpine fir (*Abies lasiocarpa*), Englemann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*). The riparian corridor is ~3% of the Stringer Creek catchment area and ~6% in SPC (Jencso et al., 2009) and is predominately grasses (*Carex*, *Juncus*, and *Poa*) and willows (*Salix*; Mincemoyer & Birdsall, 2006).

2.2. Sampling Design

We created a nested sampling design where 42 individual sampling sites were distributed across the landscape in seven transects (Figure 1). The distributed upland sampling sites included distinct convergent and divergent components of the landscape on both south and north facing aspects, while the two transects that crossed the stream reflected riparian to upland transitions, allowing for characterization of landscape variability (Figure 2). The distal ends of the transects crossing the stream were located in the forested uplands. These transects crossed the backslope (steeper area upslope of the break in slope; Conacher & Dalrymple, 1977; MacMillan et al., 2000; Webster et al., 2011), the footslope (moderately sloped transition area between steeper uplands and gently sloped lowlands), the toeslope (gently sloped area at base of hillslope), and the riparian area (often saturated). One transect ($n = 10$ sites) was located in SPC and captured the transition from a clearcut (CC) patch (14 years of modest regrowth) to a forest patch (Figure 1).

In addition to landscape-scale variability, we also investigated plot-scale variability by measuring VWC at 30 points within a spatial variability plot associated with each transect (seven plots total: five upland and two near-stream plots). Measurement locations within each plot were set with a random compass direction and distance up to 15 m from the center point (located in close proximity to site sampling locations, while minimizing impacts of walking paths). This created a sampling area of up to 707 m^2 (Figure 1). One of the two near-stream plots was fully in the riparian area (transect 2 [T2]) while the other (transect 1 [T1]) included both the riparian area and the toeslope and footslope (also referred to as the transition zone into the uplands). The five upland plots represented a wide range of landscape positions across the distributed sampling scheme (Figure 2). One of the plots was located in the CC (upland site 5(CC)), and one was located in the adjacent forest patch (upland site 4).

2.3. Environmental Measurements

At every distributed sampling site across the landscape ($n = 42$, sampled weekly) and at the 30 points within each spatial variability plot ($n = 7$, sampled biweekly), soil VWC was measured in triplicate using a Hydrosense II portable soil water content meter (12-cm rods, Campbell Scientific Inc., Utah, United States). The Hydrosense II was inserted vertically into the soil, integrating the soil water content in the upper 12 cm of soil (3,600-cm^3 sensing volume; Campbell Scientific, 2011). The seven plots were sampled within 2 days of each other, coincident with sampling of the sites distributed across the landscape which were sampled within a 3-day time period (total of 4 and 12 sampling campaigns).

2.4. Real-Time Measurements

Capacitance rods (±1 mm, TruTrack, Inc., New Zealand) were used to measure stream stage and runoff (hourly, using established rating curves), at the outlet of Stringer Creek. Snowmelt and precipitation were measured in the headwaters of TCEF (2,259 m) and near the outlet of Stinger Creek (1,996 m) at two National Resources Conservation Service SNOTEL sites. An hourly snowmelt interpolation model constrained with the two SNOTEL sites was used to determine precipitation and melt inputs to Stringer Creek (Nippgen et al., 2015). Rainfall precipitation from the SNOTEL sites was corroborated with data from rain gauges (TE525WS, Texas Electronics, ±1% up to 2.54 cm/hr) at T1 and in the patch cut of SPC. Groundwater wells, created from 50-mm

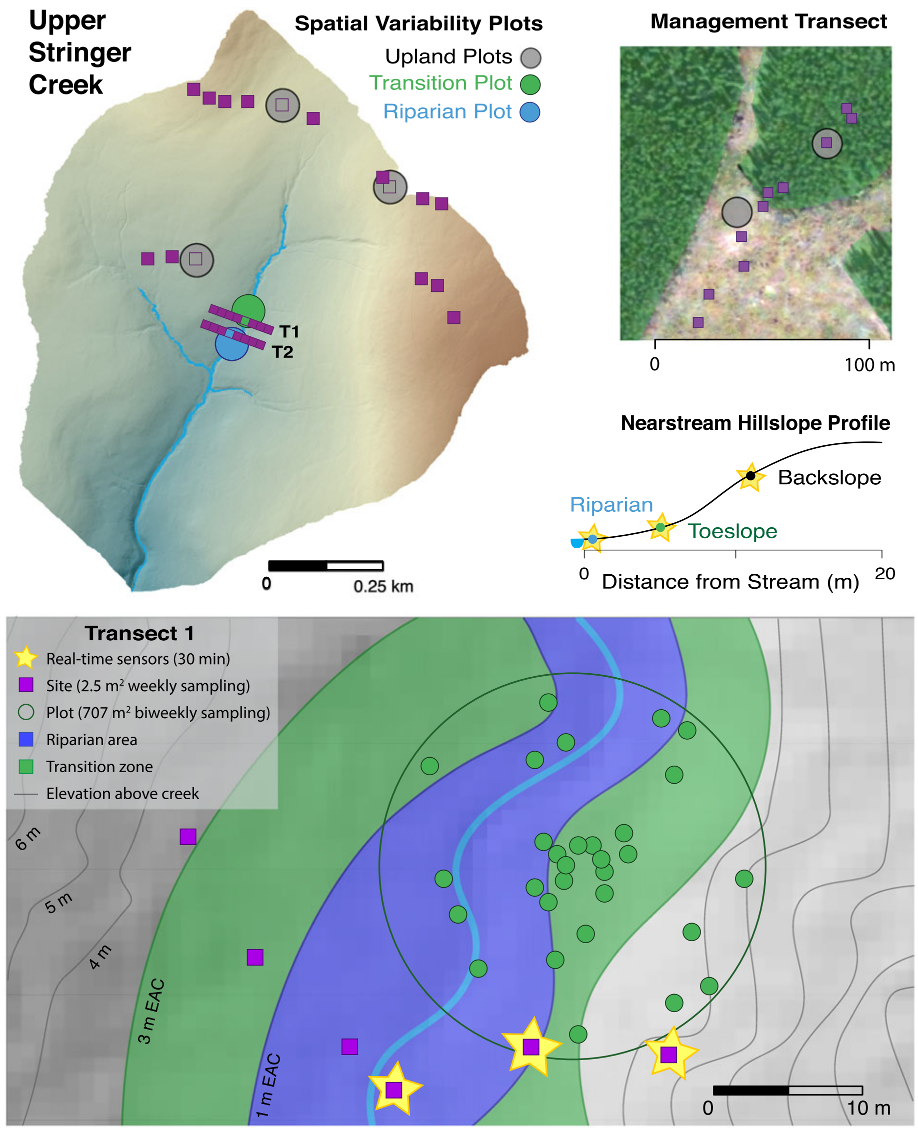

Figure 1. Map of nested sampling design showing sites, plots, transect, and their relative scales across Stinger Creek and the management transect in Spring Park. Transect 1 is one of the most heavily instrumented transects in the catchment. Real-time measurements here include groundwater level, soil water content (0–12 cm), soil temperature, and precipitation. It has eight sites (squares), which are labeled by the side of the creek they are located on (East (E) or West (W)), and numbered 1–4, with 1 being closest to the creek. T1W4 and T1E4 are not shown in this image, they are each 40 m farther up their respective hillslopes. The large circle denotes the transition zone plot with 30 measurement locations, representative of all the spatial variability plots (n = 7), but highlights the range of conditions in the near-stream area. EAC = elevation above the creek; T1 = transect 1; T2 = transect 2.

diameter PVC and screened from completion depth to within 10 cm of ground surface, were installed along the riparian-hillslope transects (T1 and T2) and along the management transect in SPC. Although only groundwater well data from T1 are included in this analysis, its interpretation was corroborated by observations from T2 and SPC. Each shallow groundwater well was instrumented with capacitance rods recording groundwater level every 30 min (Jencso et al., 2009). Well completion depths (to the soil-bedrock interface) ranged from 0.5 to 1 m in the riparian zones and 0.8 to 1.5 m in the uplands. Installation details can be found in Jencso et al. (2009). We differentiate the wet and dry-preferred states based on the connectivity of these groundwater wells in T1. When there is water present in all of the wells, we consider the system to be in the wet-preferred state because the uplands are hydrologically connected to the stream and contributing lateral flow along the soil-bedrock interface.

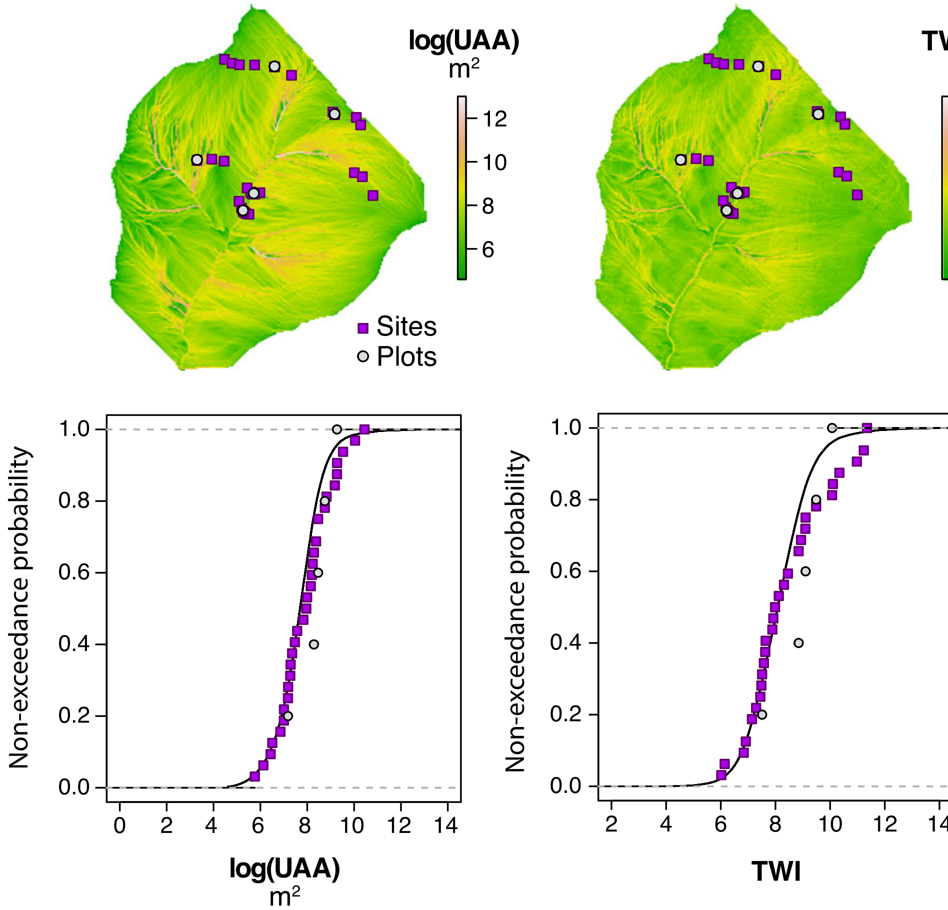

Figure 2. (top) Maps of topographic metrics and locations of plots (circles) and sites (squares). (left) Upslope accumulated area (UAA); (right) topographic wetness index (TWI) and distributed sites. (bottom) Cumulative distribution functions of 10-m landscape positions across the upper Stringer Creek catchment (lines) and the 32 distributed measurement sites (squares) and plots (circles).

Real-time environmental sensors were installed in four landscape positions in upper Stringer Creek and on both sides of the SPC management boundary (Figure 1). Campbell Scientific CS655 soil moisture sensors measured percent volumetric soil water content (VWC) and soil temperature every hour from 0 to 12 cm (Figure 1). Precipitation gauges were colocated with the T1 riparian site in Stringer Creek and in the patch cut of the management block located in SPC.

2.5. Statistical Methods

Standard metrics of central tendency and variability (mean [$\bar{x}$], standard deviation [SD], and coefficient of variation [CV]) were calculated for each plot and sampling campaign. These metrics were also calculated for the distributed landscape-scale sites where the $\bar{x}$, SD, and CV were calculated separately for upland (n = 35) and riparian sites (n = 7). Two sample t tests were performed between the CC plot (5) and the adjacent forest plot (4) for each sampling campaign and between consecutive sampling campaigns within each plot. Probability distribution functions (PDFs) were fitted to plot-scale VWC data from each plot in each sampling campaign using a gamma distribution. The gamma distribution was chosen based on its flexibility and ability to capture positively skewed distributions which are commonly observed in soil pore size distributions (McGuire et al., 2005; Tuller & Or, 2004; Weiler et al., 2003). Both variograms and correlograms were used to assess spatial correlation (Western & Blöschl, 1999) in the plots using the Spatial Nonparametric Covariance Functions package in R (ncf; Bjørnstad & Falck, 2001). No single model type could be used to fit variograms to all of the sites, so the omnidirectional variogram with the best fit (exponential, Gaussian, spherical, or nugget) was chosen using the automap and gstat packages (Gräler et al., 2016; Hiemstra et al., 2008).

Table 1
Rain Events > 0.1 mm Measured at Transect 1 During the 2013 Growing Season After the Snowmelt Period

Date	Total rain (mm)	Duration (hr)	Average intensity (mm/hr)
07/12	2.5	8	0.31
07/17	3.6	7	0.17
07/29	3.8	2	1.90
08/01	10.6	5	2.12
08/02	2.2	2	1.10
08/09	3.9	3	1.3
08/11	4.6	2	2.3
08/12	3.6	4	0.90

VWC of each site ($n = 42$) was compared to landscape-scale metrics of terrain-mediated water redistribution (topographic indices). Ten-meter digital elevation models were created by coarsening 1-m^2 resolution light detection and ranging data. This 10-m resolution is high enough to capture topographic variability while being coarse enough to decrease noise from micro-topographic features (Jencso et al., 2009). These data were collected in 2005 by the National Center for Airborne Laser Mapping. We calculated topographic characteristics that describe both incoming solar radiation at the ground surface and relative water availability of each site using digital elevation model landscape analysis methods as described in Jencso and McGlynn (2011), Nippgen et al. (2011), and McGlynn and Seibert (2003). Terrain metrics included in the analysis were UAA (m^2), the TWI, insolation (kWh/m^2), slope (%), elevation above the creek (m), distance from creek (m), and gradient to creek. UAA is the catchment area contributing to each point in the landscape and was derived using the MD∞ algorithm which assumes that subsurface flow follows surface topography (Seibert & McGlynn, 2007). TWI is another approximation for relative wetness and was calculated using the following equation (equation (1); Beven & Kirkby, 1979):

$$[TWI] = ln\left(\frac{a}{\tan\beta}\right), \tag{1}$$

where a is UAA, and β is local slope. Both UAA and TWI (Figure 2) were assessed for relationships with VWC using Spearman's rank correlation coefficients over the course of the sampling period. This nonparametric method allowed for examination of relationships given the highly nonlinear distribution of UAA across the catchment.

3. Results

The 2013 water year (1 October 2012 to 31 September 2013) had lower total precipitation (749 mm) than average ($\bar{x}$ = 886 mm, 1981–2010). In 2013, 56% of total precipitation fell as snow. Snow water equivalent (SWE) on 1 April 2013 was 314 mm, near the median 1 April SWE for the period of record (343 mm, 1981–2010). Streamflow peaked on 4 June (10.8 mm/day), within a few days of the annual average peak streamflow (29 May; Pacific et al., 2009). The first sampling campaign targeting the distributed sites occurred on 29 May. These sites were measured weekly thereafter. We began sampling the spatial variability plots on 25 June, at which point streamflow had decreased to 1.1 mm/day. Small rain events occurred on 12 July and sporadically through the sampling period (Table 1). The August precipitation events (16.6 mm cumulatively over 3 days) were the only events large enough to appreciably increase streamflow.

3.1. Real-time VWC (Riparian, Toeslope, and Backslope)

Real-time VWC sensors, located in three distinct landscape positions, measured the decline in VWC over the course of the sampling period. They also measured varied responses to rain events (Figure 3 and Table 1). The three sites showed differential drydown between landscape positions, and only the riparian site retained a shallow water table through the growing season. The toeslope position briefly responded to the 17 July rain event and exhibited a strong soil moisture response to the series of rain events in early August (increase of 10% VWC), while the VWC sensors on the backslope barely responded to the rain event (negligible increase of 1% VWC).

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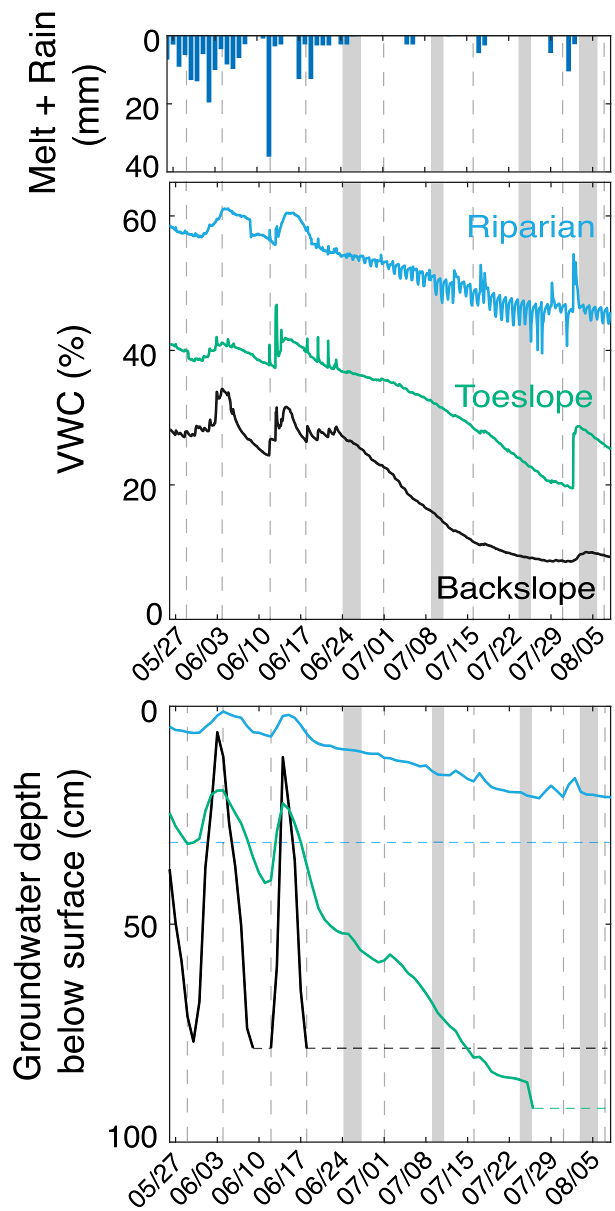

Figure 3. Real-time measurements of volumetric soil water content and groundwater levels across the transect 1 riparian—upland transition. Vertical gray bars denote when plots were measured; vertical-dashed lines denote when sites were measured. Horizontal-dashed lines denote groundwater well completion depths. VWC = volumetric water content.

3.2. Landscape-Scale VWC

Soil moisture declined through the summer growing season across all sites at the landscape scale, and mean VWC of the riparian sites was significantly higher than in the uplands (Figure 4). The riparian VWC rarely dropped below 30% VWC (9% of riparian measurements) and had a mean VWC of 44%, while in the uplands, less than 3% were greater than 29% VWC, indicating distinct saturation states in these landscape positions (Figure A1). At the landscape scale, the SD of VWC was much lower in the uplands than in the riparian area, and the two landscape units had opposite seasonal trends. The variability of VWC in the riparian area was at its lowest on 12 June and increased thereafter, while the SD of upland VWC decreased through the season (Figure 4). Interestingly, in the uplands, the relative variability of VWC (CV) at the landscape scale was higher than the riparian area throughout the season. CV of upland VWC increased until the first significant rain event on 17 July (3.8 mm), at which point the CV remained relatively consistent through the remainder of the growing season.

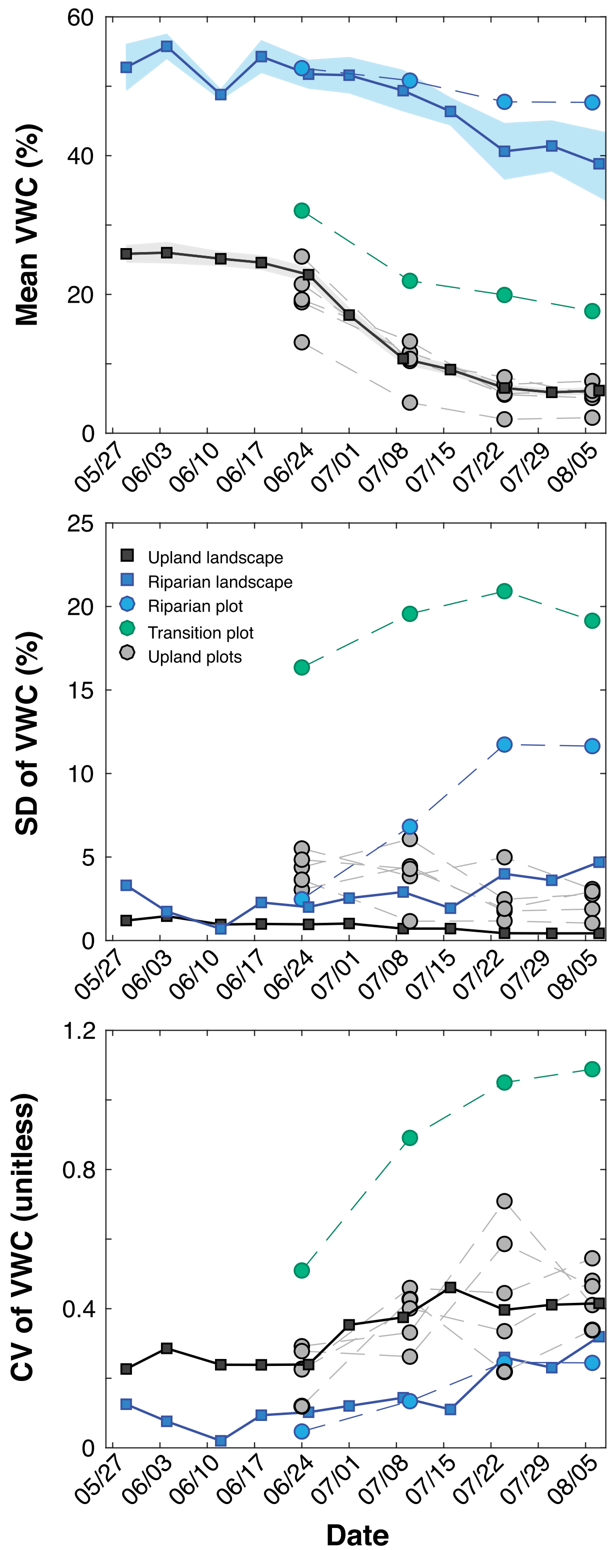

Figure 4. (top) Mean, (center) standard deviation, and (bottom) coefficient of variation of VWC for each plot (circles, $n = 7$) and sites distributed across the landscape (squares, $n = 42$). Shaded areas on the landscape mean values denote +/−1 standard deviation. CV = coefficient of variation; SD = standard deviation; VWC = volumetric water content.

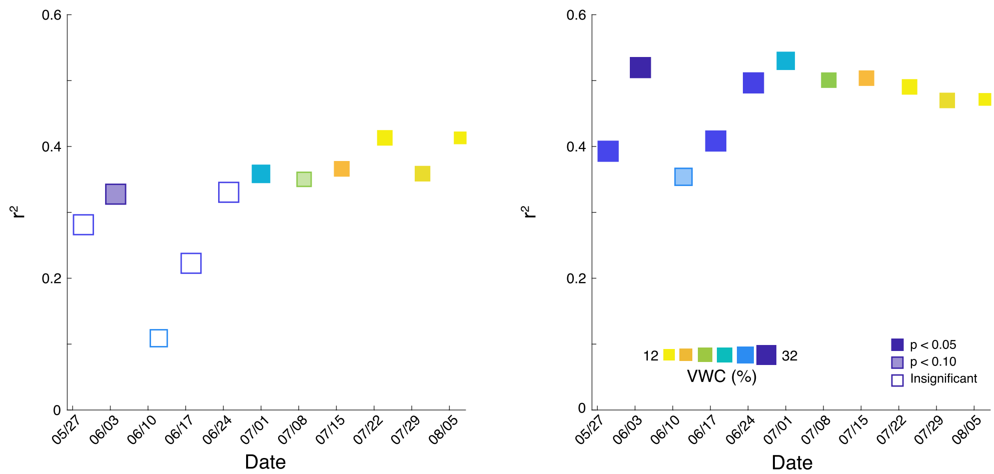

Figure 5. Strength of relationships between distributed measurements of VWC and terrain metrics ([left] upslope accumulated area; [right] and the topographic wetness index) over the growing season. Circles in the plots with no black outline indicate that the relationships were not significant ($p > 0.1$). VWC = volumetric water content.

Comparison of terrain metrics (UAA and TWI) to weekly site-scale VWC in the uplands ($n = 25$) indicated that the strength of the relationships was variable over time, particularly during the snowmelt period (Figure 5). The strength of the relationship between VWC and UAA increased as the catchment became more dry, while the relationship between VWC and TWI was strongest during the second sampling campaign when soil moisture and groundwater tables were at their highest and, again, at the beginning of July after upland groundwater wells had gone dry (Figure 5). Subsequently, the strength of the relationship between TWI and VWC decreased slightly but remained higher than many of the sampling campaigns during the snowmelt period. We also used correlograms of topographic metrics (TWI, UAA, elevation above the creek, distance from creek, gradient to creek, insolation, and slope) to determine the scale of spatial correlation across the landscape. Landscape-scale topographic metrics were spatially correlated at distances of 400–750 m (Figure A2), which is within the range of measured hillslope lengths (up to 1,200 m; Jencso & McGlynn, 2011).

3.3. Plot-Scale VWC

Mean upland VWC at the plot scale tracked mean landscape-scale upland VWC, with one upland plot lower than the rest of the plots. This plot (3) was located on a steeper slope with more coarsely textured soil than other plots (Figures 4 and 6). The SDs of upland plots were higher than the landscape scale, and both decreased over the season. Mean VWC of the riparian plot did not decrease as much as the mean VWC of the distributed riparian sites; however, the SD of the riparian plot increased an order of magnitude over the season, while at the landscape scale, SD only increased moderately (Figure 4). At both scales, the CV doubled from the beginning to the end of the growing season. The transition plot between the riparian and upland landscape positions exhibited an average VWC that fell between the riparian and upland plots (Figure 4). However, its high SD and CV values highlight that it exhibited two modes of behavior; approximately one third of the points were riparian-like, while the other two thirds exhibited VWC characteristic of upland landscape positions (Figures 6 and 7).

Although the mean VWC in the uplands (at the plot scale, $n = 5$) did not change significantly in response to rain events, the plot-scale CVs diverged from the seasonal increase in variability after the 17 July rain event (Figure 4), with CVs becoming more similar by the last sampling campaign (after the series of rain events). PDFs fitted to the distributions of VWC in upland plots for each sampling campaign show a similar pattern (Figure 8). Early in the growing season, each plot had a unique mean and range of VWC, which generally became more similar by the 10 July sampling campaign, and after the rain events, the plots diverged again (Figure 8). Bounded PDFs can become more skewed as the mean approaches a boundary (in this case both wilting point and porosity; Western et al., 2002). The riparian plot is negatively skewed, suggesting that this

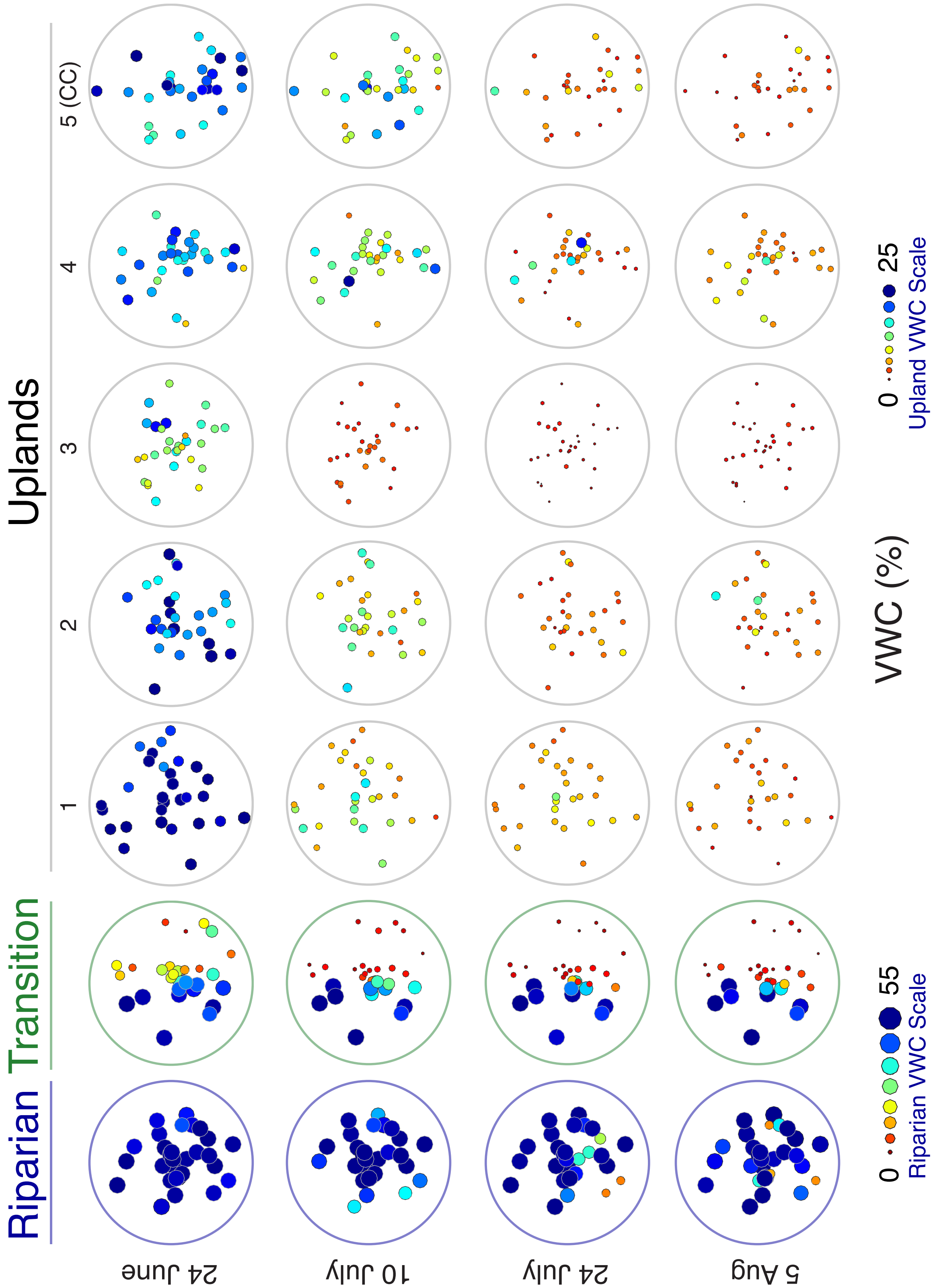

Figure 6. Volumetric water content (VWC) of each point (n = 30) within plots (n = 7) over the sampling period. The size and color of circles are scaled to the VWC. Note the different scales for the riparian/transition plots versus the upland plots. 5(CC) denotes the plot in the CC of the management transect, and 4 is the adjacent forested plot. CC = clearcut.

Table 2
Mean, SD, and CV for Each Sampling Campaign for Plots Located in the Clearcut Patch and Adjacent Forest Patch

	Mean VWC (%)		SD of VWC (%)		CV of VWC (unitless)	
Date	Forest	Clearcut	Forest	Clearcut	Forest	Clearcut
26 June	18.87 ^{p}	19.26 ^{p}	3.46	3.62	0.29	0.23
9 July	11.63	13.23	3.91	4.08	0.33	0.46
24 July	7.03 ^{t}	5.55	4.43	2.57	0.71	0.44
4 August	7.51 ^{pt}	5.09 ^{p}	2.35	1.79	0.41	0.54

Note. ^{p}denotes statistically significant differences between the plots, and ^{t} denotes statistically significant differences between sampling campaigns based on two sample *t* test, $p < 0.05$. SD = standard deviation; CV = coefficient of variation; VWC = volumetric water content.

plot approached its upper bound of porosity, while only one upland plot showed positive skewness, which would suggest that those plots were not sampled when nearing their wilting point.

We compared the forest and the CC plots in SPC and determined that the range and variability of plot-scale VWC were similar in the CC and the forest (Table 2). Shallow soil moisture was only significantly higher in the forest than in the CC in the last sampling campaign. The first rain event (3.8 mm, 17 July) was small enough that we did not measure a significant change in VWC at the plot scale in the management transect (Figures 6 and 7). After the precipitation events from 29 July to 03 August, the plot-scale variability of VWC significantly decreased in the forest, while the opposite was true for the CC (Table 2).

Variograms and correlograms can be used to determine spatial correlation scales of soil water content or the landscape itself (Legendre & Legendre, 1998; Western et al., 1999, 2004). Here we tested for spatial correlation

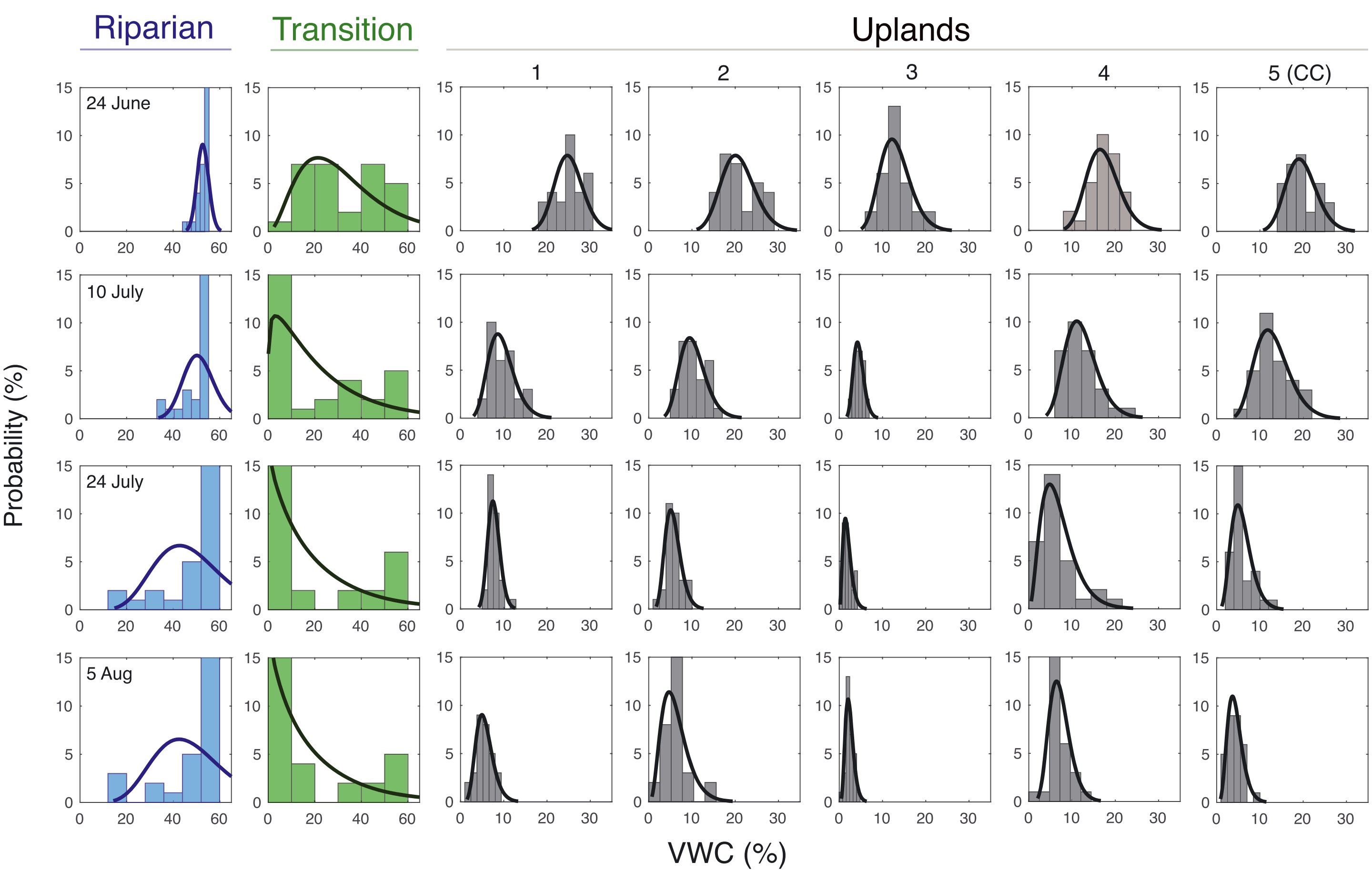

Figure 7. Histograms and fitted probability density functions of VWC at each plot over the sampling period. VWC = volumetric water content.

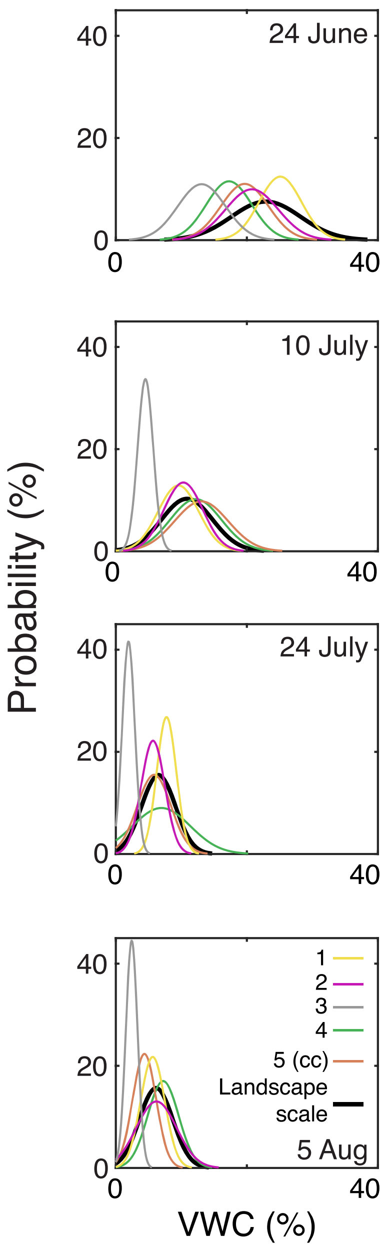

Figure 8. Fitted probability distribution functions of VWC, for each plot and landscape-scale measurements over time. Individual plots can have as much, or more, variability in VWC than the whole landscape. VWC = volumetric water content.

within each of the seven plots (using correlograms) and found no significant spatial correlation among the 30 sampling locations within any of the 707-m^2 plots at any point in the growing season. Although there was a slight positive relationship between semivariance and soil moisture in the uplands, there were no consistent patterns in the variograms over time (Figure A3). Conversely, the semivariance increased in the riparian area as the watershed became drier.

4. Discussion

The strength and timing of topographic influence on shallow soil moisture are variable across catchments (Lin, 2011; Western et al., 2004). This lack of consistency is partially due to the interplay of local and nonlocal controls that influence the spatial variability of VWC at different catchment wetness states. Therefore, it is important to quantify the variability of individual locations in the context of landscape-scale VWC. Furthermore, the underlying assumptions about terrain-mediated water movement and its persistence across wetness states dictate the utility of terrain metrics for predicting patterns in hydrologic, ecological, and biogeochemical processes. Some common assumptions include spatially uniform recharge; hydraulic gradients that are reflective of the direction and magnitude of the surface slope; uniform soil depths and shallow impermeable bedrock; and spatially consistent hydraulic conductivity (Beven & Kirkby, 1979; Western et al., 2002). Explicitly considering these assumptions and the effects of their violation is critical to evaluate where and when terrain metrics will be useful for predicting spatial contributions to streamflow, variability in shallow soil moisture, and any biological or diffusive processes that occur in the soil that are influenced by water availability. Differences in results across systems and measurement approaches suggest that assessment of which terrain metrics best represent individual hydrologic processes in various topographic and climatic environments should be explored further. For example, shallow soil moisture (10–40 cm) could be related to topographic wetness indices (UAA and TWI), whereas deeper soil moisture could be more related to elevation and vertical distance to stream, as was observed at Shale Hills (Baldwin et al., 2017). We suggest that the strong seasonality of catchment wetness at TCEF provides an ideal laboratory for examining when and to what degree individual topographic metrics might reflect hydrologic processes.

4.1. Landscape-Scale Patterns of VWC

Application of topographic metrics for characterizing hydrologic patterns is appropriate at TCEF because of the relatively uniform distribution of melt input, the shallow, homogeneous soils, and surface topography that is reflective of bedrock topography (Jencso & McGlynn, 2011; Jencso et al., 2009, 2010). Empirical evidence and modeling efforts at TCEF have shown that streamflow during the snowmelt period is driven by topographic redistribution of water and connectivity of shallow-saturated throughflow (Jencso & McGlynn, 2011; Jencso et al., 2010, 2009; Nippgen et al., 2015, 2011; Payn et al., 2012). Although the effect of topography is generally considered to have a strong effect on streamflow response during saturated conditions (Anderson & Burt, 1978; Beven & Kirkby, 1979; McGlynn et al., 1999, 2004; McGlynn & Seibert, 2003; Yeakley et al., 1998), the strength of these influences in the dry season has been shown to be weaker or insignificant (Beven & Kirkby, 1979; Devito et al., 2005; Grayson & Western, 2001; Jencso et al., 2009).

The strength of the relationship between VWC and topography was temporally variable. Yet the strength of these relationships were at their lowest during the snowmelt recession when the catchment was in an intermediate wetness state (Figures 2 and 5). Over the course of this 4-week period (10 June–10 July), average

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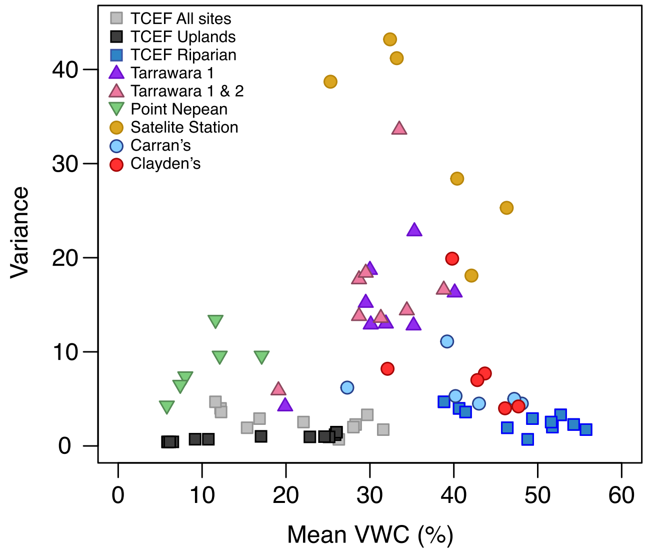

Figure 9. Comparison of the relationship between mean and standard deviation of VWC across catchments. TCEF data are shown separated by riparian and upland data as well as grouped as a whole for comparison purposes. Data for other catchments were taken from Western et al. (2004). TCEF = Tenderfoot Creek Experimental Forest; VWC = volumetric water content.

upland VWC decreased from 25% to 11% (Figure 4). This is consistent with a modeling exercise (WeCHO), where Nippgen et al. (2015) found that once shallow soil moisture dropped below ~29% VWC, the strongly nonlinear relationship between soil profile water storage and hydraulic conductivity led to an abrupt decrease in the rate of down gradient water delivery. That rate change was used to delineate areas contributing to streamflow, which consisted of *active* areas (VWC above the storage threshold) along the entirety of the flowpath to the stream. The influence of asynchronous melt and drydown resulted in saturated upland locations becoming *inactive* and disconnected at different times, thus reducing the strength of the relationship between topographic indices and VWC during this transition period.

As the landscape became more dry, UAA reflected more soil moisture variability, while the explanatory power of TWI declined. This suggests that as locations become disconnected from downslope flowpaths, their local drainage area becomes more important for describing VWC. The decline in explanatory power for TWI could be due to the decreasing importance of slope as the lateral connectivity diminished. At Tarawarra, the spatial variability of VWC in dry conditions appeared random and weakly correlated with aspect (Western et al., 1999). The discrepancy between TCEF and Tarawarra could be due to the winter snowpack and associated high spring runoff present at TCEF or differences in soil depth or sampling design. For example, soil moisture measurement grids at Tarrawarra only covered an elevation range of 32 m (Western et al., 2001), while at TCEF, we measured soil moisture patterns that spanned much greater spatial extents and hundreds of meters of elevation change.

The strength of relationships between terrain metrics and VWC might simply be a function of catchment wetness state and associated variability of VWC. However, there has been inconsistent behavior between catchments in regard to which wetness state has the greatest variability in VWC. Although the SD of VWC in the uplands declined as the catchment became more dry, the relative variability of VWC (CV) increased which might be more relevant for characterizing soil moisture variability at a given point in time. TCEF is different from other well-studied catchments in that the VWC ranged from near a general plant wilting point in the uplands to saturation in the riparian area (Figure 9). Taken separately, these landscape positions have opposite relationships between absolute variance (SD) and VWC, highlighting the value of the hydrologic response unit (Flügel, 1995) or representative elementary area (R. A. Woods et al., 1995) concepts which can constrain the variability of hydrologic processes associated with similar landscape positions. This also supports work from Park and Van De Giesen (2004) who found that a stratified sampling design based on hydrologic landscape units reduced the number of samples needed to estimate average VWC and overall error. Unfortunately, for comparative purposes, most relationships reported in the literature were based on all VWC measurements across whole catchments (riparian and upland locations). If we group our sites for comparison to other studies, TCEF exhibits a relatively consistent variance across moisture states because of the opposing relationships in riparian and upland locations (Figure 9). Interestingly, VWC variance at TCEF is lower than most other locations. This could be because of the strong transition from the wet-preferred state to the dry-preferred state imposed by the snowmelt period and subsequent dry season.

Our findings, together with those from other studies, suggest that the seasonality and magnitude of annual precipitation could regulate how and when topographic metrics are most related to soil moisture (e.g., numerous small rain events vs. a dominant wet season or snowmelt-driven system with extensive lateral flow). The relative timing of ET demands and the degree to which a system is water- or energy-limited could also influence the frequency and duration of lateral throughflow processes and the resulting VWC patterns evident in a given landscape. Here the relationship between upland VWC and terrain metrics representing water redistribution persisted even in the driest catchment state, suggesting that lateral water redistribution created a memory effect that was stronger than 1-D ET or drainage, resulting in landscape-scale patterns of soil moisture even after lateral flow was no longer occurring.

4.2. Plot-Scale Patterns of VWC

Nested within the observed landscape-scale patterns of VWC and relationships to topography, local (plot-scale) variability of soil moisture can be high. Plot-scale variability of VWC (tens of meters) can be attributed to interactions and feedbacks between soil properties (e.g., water retention characteristics mediated by soil texture, organic content, and macropores), microclimate, evapotranspiration, and vegetation (which can be both a consequence and cause of soil moisture patterns; Lin et al., 2006; Rosenbaum et al., 2012). Here we observed that the SDs of plot-scale VWC were consistently higher than at the landscape scale. Once the system entered the dry catchment state and became water-limited, the absolute variance (SD) of VWC in the uplands decreased, yet relative variability increased through the dry season, suggesting that vertical processes were imposing local variability. The riparian area had greater absolute variability of VWC than the uplands, but it had the lowest CVs at both the plot and landscape scales, which suggests that this highly connected portion of the landscape (continuous throughflow) was more hydrologically homogeneous than the drier uplands relative to the mean (Figure 4). The transition plot that was composed of both riparian and upland positions had much higher SD and CV throughout the season and highlights the sharp transition from the saturated soils of the riparian area to the drier upland soils (Figure 4).

Variograms can be used to assess and quantify the spatial correlation of measurements/locations. For example, Western et al. (1998, 1999, 2004) used variograms to assess the spatial structure of VWC in humid and subhumid catchments and found that correlation lengths were between 30 and 60 m at their sites. In these cases, variograms were unable to distinguish between wet and dry catchment conditions. Our results partially support the Western et al. (2004) findings, in that we did not find any spatial correlation of VWC at the plot scale (<30 m), suggesting that if there is a VWC correlation length at TCEF, it is greater than 30 m. Variograms of upland plots at TCEF showed no seasonal trends, but in the riparian area, semivariance did increase as the watershed became drier (Figure A3). Western et al. (2004) also assessed the variograms of a TWI, aspect, and slope and found that some of the catchments' VWC correlation lengths were similar to topographic correlation lengths, but others were not, suggesting that the scales of VWC variability were not always due to topography alone. We assessed correlograms of topographic indices and determined that topographic correlation lengths at TCEF range from 400 to 750 m (Figure A2). This is approximately the median hillslope length, suggesting that similar hillslope positions could be more similar to one another than spatially proximal locations within one hillslope.

Late growing season rain events at TCEF are generally rare, but when they occur, they provide insights into the potential effects of the temporal shift in precipitation that is expected with a changing climate (Walsh et al., 2014). One week after the small 17 July rain event (3.8 mm), CVs of the upland plots diverged; some plot-level CVs increased, while others decreased. This response was superimposed on the seasonal increase in CVs (at the plot and landscape scale) that resulted from the declining influence of hillslope-scale lateral transport. This suggests that if more precipitation were to fall on the catchment when most of the catchment is no longer connected via lateral saturated throughflow, then soil moisture could become more variable within and between plots than if that amount of precipitation had been routed through the catchment during snowmelt, when topographic redistribution influences shallow groundwater connectivity (Jencso & McGlynn, 2011; Nippgen et al., 2015).

4.3. Influence of Landcover on VWC

Forest thinning and clearcutting can impact both surface water and land surface energy balances through multiple mechanisms. For example, increased incoming insolation after clearing of vegetation changes the soil surface energy balance which generally increases growing season soil temperature, decreases above ground biomass, and decreases litter and organic matter (Striegl & Wickland, 2001). Soil compaction can occur during and after harvesting, leading to decreased porosity and infiltration capacity. Here we analyzed the spatial variability plots in the CC and the forest to assess how this landcover change affected shallow soil moisture at TCEF. Soil moisture was significantly different between the plots early in the growing season when VWC was relatively high and at the end of the season after the rain events (Table 2). Early in the season, this could have been due to differential snow accumulation and melt associated with the two landcovers (S. W. Woods et al., 2006). Differences after rain events might have been due to differences in evapotranspiration and shallow soil organic matter. This suggests that the influence of both lateral and vertical processes can create distinct differences in VWC between locations with different vegetative cover. However, under dry midsummer conditions before the rain events, there were no significant differences between plots. Although soil moisture was not significantly different between plots during these times, the relative contribution of evaporation versus transpiration to the flux of water out of the soil likely shifted, resulting in similar VWC due to compensatory evaporation in the CC area.

4.4. Implications

In complex terrain, topography is often considered a master variable for ecologic and biogeochemical processes due to its influence on incoming solar radiation and the redistribution of water, solutes, and particles. The use of topographic metrics to scale observed or hypothesized biogeochemical processes (based on their relationships with soil moisture or other environmental variables) is becoming more common. Ideally, one should identify the hydrological mechanisms that create the conditions that the ecological/biogeochemical processes are responding to through time, assess whether terrain metrics are likely to reflect these conditions, and assess whether there are times one would expect relationships to be stronger or weaker such as observed in this study. Future research on spatiotemporal patterns of soil moisture might benefit from examining how the frequency, magnitude, or seasonality of precipitation influences the relationships between topographic metrics and soil moisture across catchments.

5. Conclusions

5.1. What Is the Relationship Between Soil Water Content and Topography Across Seasonal Drydown?

We examined how VWC varied across landscape positions, land cover types, and time through a growing season in a semiarid montane catchment in central Montana. The variability of VWC (SD) increased in the riparian area as the catchment dried, while it decreased in the uplands at both plot and landscape scales. This is largely due to the associated ranges of VWC in each landscape position, the CVs make it apparent that the variability relative to the mean actually increases as the catchment dries in both landscape positions. The distinct behavior of these two elements of the landscape should be considered in future studies because grouping them could prevent identification of important seasonal trends and its associated variability.

Unlike some previously published studies, our analysis revealed that topographic wetness indices remained correlated with landscape-scale variability of VWC at the end of the growing season when the catchment was at its driest state, even though significant lateral flow had long ceased. The explanatory power of topography was the weakest at an intermediate catchment wetness state, likely because of asynchronous drydown of the catchment in the transition from wet state to dry state. These findings suggest that the legacy of saturated throughflow during wet times can be reflected in unsaturated VWC during dry times. Specifically, as upland areas become disconnected from lower hillslopes, the soil moisture was retained locally in a pattern that is reflective of upslope contributing areas.

5.2. How Does Landscape Variability of Soil Water Content Compare to Plot-Scale Variability? Do the Processes That Control This Variability Change From Wet to Dry Catchment States?

Landscape-scale variability (SD) of VWC was consistently lower than plot-scale variability. The SDs within the riparian area increased through the season, but because of the influence of downvalley and downslope contributions (connected, lateral flow), the riparian area had lower CVs than in the uplands (both at the landscape and plot scales). In the uplands, absolute VWC variability (SD) was high in the wet catchment state because the range of VWC was higher and decreased as the catchment became water-limited. Interestingly, the relative variability (CV) of upland VWC increased through the season and became more variable after small rain events, likely due to vertical processes.

Landcover differences due to clearcutting did not result in significant differences in magnitude and variability of VWC between the CC and the forest. However, shallow soil moisture was significantly different between the CC and forest when VWC was at its highest early in the growing season and after shallow rewetting events late in the season. We did not observe any spatial correlation in VWC within plots (0–30 m). However, at the landscape scale, correlation length scales were 400–750 m suggesting topographically influenced variables might also have similarly large correlation lengths, well beyond the plot scale.

These results highlight how local variability is nested within landscape patterns of water redistribution and their evolving importance through varying catchment wetness states. Early in the season, absolute variability of VWC was high across the landscape when lateral flow saturated convergent portions of the landscape. Once saturated lateral flow ceased, relative variability increased at the plot scale, but the memory effect of topographically mediated redistribution of water during the wet state was still apparent. For example, locations with large upslope contributing areas (UAA) retained moisture even after they became hydrologically disconnected from lower hillslopes and upslope contributing areas. Our results indicate an interplay between climate and topography that can influence the strength of topographic—streamflow and topographic—VWC relationships across catchments and regions worldwide. We suggest that assessing how spatial and temporal patterns in vertical and lateral fluxes manifest as hierarchical controls on VWC warrants further investigation, particularly because of their effects on the magnitude and heterogeneity of ecologic and biogeochemical processes through time.

A: Appendix

We provide supporting information for three aspects of the manuscript, the full VWC data set and geostatistical analyses of both terrain metrics and plot-scale VWC. The full VWC data set shows the distribution of samples in upland and riparian locations and their associated variability (Figure A1). Correlograms show that topographic metrics were significantly correlated at distances of 400–750 m (Figure A2), while plot-scale VWC measurements were not spatially correlated at <30 m. Variograms of plot-scale VWC also show that there were no consistent trends between spatial characteristics and wetness state (Figure A3).

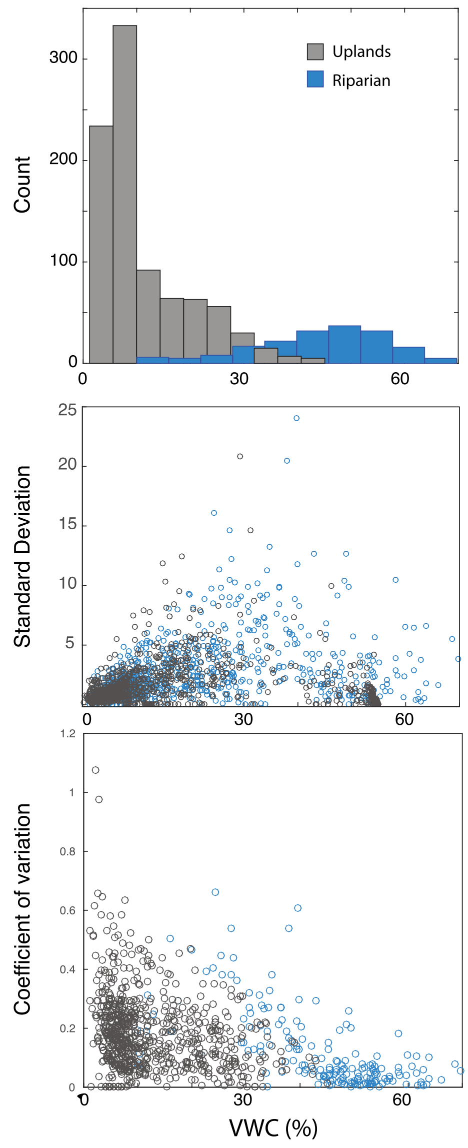

Figure A1. (top) Histograms of measured across the distributed landscape sampling (n = 32). Uplands (gray) are heavily skewed to the left (mean: 11.3% VWC median: 7.7% VWC), while the riparian area is only slightly skewed to the right (mean: 46% VWC median: 44% VWC). (center) Standard deviation and (bottom) coefficient of variation of the triplicate measures of VWC at the site scale versus the associated average percent VWC. VWC = volumetric water content.

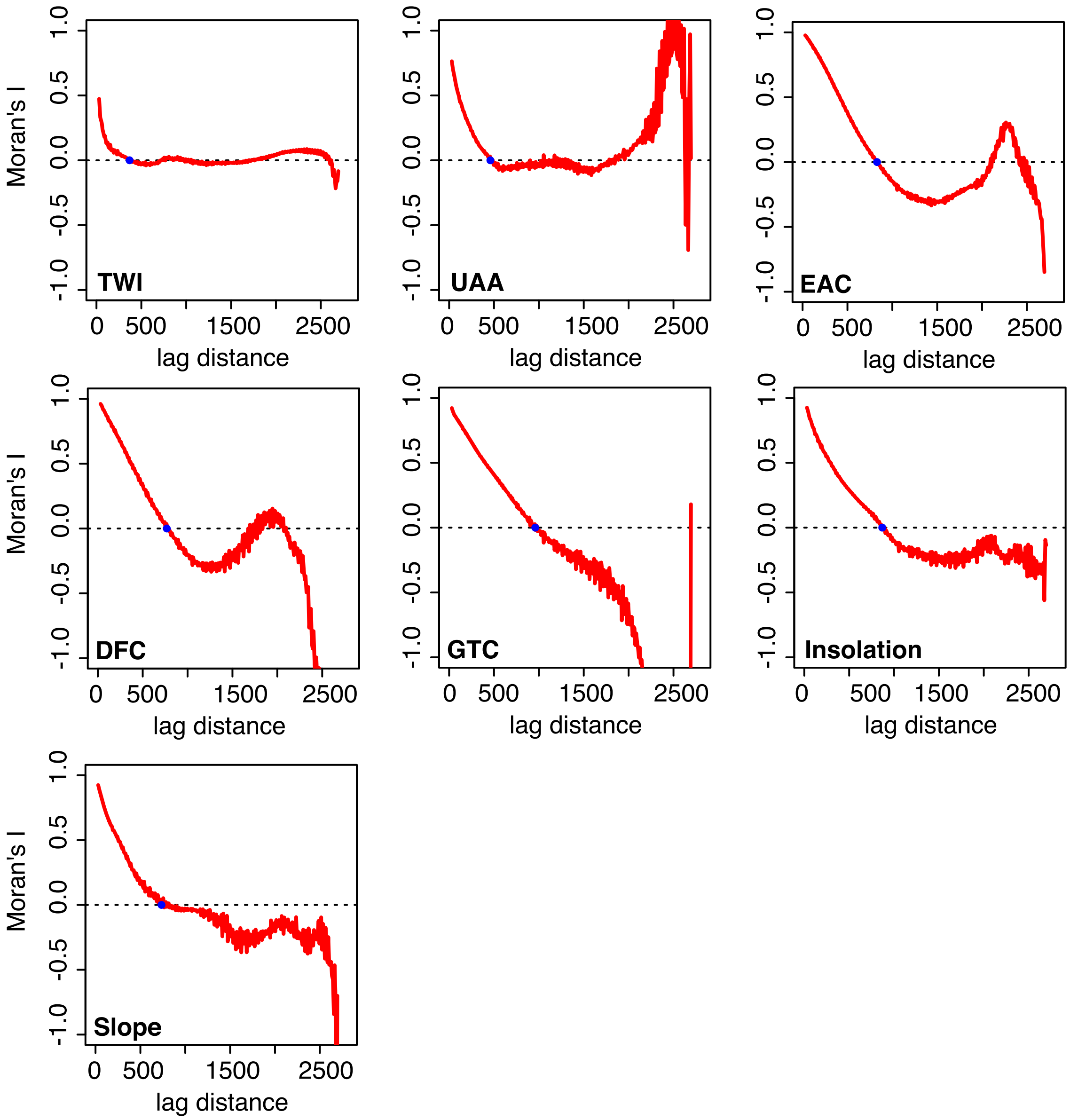

Figure A2. Correlograms of derived terrain metrics. Spatial correlation was over 400 m for each metric (blue dot denotes the first *x* intercept of the correlogram function), TWI, UAA, EAC, DFC, insolation, and slope. TWI = topographic wetness index; UAA = upslope accumulated area; EAC = elevation above the creek; DFC = distance from creek; GTC = gradient to creek.

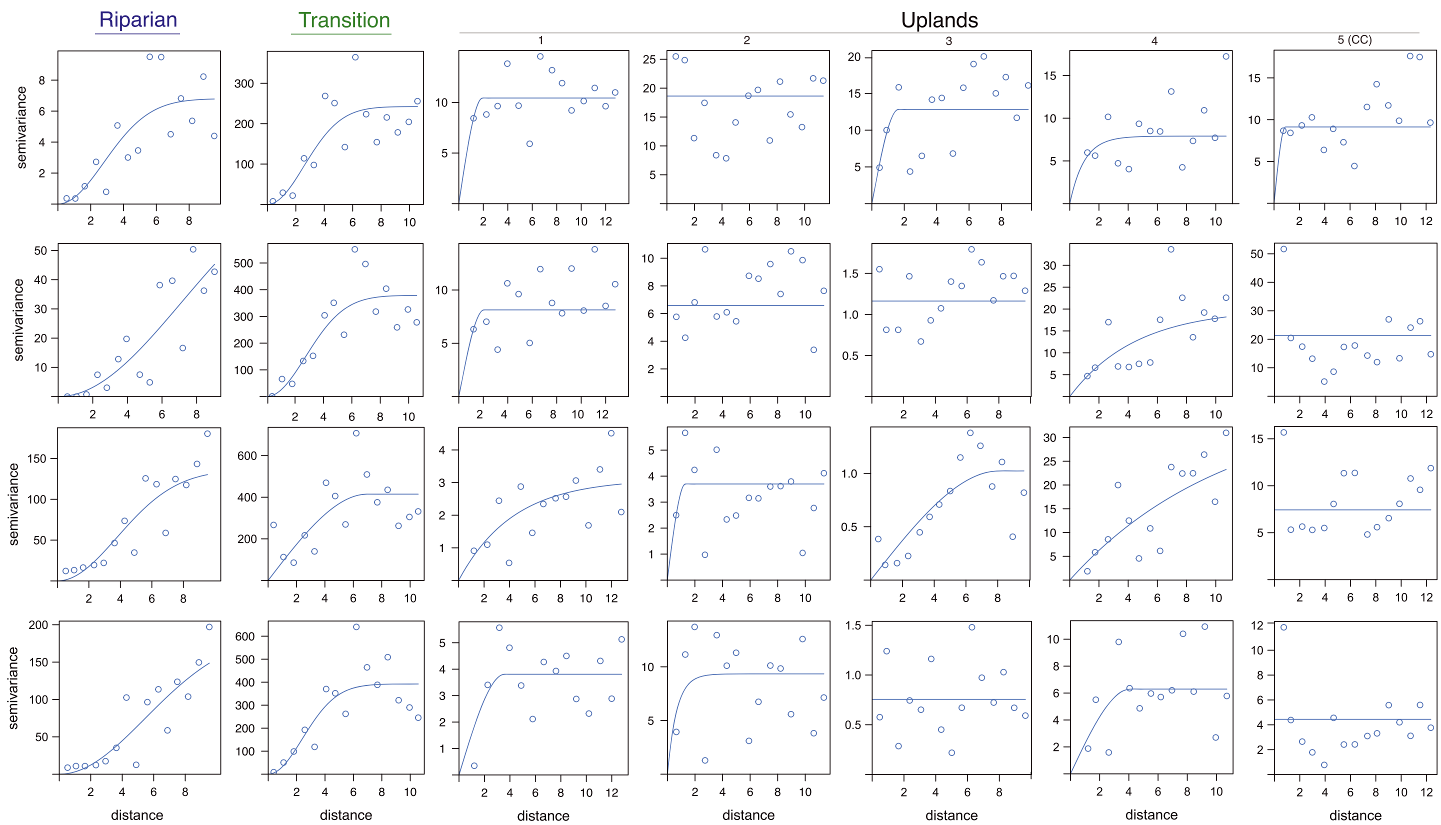

Figure A3. Variograms of plot-scale volumetric water content calculated using the omnidirectional variogram with the best fit (exponential, Gaussian, spherical, or nugget). There was no significant spatial correlation within any plot over the season based on analysis of correlograms.

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