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Terrain-Shape Indices for Modeling Soil Moisture Dynamics

This study examined spatial and temporal relationships between measured soil moisture and terrain-based proxies for soil moisture dynamics. Two catenas were intensively sampled reflecting a mosaic of differences in degree of soil development in California’s Sierra Foothill Region. A catena containing weakly developed soils (Haploxerepts + Haploxeralfs) formed from granitic parent materials was compared to a catena of well-developed soils (Haploxeralfs and Palexeralfs) formed from metavolcanic parent materials. Soil moisture was monitored at 10-, 30-, and 50-cm depths in 15 profiles in the granitic catena and 100 profiles in the metavolcanic catena. Seven post-rainfall periods during the 2008–2009 water year were selected to compare terrain shape indices and measured soil moisture. No single terrain index (slope, tangential curvature, profile curvature, mean curvature, topographic prominence, terrain characterization index, and compound topographic index [CTI]) consistently described variability in mean water content or dry-down rates, across depth or space. However, within the granitic catena, a combination of CTI and modeled beam radiance consistently accounted for 30 to 70% of the total variance in mean water content at 10 cm, and 10 to 40% at 30- and 50-cm depths. The predictive capacity of digital elevation model (DEM)-derived terrain shape indices for soil moisture dynamics varied widely in time and space, and was influenced by spatial patterns in the degree of soil development. Efforts to describe soil moisture variability are an important attribute of digital soil mapping (DSM). Moreover, soil variability influences soil moisture dynamics, thus synergistic activities are needed to integrate landscape scale variability with digital soil mapping.

Abbreviations: CTI, compound topographic index; DEM, digital elevation model; DSM, digital soil mapping; ESRA, European Solar Radiation Atlas; ET, evapotranspiration; GPS, global positioning system; GRAD, slope gradient; MAAT, mean annual air temperature; MAP, mean annual precipitation; MCURV, mean curvature; PCRUV, profile curvature; PROM, topographic prominence; PRP, post-rainfall period; RST, regularized splines in tension; RTK, real-time kinematic; SFR, Sierra Foothill Region; SFREC, Sierra Foothill Research and Extension Center; SJER, San Joaquin Experimental Range; TCI, terrain characterization index; TCURV, tangential curvature; VIF, variance inflation factor; VWC, volumetric water content; WMPD, weighted-mean particle diameter.

Landscape-scale variability in soil properties is usually driven by processes that control redistribution of sediment, precipitation, and microclimate; where the magnitude of variability is stratified by dominant soil-forming factors (Wilding et al., 1994). In many landscapes, repeating patterns of (usually overlapping) soil-forming factors give rise to predictable patterns in soil characteristics (Pennock et al., 1987). This phenomenon and its application define a paradigm for describing hydopedologic processes using field observations coupled with contextual data (aerial imagery, topographic maps, geologic maps, etc.) that are hypothesized to have a connection with active soil-forming factors (Moore et
al., 1991; Hudson, 1992; Thompson et al., 2001). The accuracy of predictions based on the soil-landscape paradigm depends on careful selection and weighting of contextual information, which is usually only possible with extensive field experience and a solid understanding of pedogenic processes (Wagenet et al., 1994). The digital implementation of this approach, supported by widely available, high-resolution spatial data coupled with statistical and mapping software, has resulted in effective quantification techniques that document soil variability and also the redistribution of soil moisture over the landscape (Western et al., 1999; McBratney et al., 2003; Scull et al., 2003; Lin et al., 2006).

Most digital mapping studies focus on external “drivers” of soil formation (e.g., hillslope processes that affect the redistribution of water, sediment, and mineral weathering), with an inferred relationship to digital proxies for these drivers. Also known as soil-environmental correlation (McKenzie and Ryan, 1999) or DSM, this approach relies on fitting statistical models to soil and environmental covariates (i.e., proxies for soil-forming factors), followed by prediction at unsampled locations. At the watershed scale, slope shape, scale shape, exposure, and compound metrics describing water flow or sediment accumulation are some of the major proxies used to characterize soil-forming processes (Moore et al., 1993; Thompson et al., 2001). These terrain-based metrics are calculated from DEMs (Wilson and Gallant, 2000a), making integration into soil survey investigations practical (McKenzie et al., 2000). Quantitative models based on digital proxies for hydrogeologic processes, represent a promising approach for detailed (e.g., > 1:24,000 scale) mapping of water dynamics in the environment (Park and van de Giesen, 2004).

Hydrologists and digital soil mappers use similar tools to describe soil- and soil moisture-variability. Topography is commonly considered one of the main static factors that affects runoff processes and the primary predictor of watershed-scale hydrology (Western et al., 1999). Slope aspect (angle), cosine-transformed aspect angle, and various models of the surface energy budget have been used as a proxy for the effects of solar radiation on soil hydrology (Beaudette and O’Geen, 2009). Compound topographic indices (wetness index, stream power index, potential solar radiation, etc.) have been used as proxies for hillslope-scale variability in soil moisture (Moore et al., 1991). Beven and Kirkby (1979) were among the first to incorporate the concept of the CTI into a watershed scale model (TOPMODEL) of soil moisture. Burt and Butcher (1985) found significant correlation between various terrain shape indices and depth to saturation in a 1.4-ha catchment. Western et al. (1999) published data from a comprehensive demonstration of digital proxies for soil moisture distribution at the watershed scale, based on slope, upslope contributing area, CTI, and potential solar radiation. They found that upslope contributing area was the best predictor of soil moisture in wet periods and potential solar radiation was the best predictor during dry periods. The relationships between digital proxies for soil moisture, however, are commonly site-dependent and usually poorly correlated with point measurements (Western et al., 1999; Grayson and Western, 2001; Swarowsky et al., 2011).

While terrain indices have performed well in terms of explaining variability in soil moisture in some settings, in other settings these tools have been shown to perform poorly (Western et al., 1999). Dynamic factors such as precipitation, evapotranspiration, drainage, lateral flow, and presence of water tables also govern the distribution of soil moisture in space and time (Reynolds; 1970; Takagi and Lin 2011). Moreover, soil properties such as horizon stratigraphy (e.g., claypans or duripans) and subsurface topography at the soil-bedrock interface also regulate the redistribution of soil moisture at catchment scales (Freer et al., 2002; McGlynn et al., 2002; Tromp-van Meerveld and McDonnell, 2006; Rains et al., 2006; Swarowsky et al., 2012).

In this study we evaluated commonly used digital proxies for spatial and temporal variability of soil moisture within two soil catenas containing a mosaic of soils with large differences in degree of soil development. Specific research questions included: (i) Do digital proxies describe spatial patterns in measured soil moisture that are consistent with the soil-landscape paradigm? and, (ii) Are the relationships between digital proxies and measured soil moisture consistent across differences in pedogenic development through time, and at different depths following rainfall events?

MATERIALS AND METHODS

Environmental Setting

The Sierra Foothill Region (SFR) of California spans 1.45 million ha consisting of predominately metamorphic 40% and granitic rocks 60%. Elevation ranges from 60 to 1500 m, mean annual precipitation (MAP) ranges from 200 to 1000 mm, and mean annual air temperature (MAAT) ranges from 7 to 18°C. The region has a characteristic Mediterranean climate with hot, dry summers and cool, wet winters (thermic, xeric). We studied two 30-ha landscapes representative of the landforms, ecosystems, soil types, and major lithologic bodies within the SFR (Fig. 1). The study sites have been managed for over 50 yr with low to moderate intensity cattle (Bos taurus) grazing.

A 30-ha collection of adjacent catenas at the San Joaquin Experimental Range (SJR), was selected to represent the rolling terrain and blue oak (Quercus douglasii Hook. & Arn.) savanna of granitic landscapes of the central and southern SFR. Foothill pine (Pinus sabiniana Douglas), buckbrush [Ceanothus cuneatus (Hook.) Nutt. var. cuneatus], and a mixture of annual grasses and forbes [(Bromus hordeaceus L., B. diandrus Roth, Valpia myuros L., B. madretrans L., and Erodium botrys (Cav.) Bertol.] are found throughout the area. Tree canopy cover was estimated to be 20%, using supervised classification of panchromatic (red, green, and blue channels) from aerial imagery (SMAP algorithm (Bouman and Shapiro, 1994)). Local geology is dominated by Mesozoic granodiorite with patches of granite, tonalite, and diorite (Strand, 1967). Soils at SJR are typical of those mapped within this region: Ahwahnee (coarse-loamy, mixed, active, thermic Mollic Haploxeralfs) on summit positions, and Vista (coarse-loamy, mixed, superactive, thermic Typic Haploxerepts) on the backslope positions (Natural Resources Conservation Service, 1970; USDA-ARS, 1978).
Elevation within the SJER catena extends from 330 to 370 m, MAP is 500 mm, and MAAT is 16.0°C.

A single 30-ha headwater catchment at the Sierra Foothill Research and Extension Center (SFREC) was selected to represent the steeper and more densely wooded metamorphic landscapes of the northern SFR. Blue oak, interior live oak (*Q. wislizeni*), California black oak (*Q. kelloggii* Newb.), and foothill pine are the most common tree species in the area, with thicker stands on northern aspects. Tree canopy cover was estimated to be between 55 and 65% (Chow et al., 2009). Understory vegetation is dominated by annual grasses and forbs (*Bromus mollis* L., *Hordeum hystrix* Roth, *Avena barbata* Link, *Anahallis arvensis* L., and *Geranium molle* L.) on warmer slopes, while cooler slopes are dominated by a mixture of annual grasses, forbs, and poison oak (*Toxicodendron diversilobum* [Torrey & A. Gray] E. Greene). Local geology is dominated by Mesozoic metavolcanic rocks (greenstone) of the Smartville complex (Hacker, 1993). Dominant soils included: Sobrante (fine-loamy, mixed, active, thermic Mollic Haploxeralfs) and Timbuctoo (fine, parasolsodic, thermic Typic Rhodoxeralfs), both occurring on backslope and summit positions (Natural Resources Conservation Service, 1998). Elevation within the SFREC catena extends from 160 to 410 m, MAP is 705 mm, and MAAT is 16.6°C.

**Soil Sampling and Sensor Installation**

Locations for soil moisture instrumentation were selected according to a random-stratified design (de Gruijter et al., 2006) within expert-delineated landscape positions at both catenas. Soil profiles were excavated to bedrock, morphological characteristics were described using standard soil survey techniques, and soil samples were collected by genetic horizon. A total of 15 soil profiles at SJER were instrumented with Decagon EC-5 (Decagon Devices Inc., Pullman, WA) volumetric water content (VWC) sensors at 10-, 30-, and 50-cm depths (Fig. 1). Two shallow profiles were instrumented with sensors at 10- and 30-cm depths. A total of 100 soil profiles at SFREC were instrumented with sensors, however data from only 45 of these profiles were used due to sensor failure that occurred during the 2008–2009 water year (Fig. 1). Soil moisture sensors installed in the A (10 cm), BA-Bt transition (30 cm), and middle of Bt (50 cm) horizons were used in this study. A more comprehensive description of the sensor installation is given by Swarowsky et al. (2012).

Particle-size distribution was determined by pipette method (Soil Survey Staff, 2004). Coarse fragment volume was estimated in the field. Particle-size data were associated with each soil moisture sensor according to the nearest sampled horizon. Weighted-mean particle diameter (WMPD) was computed for each horizon:

\[
WMPD = \frac{\sum w_i \times d_i}{\sum w_i}
\]

where \(w_i\) is the measured quantity (mass percent) of each size class, and \(d_i\) is the corresponding median diameter from each size class.
Digital Terrain Modeling

A detailed elevation survey was conducted at both catenas with a Trimble R7 real-time kinematic (RTK) global positioning system (GPS) with approximately 35 observations per hectare (Trimble Navigation Limited, Sunnyvale, CA). The RTK sampling locations were determined by iteratively increasing the spacing between intersecting nodes derived from existing (USGS 10-m national elevation data) contour lines, drainage network lines, and ridge lines until root-mean-square-error of the interpolated surface stabilized. A gridded elevation model (1-m horizontal spacing) was generated via regularized splines in tension (RST) interpolation, allowing for increased smoothness in the elevation surface where GPS observations were of lower (~10 cm) vertical precision (Mitasova and Mitas, 1993).

Primary topographic parameters (slope angle, aspect angle, profile curvature [PCURV], tangential curvature [TCURV], and mean curvature [MCURV]) were generated from partial first and second derivatives of the elevation surface fit by RST interpolation (Mitasova and Hofierka, 1993). Profile curvature is interpreted as an indicator of local changes in flow velocity (Western et al., 1999). The TCURV is analogous to plan curvature (i.e., curvature along a contour line), and typically interpreted as an index of local flow convergence (Mitasova and Hofierka, 1993; Western et al., 1999). The MCURV is the mean of profile and tangential curvature, and represents areas that are predominately convex (positive values), concave (negative values), or linear (values near 0).

Secondary topographic parameters including the compound topographic index (CTI) (Wilson and Gallant, 2000b) and terrain characterization index (TCI) (Park et al., 2001) were computed within GRASS GIS (GRASS Development Team, 2009). Low CTI values correspond with regions that are (theoretically) water-shedding (2–4 in our catenas), and high CTI values correspond with regions that are water-focusing (9–11 in our catenas). The CTI values >11 to 12 correspond to locations of ephemeral streams. The TCI uses negative values to indicate local, three-dimensional focusing of water and sediment, and positive values to suggest the opposite (Park et al., 2001).

Llobera’s topographic prominence index (PROM) is a relative measure of terrain ruggedness when evaluated over several scales, and a measure of relative hillslope position when evaluated at large (<1000 m²) cartographic scales (Llobera, 2001). This index ranges from −1 in lower landscape positions (within a user-defined search radius) to 1 in higher landscape positions. Due to the differences in landform size between the two catenas, this index was computed using a 50-m search radius at SJER and a 100-m search radius at SFREC.

Daily estimates of beam radiation were modeled with the ESRA solar radiation model (Rigollier et al., 2000), and summed to generate an annual beam radiation surface. A constant Linke turbidity (Kasten, 1996) representative of the study sites ($T_L = 3.0$) was used to partition beam from diffuse radiance. Output from the ESRA model is an effective index of microclimate in this region, integrating slope angle, slope aspect, and shading from adjacent terrain (Beaudette and O’Geen, 2009).

Distributions of select terrain attribute values in each catena (annual beam radiance, CTI, and mean curvature) were extracted at soil profile locations and compared with corresponding distributions derived from entire raster surfaces. Visual inspection of box and whisker plots confirmed that there was generally good agreement between distributions of terrain attribute values extracted at soil profile locations and distributions from entire catenas (Fig. 2). Sampled sites were slightly biased towards landscape positions receiving more annual beam radiance (more so at SJER), and to concave surfaces (more so at SJER) (Fig. 2). Differences between the shape and central tendency of distributions are expected to contribute some bias to the statistical models developed. The truncated distributions associated with values extracted at soil profile locations limit our ability to extrapolate across the full range of the terrain attributes within each catena.

Statistical Analysis

Spearman rank correlation coefficients were used to gauge the sign and magnitude of relationships between terrain-shape indices and measurements of soil moisture. Spearman’s rank correlation coefficient ($r_s$) is a rank-based metric used in cases when nonlinear, but strictly monotonic, relationships are hypothesized (Verzani, 2004). Partial Spearman rank correlation coefficients were computed to adjust for mutual correlation among terrain-shape indices, measured soil moisture, and weighted-mean particle diameter (WMPD):

$$r_{12.3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{1-r_{13}^2} \sqrt{1-r_{23}^2}}$$  \[2\]

where $r_{12.3}$ is the partial Spearman correlation coefficient between Variable 1 and 2, after adjusting for Variable 3. The parameters $r_{12}$, $r_{13}$, and $r_{23}$ are the Spearman correlation coefficients between Variables 1 and 2, 1 and 3, and 2 and 3, respectively (Legendre and Legendre, 1998).

Collinearity within all models was evaluated with the variance inflation factor (VIF):

$$VIF_i = \frac{1}{(1-R_i^2)}$$  \[3\]

where VIF, is the variance inflation factor for variable $i$ and $R_i^2$ is the coefficient of determination when variable $i$ is regressed on
all other predictors (Harrell, 2001). All models described within this study had VIF values between 1 and 3, suggesting that collinearity was not large enough to confound interpretation of partial explained variances, coefficients, or standard errors.

Seven post-rainfall periods (PRP) were selected as a basis for comparisons between DEM-derived terrain shape indices and measured soil moisture (Fig. 3, Supplemental Fig. 1 and 2). This style of analysis was selected based on the observations that: (i) volumetric water content typically decreased linearly after each rain event; (ii) the slope and mean water content within each PRP have a direct interpretation; and, (iii) a simple linear modeling framework could be used for analysis. The PRP numbers 1 to 2 are representative of the early winter wet-up phase, numbers 3 to 4 representative of the winter wet phase, and numbers 5 to 7 representative of the dry-down (spring utilization) phase. Within each PRP, a linear model was fit to the soil moisture data (by sensor) such that model intercepts described soil moisture values at the midpoint of each PRP and model slopes described rates of soil moisture change through the duration of the PRP (Fig. 3). Fitted intercepts can be interpreted as PRP-wise mean VWC, and are denoted as $\bar{\text{VWC}}$. Likewise, fitted slopes are interpreted as either PRP-wise wet-up rates (positive change in VWC per day) or PRP-wise dry-down rates (negative change in VWC per day), and are denoted as $\Delta\text{VWC}$. Multiple linear regression was used to determine the partial variance in $\bar{\text{VWC}}$ and $\Delta\text{VWC}$ explained by beam radiance, CTI, WMPD, and canopy cover (SFREC only) within each PRP. Regression models were fit for each sensor depth (10, 30, and 50 cm) and within each PRP. Canopy cover (SFREC only) was determined in the field and converted into a categorical variable describing observations as either: closed canopy, partial canopy, or open canopy. Of the many terrain-shape indices compared in this paper, CTI was selected for the variance partitioning component of analysis due to the fact that it is one of the most widely applied indices of water
and sediment redistribution. Partial effects (i.e., partial slopes) and corresponding standard errors were used to describe temporal changes in sign, magnitude, and statistical significance of CTI and beam radiance.

RESULTS AND DISCUSSION

Soil Properties

Soil depth at SJER ranged from shallow (<50 cm) to very deep (>150 cm), with lithic or paralithic contact typically occurring near 80 to 90 cm. At summit positions, soils were generally shallow with loamy particle size classes when bedrock was closer in composition to granite, while soils formed on granodiorite or diorite were moderately deep and coarse-loamy. In swale positions, soils were very deep and coarse-loamy, but fine-loamy in swales found at the base of landforms where bedrock was predominantly diorite. Soils on backslopes were typically moderately deep to deep, and coarse-loamy, regardless of bedrock composition. Cambic and weak argillic horizons were common, typically with little evidence of clay illuviation and iron oxide production (10YR hues) (Table 1). Evidence of more soil development was present in soils formed from dioritic residuum and colluvium, with greater clay production, redder hues (7.5YR), and greater occurrence of clay films.

Soil depth at SFREC ranged from shallow to deep, with lithic or paralithic contact typically occurring near 80 to 90 cm. Soil textures were generally loamy-skeletal or fine-loamy, having few clear patterns with respect to landscape position. Most profiles had thick argillic horizons (20–70 cm) with abrupt or clear horizon boundaries, nearly 100% of ped faces had distinct clay films, bright red colors (5YR to 2.5YR hue and chroma of 4–6) as well as an absolute increase in clay content relative to overlying horizons of 10 to 25% (Tables 1 and 2). Profile development at SFREC did not follow clear relationships with regards to landscape position, however, more developed soils coincided with areas of bedrock having higher iron content (data not shown).

Weighted-mean particle diameter (WMPD) was used as a proxy for water-holding capacity, based on the assumption that WMPD values were inversely, monotonically, and approximately linearly related to water-holding capacity. It should be noted that WMPD values do not account for differences in water-holding capacity that are driven by other factors such as organic matter content, rock fragment content, compaction, or soil structure. The WMPD values ranged from 0.30 to 0.61 mm at SJER and from 0.05 to 0.49 mm at SFREC (Table 2). Median WMPD values were typically three times larger at SJER as compared to SFREC at 10-, 30-, and 50-cm depths (Table 3). Site-wide variation in WMPD was fairly consistent with depth at SJER (0.064–0.075 mm inter-quartile range), and generally 1.5 to 2 times greater than corresponding site-wide variation in WMPD at SFREC (Table 3). In contrast, site-wide variation in WMPD varied greatly (0.039–0.068 mm inter-quartile range) with depth at SFREC. Differences in WMPD variability with depth mirror the relative differences in profile development found at each study site.

Soil Moisture

At SJER, soil moisture content (θv) near the surface was consistently greater than at depth during the early winter wet-up phase (PRP 1–2: November though late December), approximately equal through the winter-wet phase (PRP 3–4: mid-January through March), and consistently lower during the spring (PRP 5–7: March through May) dry-down phase (Fig. 4).

Table 1. Representative soil morphologic data from each study site, from selected soil profile descriptions. Soil profile “007” from the San Joaquin Experimental Range (SJER-granitic lithology) was sampled on a north-facing backslope and is classified as fine-loamy, mixed, superactive, thermic Typic Haploxeralf. Soil profile “N35” from the Sierra Foothill Research and Extension Center (SFREC-metavolcanic lithology) was sampled on a northwest-facing backslope and is classified as fine-skeletal, mixed, superactive, thermic Mollic Haploxeralf.

<table>
<thead>
<tr>
<th>Site</th>
<th>Horizon</th>
<th>Depth</th>
<th>Boundary†</th>
<th>Color</th>
<th>Structure‡</th>
<th>Consistency§</th>
<th>&gt;2 mm</th>
<th>Texture¶</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJER (007)</td>
<td>A</td>
<td>0–5</td>
<td>AW</td>
<td>10YR 5/3</td>
<td>10YR 4/3</td>
<td>1 F SBK</td>
<td>VFR, SS, PO</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>AB1</td>
<td>5–22</td>
<td>GW</td>
<td>10YR 4/2</td>
<td>10YR 4/2</td>
<td>2 M SBK</td>
<td>FR, SS, PO</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>AB2</td>
<td>22–45</td>
<td>GW</td>
<td>10YR 4/2</td>
<td>10YR 4/2</td>
<td>2 CO SBK</td>
<td>FR, SS, PO</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Bw1</td>
<td>45–65</td>
<td>CW</td>
<td>10YR 4/2</td>
<td>10YR 4/2</td>
<td>2 M ABK</td>
<td>FR, SS, PO</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Bw2</td>
<td>65–80</td>
<td>Ci</td>
<td>10YR 7/3</td>
<td>10YR 5/2</td>
<td>MA</td>
<td>FR, MS, SP</td>
<td>10</td>
</tr>
<tr>
<td>SFREC (N35)</td>
<td>R</td>
<td>80+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>A</td>
<td>0–10</td>
<td>CW</td>
<td>10YR 5/3</td>
<td>10YR 4/3</td>
<td>1 F SBK</td>
<td>VFR, SS, PO</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>0–10</td>
<td>CW</td>
<td>10YR 5/3</td>
<td>10YR 4/3</td>
<td>2 M ABK</td>
<td>FR, SS, PO</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>26–53</td>
<td>AW</td>
<td>10YR 4/2</td>
<td>10YR 4/2</td>
<td>2 CO SBK</td>
<td>FR, SS, PO</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2B1</td>
<td>53–72</td>
<td>AW</td>
<td>10YR 4/3</td>
<td>10YR 4/3</td>
<td>2 M ABK</td>
<td>FR, SS, PO</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2B1/Crt</td>
<td>72–88</td>
<td>CW</td>
<td>10YR 4/3</td>
<td>10YR 4/3</td>
<td>2 M ABK</td>
<td>FR, SS, PO</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>88+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

† Boundary: AW = abrupt wavy, GW = gradual wavy, CW = clear wavy, Ci = clear irregular.
‡ Structure: F = fine, M = medium, CO = coarse, SBK = sub-angular blocky, ABK = angular blocky, MA = massive.
§ Consistence: VFR = very friable, FR = friable, SR = slightly rigid, SS = slightly sticky, MS = moderately sticky, PO = not plastic, SP = slightly plastic, MP = moderately plastic, VP = very plastic.
¶ Texture: COSL = coarse sandy loam, L = loam, GRL = gravelly loam, CBCL = cobbly clay loam.

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This pattern is typical of most freely drained soils where the soil profile “fills” from the top-down at the onset of the winter rainy season, remains at or above field capacity during the peak of the rainy season, and “empties” from the top-down during spring and early summer. Once soil profiles at SJER reached field capacity (PRP 4), measured at 10-, 30-, and 50-cm depths were similar. This was likely due to the relatively low degree of soil profile development at SJER, with clear and gradual horizon boundaries and little change in soil texture (and therefore water-holding capacity) over depth. Site-wide median WMPD values were consistent over the three depths where soil moisture was measured: 0.47 mm WMPD at 10 cm, 0.45 mm at 30 cm, and 0.44 mm at 50 cm. Water content measured at 10 cm was consistently more temporally and spatially variable than at 30- and 50-cm depths due to rapid infiltration, percolation, and loss to evapotranspiration (Fig. 4).

At SFREC, $\theta_v$ at 10 cm was only greater than measurements collected from 30 and 50 cm. Higher water-holding capacity in the BA and Bt horizons, coupled with near-surface water use by annual grasses were probably responsible for the strong vertical differentiation in soil moisture. Annual grass roots are typically confined to the upper 10 cm of soil in early March through April, and ultimately extend to a maximum of about 30 cm at maturity (Gordon and Rice, 1992; Holmes and Rice, 1996). At 10 and 30 cm, $\theta_v$ converged during the first major rainfall event in 2008 (November), and exceeded $\theta_v$ at 50 cm during the second major rainfall event in 2008 (Fig. 5). From January 2009, $\theta_v$ at 50 cm steadily increased through the rainy season until becoming recharged to field capacity in early March 2009 (Fig. 5). By PRP 3, $\theta_v$ was greatest at 50 cm, and decreased with proximity to the soil surface. This was likely due to the strong degree of soil development at SFREC, partially expressed as abrupt and clear horizon boundaries and strong vertical differentiation of soil texture (and water-holding capacity). Soil textures at 10 cm were typically loams, while textures at 30 and 50 cm were clay loams. During spring (March–June), soil moisture was rapidly lost between rainfall events, with the greatest rates of dry-down near the surface. The timing of annual grass growth and blue oak bud break (early March) coincided with increased steepening of soil moisture profiles as reported by $\theta_v$ measurements.

### Table 2. Particle-size distribution for representative soils from each study site. Sand fraction classes correspond to limits defined by the USDA.

<table>
<thead>
<tr>
<th>Site</th>
<th>Horizon</th>
<th>Clay</th>
<th>Silt</th>
<th>Total sand</th>
<th>VCS†</th>
<th>CS‡</th>
<th>MS§</th>
<th>FS¶</th>
<th>VFS#</th>
<th>WMPD††</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJER‡‡</td>
<td>A</td>
<td>8</td>
<td>16</td>
<td>76</td>
<td>12</td>
<td>22</td>
<td>12</td>
<td>21</td>
<td>10</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>AB1</td>
<td>7</td>
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<td>Bw2</td>
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<td>SFREC</td>
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<td></td>
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<td>11</td>
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<tr>
<td></td>
<td>2Bt/Crt</td>
<td>39</td>
<td>27</td>
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<td>5</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>0.22</td>
</tr>
</tbody>
</table>

† VCS = very coarse sand.
‡ CS = coarse sand.
§ MS = medium sand.
¶ FS = fine sand.
# VFS = very fine sand.
†† WMPD = weighted mean particle diameter.
‡‡ SJER = San Joaquin Experimental Range; parent material derived from granitic rocks; SFREC = Sierra Foothill Research and Extension Center; parent material derived from metavolcanic rocks.

### Table 3. Weighted mean particle diameter (WMPD) values, summarized by site and sensor depth. Spread around the median and mean is given as the inter-quartile range (IQR) and standard deviation (SD).

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth</th>
<th>Minimum</th>
<th>First quartile</th>
<th>Median</th>
<th>Mean</th>
<th>Third quartile</th>
<th>Maximum</th>
<th>IQR</th>
<th>SD</th>
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<tbody>
<tr>
<td>SJER‡‡</td>
<td>10</td>
<td>0.36</td>
<td>0.43</td>
<td>0.47</td>
<td>0.47</td>
<td>0.51</td>
<td>0.63</td>
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<td>0.072</td>
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<td>0.46</td>
<td>0.50</td>
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<td>SJER</td>
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<td>0.42</td>
<td>0.44</td>
<td>0.46</td>
<td>0.49</td>
<td>0.61</td>
<td>0.072</td>
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<tr>
<td>SFREC</td>
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<td>0.18</td>
<td>0.18</td>
<td>0.19</td>
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<td>0.17</td>
<td>0.49</td>
<td>0.068</td>
<td>0.077</td>
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</tbody>
</table>

† SJER = San Joaquin Experimental Range; SFREC = Sierra Foothill Research and Extension Center.
dry-down rates observed between March and May 2009 (Fig. 5). The similar dry-down rates at 30 and 50 cm were likely due to similar water-holding capacity (estimated via WMPD; Table 3) and utilization by deeper-rooted oak and pine species as opposed to annual grasses.

**Temporal Stability of Terrain-Shape Indices**

A sequence of partial Spearman correlation coefficients was used to construct a temporal matrix of how well selected terrain-based proxies were correlated with $VWC$ (mean volumetric water content) and $\Delta VWC$ (change in volumetric water content) (Fig. 6). Terrain-based proxies were generally better predictors of $\Delta VWC$ as compared to $VWC$ (both sites), and correlations were always greater at SJER compared to SFREC (Fig. 6). However, no single terrain-based proxy showed a high level of consistency in terms of correlation with $VWC$ or $\Delta VWC$ over time, across depth, or between sites. It should be noted that many of these proxies were highly correlated with each other, and therefore
much of the information regarding terrain shape is shared among proxies. For example, slope gradient (GRAD) and PCURV were moderately correlated with each other at both catenas ($r_s = 0.2–0.4$), and TCI, CTI, MCURV, TCURV, and PROM were highly correlated with each other at both catenas ($r_s = 0.5–0.9$). However, this correlation structure was not always apparent in the temporal fluctuation of partial correlation between measured soil moisture and terrain-shape proxies (Fig. 6).

At SJER, correlation between $\overline{VWC}$ and terrain-based proxies was generally greatest at 30 cm. The dominant predictors of $\overline{VWC}$ varied by depth, with MCURV and TCI performing the best at 10 and 30 cm, and GRAD performing the best at 50 cm (Fig. 6). The temporal stability of these correlations (i.e., the consistency of dominant predictors of $\overline{VWC}$ across all PRP) was greatest at 30 and 50 cm, with a maximum correlation at PRP 5 and 6. Correlation between $\Delta VWC$ and terrain-based proxies was generally greatest during PRP 1 and 2 at 10 cm, PRP 3, 5, and 6 at 30 cm, and PRP 5, 6, and 7 at 50 cm. The CTI, TCURV, and PROM were the best performing proxies for $\Delta VWC$ (Fig. 6). As is the case in other studies, correlation between soil moisture dynamics and terrain attributes appears to be stronger in landscapes where soil profile variability is uniform. In a study having pronounced wet and dry seasons, elevation, slope, and distance to stream channels were the best predictors of soil wetness (Campling et al., 2002). The accuracy of prediction decreased, however, when comparing landscape positions that were increasingly well drained. A diminished capacity to predict soil moisture variability at broader scales was also observed by Park and van de Giesen (2004). They were able to increase their ability to explain soil moisture variability with terrain attributes by stratifying the landscape into hydrologic landscape units, which effectively reduced the spatial variation of soil moisture across a given portion of the landscape.

At SFREC, correlation between $\overline{VWC}$ and terrain-based proxies was greatest at 30- and 50-cm depths, however, the magnitude of correlations was low ($0.0 < r_s < 0.3$) (Fig. 6). Slope...
Studies have shown that was largely explained by solar radiation and at PRP 2 (10 cm), 3 (30 cm), and 5 (50 cm) for VWC and at PRP 2 (10 cm), 3 (30 cm), and 5 (50 cm) for ΔVWC (Fig. 6). While much less pronounced, sudden increases in θs occur within the SJER catena at PRP 2 (10 cm), 4 (30 cm), and 5 (50 cm) for VWC, and at PRP 3 (10, 30, and 50 cm) for ΔVWC (Fig. 6). Large negative changes in θs between PRPs may be attributed to either loss of sufficient soil moisture to support spatial organization, or conditions where soil texture, macropore drainage, ET, or some other parameter was the dominant factor controlling spatial patterns in θs.

### Partitioning Variance in Soil Moisture

At SJER, total explained variance in VWC by solar radiation, CTI, and WMPD, within a single PRP, and at a single depth was greatest near the soil surface and generally decreased with depth (Fig. 7). Partial variance in VWC was largely explained (30–70% of total) by modeled beam radiance and CTI at 10-cm depth, moderately explained by CTI (15–40% of total) at 30-cm depth, and weakly to moderately explained by a combination of CTI, modeled beam radiance and WMPD (20–40% absolute) at 50 cm (Fig. 7). Partial variance in VWC explained by modeled beam radiance (5–25% absolute) and CTI (15–50% absolute) was greatest near the surface (10 cm) and during the early winter wet-up (PRP 1 and 2) phases. At 30 cm, CTI was the best predictor of VWC, and explained increasing amounts of variance from PRP 1 (15% absolute) to PRP 7 (36% absolute). Partial variance explained by WMPD was low overall, but greatest at 50 cm (2–10% absolute). The relatively weak predictive power of WMPD was likely due to the homogeneity of soil texture and infrequent occurrence of argillic horizons at SJER (Tables 2 and 3). The timing of maximum partial variance explained by WMPD (wet-up and dry-down) corresponds to times when soil water potential (not measured) was likely within the window of water potential (10–100 kPa) where maximum correlation between particle size distribution and soil water content has been described (Pachepsky et al., 2001).

These patterns suggest that spatial variability of VWC landscapes similar to SJER is most readily predicted via terrain and microclimate proxies near the soil surface and during the wet-up and dry-down phases of the water year. In addition, differences in water-holding capacity (as expressed in terms of WMPD) explained (marginally) more partial variance in VWC with depth. Mirroring trends in the temporal stability of partial correlation between VWC and terrain-based proxies (Fig. 6), temporal stability in partial variance explained was greatest at 30 cm.
In contrast to SJER, total explained variance in $VWC$ was generally low (20–40% at 30 cm) to very low (2–20% at 10 and 50 cm) at SFREC (Fig. 8). Partial explained variance in $VWC$ was mainly accounted for by a combination of WMPD and canopy cover, with CTI and modeled beam radiance accounting for <10%. The small amount of partial variance in $VWC$ explained by modeled beam radiance was greatest during the spring dry-down phase (PRP 5, 6, 7). Partial variance explained by CTI was greatest during the winter wet-phase at 10 and 30 cm, and during the wet-up phase at 50 cm. These patterns suggest that in landscapes similar to SFREC, spatial variation in $VWC$ is probably controlled by differences in water-holding capacity among horizons and vegetation density; as well as factors that were not explicitly modeled: soil structure, macroporosity, perched water tables, abrupt textural changes, etc.

At SJER, total explained variance in $\Delta VWC$ varied widely across depths and PRP (Fig. 9). Near the surface (10 cm), modeled beam radiance explained the largest proportion of total variance during the spring dry-down phase (PRP 6 and 7), while CTI explained the largest proportion of total variance during the early winter wet-up phase (PRP 1 and 2). This shift in the dominance of beam radiance vs. CTI was likely caused by seasonal changes in landscape processes that control rates of soil moisture redistribution and utilization (Swarowsky et al., 2011). In fall wet-up months (PRP 1 and 2), annual grasses and forbes that typically use most of the soil moisture in the top 10 to 15 cm of soil are just germinating; resulting in a gravitational gradient-controlled redistribution of soil moisture (i.e., dominance of partial variance explained by CTI). In the late spring dry-down phase (PRP 6 and 7), rapid growth of annual grasses and forbes, coupled with the low water-holding capacity of surface horizons, likely results in evapotranspiration-controlled redistribution rates (i.e., the dominance of beam radiance explained by beam radiance). At 30 cm, CTI was always the best predictor of $\Delta VWC$, explaining the largest proportion of partial variance during the spring dry-down phase (PRP 5, 6, 7). The CTI and modeled beam ra-

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**Fig. 7.** Partial variance in mean volumetric water content ($VWC$) at San Joaquin Experimental Range (SJER) explained by beam radiance, compound topographic index (CTI), and weighted mean particle diameter (WMPD), by post-rainfall periods (PRP) and sensor depth. Partial variances sum to approximately the total variance explained by multiple regression.

**Fig. 8.** Partial variance in mean volumetric water content ($VWC$) at Sierra Foothill Research and Extension Center (SFREC) explained by beam radiance, compound topographic index (CTI), weighted mean particle diameter (WMPD), and canopy cover, by post-rainfall periods (PRPs) and sensor depth. Partial variances sum to approximately the total variance explained by multiple regression.
diance accounted for a greater proportion of the total variance explained in $\Delta VWC$ at 30 and 50 cm, as compared to their predictive capacity in terms of $VWC$. This may have been due to the fact that rates of soil moisture change at depth are somewhat “insulated” from processes that affect soil moisture utilization near the surface at the meter to centimeter scale (i.e., less predictable), and therefore are more likely to be controlled by gravitational gradients and possibly vegetation density operating over 10s to 100s of meters. Partial variance explained by WMPD was generally greatest (5–20%) during the winter-wet phase and the beginning of the spring dry-down phase. The WMPD was a relatively better predictor of partial variance in $\Delta VWC$ than $VWC$ at SJER. This suggests that post-rainfall dry-down rates ($\Delta VWC$) in these landscapes are more affected by differences in WMPD compared to post-rainfall average soil moisture ($\overline{VWC}$).

At SFREC, total explained variance in $\Delta VWC$ was greatest near the surface (10–35%), with the largest proportion of partial variance explained by canopy cover (Fig. 10). The greater importance of canopy cover at 10 and 30 cm may be related to differences in soil moisture utilization by understory vs. inter-canopy species (Jackson et al., 1990). Thicker A horizons, higher organic matter content, and larger structural units associated with soils found under tree canopies in this type of ecosystem coupled with an estimated 27% canopy interception rate (Dahlgren et al., 1997) likely contributed to variance explained by the canopy cover variable. Near the soil surface (10 cm), CTI accounted for a small amount (5–10%) of the total variance during the beginning of the wet-up phase (PRP 1) and end of the spring dry-down phase (PRP 7), whereas beam radiance accounted for 8 to 15% during the winter-wet phase (PRP 3 and 4). At 50 cm, CTI accounted for 5 to 20% of the total variance in $\Delta VWC$ during the end of the wet-up and for the duration of the winter-wet phases. The small shift in dominance from beam radiance near the soil surface (10 cm) to CTI at depth (50 cm), tracks expected dominance of processes affecting soil moisture redistribution: evapotranspiration demand near the surface and lateral flow at

![Figure 9](image-url)

**Fig. 9.** Partial variance in change in volumetric water content ($\Delta VWC$) at San Joaquin Experimental Range (SJER) explained by beam radiance, compound topographic index (CTI), and weighted mean particle diameter (WMPD), by post rainfall periods (PRPs) and sensor depth. Partial variances sum to approximately the total variance explained by multiple regression.

![Figure 10](image-url)

**Fig. 10.** Partial variance in the change in volumetric water content ($\Delta VWC$) at Sierra Foothill Research and Extension Center (SFREC) explained by beam radiance, compound topographic index (CTI), weighted mean particle diameter (WMPD), and canopy cover, by post rainfall periods (PRPs) and sensor depth. Partial variances sum to approximately the total variance explained by multiple regression.
depth (Western et al., 1999; Swarowsky et al., 2012). Proxies for effective precipitation (CTI) and microclimate (annual beam radiance) accounted for a larger proportion of explained variance in $\Delta VWC$, as compared with explained variance in $VWC$, while the opposite was true for WMPD.

As for SJER, CTI was a dominant explanatory variable for predicting soil moisture content in a semiarid catchment in the Coast Ranges of California (Chamran et al., 2002). These Coast Range soils closely resemble those of SJER in terms of degree of argillic horizon expression (weakly developed or completely absent). The diminished capacity of CTI to explain variance in soil water content at SFREC may be due to the presence of a well-developed argillic horizon, and its high degree of spatial variability within the watershed. These findings suggest that stratifying studies relative to catena types (e.g., degree of soil development and/or soil stratigraphic characteristics) may improve our understanding of which DEM derived proxies work best across a range of soil properties and landscape attributes.

**Further Investigation of Partial Effects at San Joaquin Experimental Range**

Partial effects were investigated at SJER to determine the intensity of changes and temporal variation in $VWC$ along gradients of CTI and modeled beam radiance. Partial effects were not examined at SFREC, due to the very small proportion of variance explained in $VWC$ by either CTI or modeled beam radiance. Interpretation of a partial effect on $VWC$ is based on the sign, magnitude, and standard error of the partial slope fit to a single predictor variable (e.g., CTI) within a multiple regression model, when all other predictor variables are held constant. Partial effects are presented in terms of a four unit change in CTI (roughly equivalent to moving from summit to backslope or backslope to swale position at SJER), and in terms of a 300 MJ/m$^2$ change in modeled beam radiance (roughly equivalent to moving from a north-facing to south-facing slope at SJER).

At 10 and 30 cm, the partial effect of CTI on $VWC$ at SJER was always positive (i.e., higher $VWC$ associated with larger values of CTI), significantly different than 0 in most PRPs, and generally increased in value over the course of the water year (Fig. 11). The partial effect of CTI on $VWC$ was strongest at 30 and 50 cm, however, confidence in the estimate of this effect was best at 10 cm. The sign of the partial effect of CTI follows soil moisture patterns suggested by the standard hillslope model: lower positions in the landscape (larger CTI) are significantly wetter than higher positions in the landscape (smaller CTI). In addition, the magnitude of this relationship was greatest during the spring dry-down phase (PRP 5, 6, 7) when inputs from precipitation were less frequent and the redistribution of soil moisture reflects recharge and discharge areas across the catenas. This effect was probably masked during the winter wet phase (PRP 3 and 4) due to the greater homogeneity of soil moisture caused by frequent rainfall. Observations from SJER suggest that soils found on backslope positions will have approximately 2% (absolute) greater $VWC$ compared to soils found on summit positions (i.e., a four unit increase in CTI) during the early winter wet-up phase, all else equal (Fig. 11). Similarly, a four unit change in CTI results in approximately 6 to 8% (absolute) greater $VWC$ during the spring dry-down phase, all else equal. While these partial effect sizes seem small, they are significant with respect to the range in $VWC$ within any given PRP. For example, at the 10-cm depth within PRP 1, the inter-quartile range of $VWC$ was approximately 3 to 5% compared to approximately 5 to 7% during PRP 7.

The partial effect of modeled beam radiance on $VWC$ at SJER was either negative or close to 0 at the 10-cm depth and not significantly different than 0 at 30- or 50-cm depths (Fig. 12). Temporal patterns in the magnitude and confidence in the partial effect of modeled beam radiance on $VWC$ mirror temporal patterns in partial explained variance (Fig. 7), with the strongest and most precise estimates during the early winter wet-up phase (PRP 1 and 2) at 10 cm, and during the last PRP (at all depths) associated with the spring dry-down phase. Observations from SJER suggest that in similar landscapes and within post-rainfall dry-down events, a change of 300 MJ/m$^2$ of beam radiation (i.e., moving from a north- to south-facing slope) will result in approximately 1 to 3% (absolute) lower $VWC$ at 10-cm depth (Fig. 12). While the magnitude of differences in soil moisture along gradients in modeled beam radiance (0–0.04 m$^3$/m$^3$ on north- vs. south-facing slopes at SJER) were slight, the cumulative effect is likely related to significant differentiation in soil-forming environments over time (Reid, 1973; Beaudette and O’Geen, 2009).

![Fig. 11. Partial effect of compound topographic index (CTI) on mean volumetric water content (VWC) at San Joaquin Experimental Range (SJER), with 95% confidence envelope (line segments). Units on the y axis represent the change in VWC expected for a four-unit increase in CTI, for each event. In landscapes similar to SJER, a four-unit increase in CTI represents moving from the summit to backslope position, or from backslope to swale position.](image-url)
CONCLUSIONS

After adjusting for differences due to water-holding capacity (using WMPD) and canopy cover, it was clear that spatial patterns in soil moisture and dry-down rates were more predictable in the more weakly developed granitic landscapes (SJER) as compared to the more highly developed metavolcanic landscapes (SFREC). No single terrain-shape index (GRAD, TCURV, PCURV, MCURV, PROM, TCI, and CTI) consistently accounted for the majority of variability in either \( \theta \) or \( \Delta \theta \), across depth or study site. However, at SJER, a combination of CTI and modeled beam radiance was able to consistently account for 30 to 70% of the total variance in \( \theta \) at 10 cm, and 10 to 40% at 30 and 50 cm. During the early winter wet-up and spring dry-down phases at SJER a combination of CTI and modeled beam radiance was able to consistently account for 30 to 60% of the total variance in \( \Delta \theta \) at all depths. The degree to which soil moisture dynamics were explained by a combination of terrain and microclimate proxies was better than most studies (generally <50% explained variance) at SJER, and not surprisingly low at SFREC given the complex patchwork of soils with argillic horizons that form perched water tables. It is likely that variation in soil depth and contact type (paralithic vs. lithic) within both landscapes reduced the precision of our approach to partitioning explained variance in \( \theta \) at depths of 50 cm.

Soil systems contain multiple, variably coupled, feedback mechanisms some of which simultaneously control (and are controlled by) soil moisture dynamics. Over geologic time scales, hillslope-scale differences in soil moisture affect pedogenic expression of soil properties and horizonation. In turn, differences in soil properties and horizonation alter the hydrologic behavior of the hillslope. Over seasonal and annual time scales, vegetation patterns adjust to favorable soil conditions; compounding the magnitude of spatial variability in soil moisture. In the less developed soils at SJER, soil stratigraphy and textural differences play a role in the redistribution of soil moisture resulting in spatial patterns that more closely match the scale of proxies used in this study. In the more highly developed soils at SFREC, the wide range in argillic horizon depth, thickness, and texture change, coupled with differences in vegetation density, likely had a strong impact on lateral and vertical redistribution of water; resulting in spatial patterns of soil moisture much smaller than the scale of our selected proxies. This study demonstrates that (within landscapes similar to the Sierra Foothill Region of California) the interpretation of DEM-derived proxies for soil moisture dynamics vary widely in time and space.

ACKNOWLEDGMENTS

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