Moisture Stress Indicators in Giant Sequoia Groves in the Southern Sierra Nevada of California, USA

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Giant sequoia [Sequoiadendron giganteum (Lindl.) J. Buchholz] trees and their ecosystems are unique natural treasures in the Sierra Nevada, California, where most groves are federally managed for biodiversity, perpetuation of the species, and aesthetic, recreational, ecological, and scientific values. Increasing temperatures during the next several decades may create conditions unfavorable for these giant sequoias. Therefore, it is necessary to develop effective management systems to preserve the health of these giant sequoia groves. This study used a topographic wetness index (TWI) as the indicator of soil moisture conditions to evaluate the vulnerability of giant sequoia groves to soil moisture stress and focused on evaluating TWI distributions among all 70 sequoia groves to assess their vulnerability to soil moisture stress. The TWI values were derived using a 10-m digital elevation model and compared with soil, geology, slope, aspect, and elevation at the sequoia groves to understand the vulnerability of the groves to soil moisture stress. The TWI values were also compared with snow cover persistence derived from 12 yr of MODIS snow cover products. In addition, satellite soil moisture products were used to compare the dry and wet periods predicted by snow cover persistence. Results showed that the groves located at higher elevation are less vulnerable unless the TWI across the groves is low. For the large number of groves with elevations mainly in the 1800- to 2100-m range, the TWI distributions can serve as a first-order indicator of relative vulnerability. Further, this analysis showed that areas with milder slopes and more converging area (higher TWI), plus longer snow cover persistence, should be less susceptible to low summer soil moisture than areas having steeper slopes, more diverging topography (lower TWI), and earlier snowmelt. This analysis can be used to highlight groves that are potentially more vulnerable, particularly when considering TWI, snow cover persistence, and satellite soil moisture together.

Core Ideas
- The vulnerability of giant sequoia groves to soil moisture stress was evaluated.
- Giant sequoia groves with a vulnerability to soil moisture were identified.
- A topographic wetness index (TWI) was used to study soil moisture stress of sequoia groves.
- The relationship between TWIs and snow distribution pattern was studied.
- Remotely sensed soil moisture, TWI, and snow cover persistence were compared.

The native habitat of the giant sequoia is in the Sierra Nevada, California (Willard, 1994). They are the largest trees on the planet and among the oldest, sometimes living for 3200 yr or longer (Stephenson, 1996; York et al., 2011), and are one of the best-known species of plants in the world today (Rundel, 1971). Although the ancient ancestors of the giant sequoia were widespread throughout the Northern Hemisphere during the Late Mesozoic period, climate change has restricted the native sequoia to the west slopes of the Sierra Nevada (Harvey, 1986).

Giant sequoias and their ecosystems are natural treasures unique to the Sierra Nevada. They are managed for biodiversity, perpetuation of the species, and aesthetic, recreational, ecological, and scientific values (Piirto and Rogers, 2002). Despite the numerous popular articles on the species, the biological and physical environments of the giant sequoia
groves are poorly understood (Rundel, 1971). In the southern Sierra Nevada, 70 giant sequoia groves stretch across two jurisdictions, including Sequoia and Kings Canyon National Parks (SEKI) and Sequoia National Forest/Giant Sequoia National Monument (SNF/GSNM) (York et al., 2013). Much of what is known about the sequoias comes from these southern groves. The challenges associated with the long-term preservation of giant sequoias have become increasingly complicated (Parsons, 1994). While they are a unique and significant part of the natural heritage of the region and even of the country, their existence may be threatened by climate change (Sydoriak et al., 2013).

According to a Natural Resources Condition Assessment, increasing temperatures during the next several decades will induce earlier snowmelt and will prolong summer droughts, which may create conditions unfavorable for giant sequoias (York et al., 2013). A direct effect could be a widespread and continuing failure in giant sequoia reproduction. Even in the presence of prescribed fires, giant sequoia seedlings are vulnerable to prolonged drought (Harvey et al., 1980; Mutch, 1994; Mutch and Swetnam, 1995).

Climate change studies predict that the temperature in the southern Sierra Nevada will increase. Effective drought will increase as snow melts earlier and evaporation increases due to a warmer climate. Changes in precipitation in the region are uncertain. Approximately half of the 18 general circulation models show a projected decrease, whereas the other half show a projected increase in total annual precipitation in this region (Gonzalez, 2012). Regardless of what occurs with precipitation due to climate change, sequoia regeneration and growth will be most affected by changes in the fire regime and water availability because adequate soil moisture is critical for regeneration and growth (Weatherspoon, 1990). Death rates might increase among adult sequoias and associated species as drought stress makes them more vulnerable to insects, pathogens, air pollution, and intense fires (Ferrell, 1996). To effectively and efficiently allocate management efforts to conserve giant sequoias, the vulnerability of giant sequoia groves must be evaluated.

Vegetation can be stressed from any disturbance that severely impacts the growth of the plant, such as insufficient water or nutrients, adverse climatic conditions, plant diseases, and insect damage (Jackson, 1986). There are several factors that affect a plant’s water stress. These include reduced soil moisture, increased canopy temperature and evapotranspiration, and reduced leaf water content, which influences the canopy moisture conditions (Blum, 2011).

Topography may influence vegetation patterns because only small changes in elevation may cause large differences in soil moisture (Okland et al., 2008; Moeslund et al., 2013). The relationships among topographic gradients, aspects, and topographic wetness indices are very important in order to understand the vegetation pattern of any watershed. Topographically controlled soil moisture is a primary candidate in controlling plant diversity patterns (Moeslund et al., 2013). Topography affects patterns of temperature, radiation, and wind on a local scale, which ultimately affects the spatial patterns of vegetation.

Soil moisture is highly variable in space and time and difficult to measure in mountain watersheds. An alternative method to measure soil moisture distribution is the topographic wetness index (TWI). The TWI, a commonly used indicator for locating soil moisture storage and/or soil water stress on a landscape, is widely used to simulate soil moisture wetness states in a watershed (Beven and Kirkby, 1979; Lin et al., 2006; Grabs et al., 2009; Ali et al., 2013). Soil moisture is a critical hydrologic variable used to determine if a catchment is characterized as being in a dry or wet state (Ambroise, 2004; Ali et al., 2010). A region with high TWI values in a catchment tends to saturate first and therefore indicates potential surface or subsurface contributing areas (Christopher et al., 2008). Thus, there is a strong correlation between TWI and wetting–drying cycles.

While TWI patterns can be used as a first-order estimate of soil moisture distribution, there are other features, e.g., vegetation, topography, and soil properties, that also control soil moisture distributions, so correlations between TWI and actual soil wetness or zones of surface saturation can give mixed results (Lin et al., 2006), and predicting the spatial distribution of soil moisture accurately can still be a challenge. However, the TWI can be used to predict approximate relative soil moisture patterns (Buchanan et al., 2014). Further, Buchanan et al. (2014) found a moderate correlation between TWIs and observed soil moisture patterns, whereas Tague et al. (2010) revealed that mean soil moisture closely follows a linear trend with TWIs at the plot scale.

Many researchers have recognized a strong link between soil moisture and photosynthetic capacity and tree growth (Hernández-Santana et al., 2008; Wang et al., 2012; Anning and McCarthy, 2013; Anning et al., 2014). For example, Wang et al. (2013) and Gouveia et al. (2009) identified the TWI as having the most explanatory power for explaining spatial variations in the normalized difference vegetation index (NDVI) and a useful indicator to study vegetation heterogeneity across landscapes.

Grabs et al. (2009) found TWI to be a widely used tool to describe wetness conditions at the catchment scale. However, since it is derived with an assumption that groundwater gradients are equal to surface gradients, they suggested deriving modeled soil moisture wetness indices to identify spatial patterns of wet and dry areas in catchments. It appears that very few studies have investigated the relationship between TWI and giant sequoia groves in the southern Sierra Nevada (Halpin, 1995; Beaty and Taylor, 2001).

Beaty and Taylor (2001) used a topographic relative moisture index to study spatial and temporal variations in fire regimes in a mixed
conifer forest landscape, including a giant sequoia community. Halpin (1995) identified 75 sequoia groves within the vicinity of SEKI. However, there were no intercomparison analyses of the TWI for the 75 groves. He reported the TWI in detail only at the Log Creek catchment, a 49-ha subarea within the larger 970-ha Giant Forest grove. As far as known, few if any studies exist that have investigated the soil moisture or wetness distributions among groves that can aid in understanding their vulnerability to soil moisture under a changing climate.

Because the TWI is based solely on topography, the estimated TWI values are considered static and remain unchanged even if temperature and precipitation change (Dyer, 2009; Temimi et al., 2010). Therefore, TWI values are unable to capture the temporal variability of soil moisture (Temimi et al., 2010). Because the TWI has such limitations, it is important to compare the static TWI with other static topographic features (e.g., elevation, slope, aspect) and dynamic hydrologic variables (e.g., snow, soil moisture) to understand the spatial and temporal distribution of soil wetness.

Because this study region did not have any in situ soil moisture data, it was necessary to use available satellite snow cover persistence and soil moisture data to evaluate the TWI-based approach to understand soil moisture vulnerability of the sequoia groves. Snow processes are important in this study region because it is dominated by snow. Also, soil moisture, in this region, is linked to rain and snowmelt patterns, and snowmelt has a most important dynamic control on soil moisture (Bales et al., 2011; Blankinship et al., 2014). Therefore, in this study, snow cover persistence was used to predict moisture states.

This study focused on evaluating TWI distributions among all 70 sequoia groves and compared digital elevation model (DEM)-derived TWIs at small to large groves by area to identify wet and dry sequoia groves to assess the vulnerability of these groves to soil moisture or water stress. This study sought to improve the methodologies for understanding the interactions between soil moisture storage, topographic features, and snow in identifying the relationship between soil moisture and vegetation (the sequoia groves in this study) patterns. The sequoias require relatively higher soil moisture; the distribution of sequoias at lower elevations is limited mainly by deficient soil moisture during the growing season (Weatherspoon, 1990).

By correlating TWI maps with snow distributions, satellite soil moisture, and topographic features such as slope, elevation, aspect, etc., at sequoia groves in the southern Sierra Nevada, California, this study addressed four key research questions:

1. Does the TWI provide reasonable estimates of the soil moisture distribution in the southern Sierra Nevada mountain range?

2. Are all of the sequoia groves equally vulnerable to soil moisture stress?

3. Can the TWI be used to study the soil moisture vulnerability of sequoia groves?

4. Is there a relationship between dynamic snow and soil moisture distribution patterns and static TWIs?

Materials and Methods

Study Area

This study included 70 giant sequoia groves in the southern Sierra Nevada of California (Fig. 1). About 75 giant sequoia groves have been identified in the literature (e.g., Rundel, 1972; Willard, 1994; Parsons, 1994; Stephenson, 1996; Piirto and Rogers, 2002), except York et al. (2011), who listed only 67 groves. In this study, the 75 giant sequoia groves were regrouped into 70 giant sequoia groves to eliminate identical names in the west of the southern Sierra Nevada.

First, a study region was selected to cover the 70 sequoia groves (Fig. 1c). These groves are found only within a 420-km-long, 15-km-wide strip along the southwestern Sierra Nevada, within elevations of 1400 to 2150 m (Harvey et al., 1980). The areas of the individual groves range from 0.01 to 15.51 km² (Table 1). The total grove area is about 150 km², with the six largest groves accounting for half of the area (Mountain Home, Converse, Redwood Mountain, Evans, Belknap, and Giant Forest) and the smallest two thirds of the groves making up only 10% of the total grove area.

Climate

Giant sequoia groves within the study area have warm, dry summers and cool, wet winters; most of the precipitation falls in the form of snow in the winter between October and April (Weatherspoon, 1990; Knigge, 1994; Meyer and Safford, 2011). Based on 14 yr of precipitation data (2001–2014), the mean annual precipitation was 96 cm at Grant Grove, 68 cm at Wolverton, and 58 cm at Johnstown meteorological stations, located at the northern, middle, and southern parts of the sequoia study region (Fig. 1c), respectively. Precipitation decreases from north to south in the sequoia study region. Recent prolonged drought has reduced the annual precipitation average since 2005. The prior annual precipitation average was 107 cm at Grant Grove (York et al., 2011). Temperature ranges were variable across the range of giant sequoia, keeping with the Mediterranean climate, with cool, wet winters and warm to hot, dry summers. Weather records are lacking for most groves, but the indication is that average summer highs are approximately 29°C (84°F), with extreme high temperatures reaching 40°C (104°F). Average winter lows are −5°C (25°F) and extreme lows can reach −24°C (−12°F) (Rundel, 1969; Weatherspoon, 1986).

Because Wolverton National Climatic Data Center (NCDC) station is located in the middle of the sequoia study region, this station was selected to analyze the distribution of annual and monthly precipitation and maximum and minimum
temperatures. Figure 2a shows an annual plot of precipitation and maximum and minimum temperatures for the entire study period (2001–2014). The plot shows variations of precipitation in dry and wet years during the study period. Following the dry water years (WYs) of 2007 to 2009, WY 2010 was wetter than average; however, a continuous falling trend of annual precipitation was observed from 2011 to 2014.

Although significant variations in maximum and minimum temperatures between dry and wet years were not observed, higher maximum temperatures were noted in dry years. For example, the observed annual maximum temperature in WYs 2013 (dry year) and 2006 (wet year) were 38.3 and 36.1°C, respectively. Figure 2b shows a comparison of monthly precipitation and maximum and minimum temperatures for selected dry (2013) and wet (2006) WYs. Significant differences in monthly precipitation and moderate variations in monthly maximum and minimum temperatures were observed for dry and wet years. The wet year 2006 received 214% more rain and snow than the dry year 2013, whereas WY 2013 was about 2.2°C warmer than WY 2006.

During both dry and wet years, there was little rainfall from May to October, predictably making summer the driest time of the year. The sequoias had to cope with a drop in soil moisture from June through October. Soil moisture during this period was often dependent on melting snow either onsite or uphill. Warmer annual temperatures, including those associated with climate change, will reduce the snowpack and will prolong the low soil moisture period (Cayan et al., 2010). Any vegetation, including giant sequoias, could have considerable moisture stress, primarily during the dry years. However, not necessarily all vegetation would be equally stressed because the soil moisture distribution is controlled by topography under similar climatic conditions.

Soil

The soil bedrock is hard in the upper reaches of the basin (>2000 m), where glaciers scoured the parent material approximately 18,000 yr ago (Bales et al., 2011). Relatively shallow and rocky soils support most of the trees, whereas some large trees are vigorous due to the availability of groundwater percolating through weathered saprolite (Weatherspoon, 1990; Bales et al., 2011). Although soils of sequoia groves are derived from a variety of rock types, most groves are on granitic-based residual and alluvial soils and glacial outwash from granite (Fig. 3a). This study region is dominated by granodiorite, a class of igneous rocks that are commonly but inaccurately known as granites. However,
granodiorite is intermediate between granite and quartz diorite and contains more than 20% quartz (Staack, 1938). About 85% of sequoia groves are on granodiorite and only 13% of them are on schist rock.

Giant sequoia trees grow best in deep and well-drained sandy loams (Weatherspoon, 1990). The STATSGO soil map consists of 11 soil layers. A soil map with a single layer (surface soil layer) was developed based on the common or majority of soil textures in the 11 soil layers (Fig. 3b). The maximum soil depth in sequoia groves was 150 cm. The STATSGO soil depths support the depths used by previous studies (e.g., Halpin, 1995; Rundel, 1969, 1971; Hartesveldt et al., 1975; Harvey et al., 1980; Huntington et al., 1985; Riegel et al., 1988).

<table>
<thead>
<tr>
<th>Grove</th>
<th>TWI</th>
<th>Slope</th>
<th>Elevation</th>
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<tr>
<td></td>
<td>Area</td>
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<td>Max.</td>
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<td>Putnamfrancis</td>
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<td>5.69</td>
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<tr>
<td>Squirrel Crk</td>
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<tr>
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<td>6.36</td>
<td>12.20</td>
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<tr>
<td>Cunningham</td>
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<td>5.80</td>
<td>20.68</td>
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<td>Lower Hrs Crk</td>
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<td>0.10</td>
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<tr>
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<td>Bigtump</td>
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<td>Midl Tu le</td>
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<td>Redwdmtt</td>
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<tr>
<td>Mt Home</td>
<td>15.51</td>
<td>4.74</td>
<td>23.08</td>
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The majority of sequoia groves (77%) grow on sandy loam textured soil (Fig. 3b). Soil textures play an important role in soil moisture storage or the water holding capacity of a soil, but the depth of the soil does not indicate relative water storage. The deeper soil strata account for a significant fraction of water used by forest vegetation in the southern Sierra Nevada mixed-conifer forests (Arkley, 1981; Rossi and Graham, 2010).

Vegetation
Giant sequoia groves account for approximately 55 to 75% of the total basal area and about 10% of the total trees (Piirto and Rogers, 2002). Vegetation in each grove is mixed conifer (York et al., 2011). Typically, the relative density of giant sequoia is about 5%, and the dominant species in the giant sequoia groves is white fir \( (\text{Abies concolor} \text{ (Gordon & Glend.) Lindl. ex Hildebr.}) \) (Rundel, 1971). Other common associates include sugar pine \( (\text{Pinus lambertiana} \text{ Douglas}) \), Ponderosa pine \( (P. \text{ ponderosa} \text{ P. Lawson & C. Lawson}) \), incense cedar \( (\text{Calocedrus decurrens} \text{ (Torr.) Florin}) \), black oak \( (\text{Quercus kelloggii} \text{ Newb}) \), and often Douglas-fir \( (\text{Pseudotsuga menziesii} \text{ (Mirb.) Franco}) \), red fir \( (\text{Abies magnifica} \text{ A. Murray bis}) \), and/or Jeffrey pine \( (\text{Pinus jeffreyi} \text{ A. Murray bis et al.}) \) (Harvey et al., 1980; Meyer and Safford, 2011). Uncommon associates in the mid-story include Pacific dogwood \( (\text{Cornus nuttallii} \text{ Audubon}) \), canyon live oak \( (\text{Q. chrysolepis} \text{ Liebm}) \), Scouler’s willow \( (\text{Salix scouleriana} \text{ Barratt ex. Hook}) \), and California nutmeg \( (\text{Torreya californica} \text{ Torr.}) \) (Meyer and

Fig. 2. Variations in precipitation and temperature at Wolverton National Climatic Data Center station located in the middle of the sequoia study region: (a) annual total precipitation (Precip), annual maximum (Tmax) and minimum temperature (Tmin) from 2001 to 2014; and (b) monthly precipitation and maximum and minimum temperature for selected wet and dry water years (WY) 2006 and 2013, respectively.
Safford, 2011). The combination and frequency of those dominant, common, and uncommon associates in any grove depends on elevation, latitude, exposure, soil moisture, and the length of time it has been afforded protection from lumbering and fire (Harvey et al., 1980).

A majority of the sequoia groves have conifer and mixed-conifer land-cover types, while some of the sequoia groves are very close to the hardwood forest and shrub land cover (Fig. 3c). Mixed conifer and conifer cover about 60% of the sequoia study region, with one to five vegetation types within each sequoia grove. For example, Redwood Mountain sequoia grove has five types of vegetation: herbaceous rangeland, shrub and brush rangeland, mixed conifer, conifer, and hardwood.

**Wetness Index: Theory**

The wetness index is based on the assumption that topography is the controlling factor for groundwater, surface water, and flow paths. In many cases, there are other factors, such as soil and hydrologic characteristics, that control groundwater and flow paths (Grabs et al., 2009). The TWI is defined as the upslope area per unit contour length divided by the local slope (Fig. 4a ). The TWI is a measure of the potential for a landscape to hold water based on its surface characteristics. It is calculated as a measure of the slope within a catchment area. The TWI is smallest in areas with steep slopes and diverging topography and highest in areas where water pools, areas with milder slopes, and converging topography. The TWI is a proxy for actual soil moisture at the landscape scale. As a proxy for soil moisture, it may be confounded when surface topographic characteristics do not reflect the subsurface terrain. Cracks, fissures, and other subsurface features may pool water. Therefore, sequoia roots may have access to water in these areas, although they are typically shallow. Roots may extend laterally a significant distance, adding some uncertainty in pinpointing where water uptake occurs.

The TWI integrates topographical information to capture the hydrologic variation in soil water content. The applied approach developed by Beven and Kirkby (1979) to calculate TWI is

$$\text{TWI} = \ln \left( \frac{A_s}{\tan \beta} \right)$$

[1]
where $A_s$ is the specific catchment area and $b$ is the local slope angle in degrees. When flow accumulation is multiplied by cell area, it refers to the contributing area. According to the TWI concept, the soil moisture and groundwater level of a location are the result of the accumulated upslope area, $A$ (Fig. 4a), and the drainage expressed as the slope, $\tan b$. Many researchers have used the TWI to spatially estimate hydrological, physical, and chemical properties of soils (Seibert et al., 2007; Ali et al., 2013).

For flow direction, the $D_\infty$ algorithm was used, which deals with flow convergence as well as flow divergence when used in combination with slope, and routes water to one or two neighboring cells determined by the greatest slope (Lang et al., 2013; Ågren et al., 2014). If the flow direction of the greatest descent leads directly to a single pixel, water is routed to that pixel; if the flow direction is situated between pixels, water flow is proportioned between the two pixels based on how close the angle is to the adjacent pixels (Tarboton, 1997).

**Data Analysis**

This study used higher resolution DEM data for the sequoia groves regions. A 10-m DEM was obtained from SEKI and used to derive the TWI. A soil database was obtained from STATSGO (http://soils.usda.gov/survey/geography/statsgo/). The daily precipitation and maximum and minimum temperatures were obtained from the NCDC for the selected meteorological stations; Wolverton is located at an elevation of 1600 m (2001–2014).

Topographic wetness index maps were developed for SEKI and SNF/GSNM at the watershed scale, covering 70 sequoia groves, and compared with static variables such as geology, aspect, and soil type. All DEM processing was done using ArcGIS 10.2 modeling tools and TauDEM 5.0 (Tarboton, 1997). A 10-m DEM was used to derive slope, specific catchment area, and aspect of the study region.

The flowchart in Fig. 4b shows the major processes used for estimating and evaluating the TWI. Further details about the major processes are included below. Elevation, slope, and aspect maps were compared with the TWI map to understand the variations in soil-moisture wetness. The improved approach was used in the current analysis to classify aspect into shady slope, sunny slope, and semi-shady and semi-sunny slopes, considering more southerly aspects to be sunny and more northerly aspects to be shady (Ma et al., 2010). For example, the soil-moisture content of a shady slope is expected to be greater than a sunny slope; however, it is necessary to analyze whether TWI values differ on shady vs. sunny slopes. For equal values of $A_s$, TWI decreases with local slope angle.

In addition, the TWI was compared with the snow cover persistence to evaluate the relationship between high or low TWI values vs. high or low snow cover persistence within the sequoia groves. A 500-m Moderate Resolution Imaging Spectroradiometer (MODIS) fractional snow cover product was used to generate 12 yr (2000–2011) of snow cover persistence maps for first day of each month from March to June (Painter et al., 2009; Rice et al., 2011). The index (0–12) of snow cover persistence is the number of years during which each pixel had >20% snow cover on the first day of that particular month. For example, a pixel value of 4 for 1 March shows that there was snow cover at least 4 of the 12 yr.

Because in situ soil moisture measurements were not available, daily Advanced Microwave Scanning Radiometer-EOS (AMSR-E) and Soil Moisture Active and Passive (SMAP) soil moisture products were used to study the temporal distribution of soil moisture at four selected meteorological stations (Fig. 1). An effort was made to develop a continuous time series of satellite soil moisture measurements from 2003 to 2015; however, because 80% of Soil Moisture and Ocean Salinity (SMOS) soil moisture measurements were missing during the drought periods (2012–2014) in the study region, analysis using SMOS soil moisture measurements (2012–2014) were not included in this study. Only AMSR-E and SMAP soil moisture measurements were used in this study. Because AMSR-E and SMAP soil moisture observations were also missing on a significant number of days, a weekly moving average
soil moisture was calculated for each date by averaging that day’s soil moisture with that of the six preceding days. This study used AMSR-E soil moisture Level 3 products (2003–2011) and SMAP soil moisture Level 3 products (April 2015–January 2016) on a daily basis. Both AMSR-E and SMAP Level 3 soil moisture products were obtained from the NASA Earth Observing System Data Gateway through the National Snow and Ice Data Center.

Results

This study developed an approach to analyze the soil moisture distribution and state of soil moisture stress at giant sequoia groves in the southern Sierra Nevada, California. Although DEM-derived TWI values were compared at all 70 giant sequoia groves, this study mainly focused on 25% of the largest and 25% of the smallest giant sequoia groves by area to study giant sequoia vulnerability to soil moisture stress. These two groups were determined by considering only 25% of the giant sequoia groves ranked smallest to largest by area from the total of 70 giant sequoia groves.

Topographic Wetness Index

Results showed a range of TWI values both across and within groves (Fig. 5). In general, the differences among mean TWI values across groves were relatively small compared with the range of TWI values within each grove. This was in contrast to slope, which showed significant differences across the 70 groves. Figure 5 shows only one grove with a mean TWI below 7.5 and also few groves with a TWI above 9.2. In addition, most of the groves had mean TWI values in the range of 8 to 9, with standard deviations on the order of ±2, or well within the range of 6 to 11.

The difference in TWI among groves may still be important in distinguishing groves with a higher vs. lower potential for soil moisture stress. Assuming that water drainage follows topography, each sequoia grove can be less vulnerable to soil moisture stress at converging areas and more vulnerable at diverging areas. The highest TWI values were in 11 small, relatively less steep groves, plus two medium-sized groves (Redwood Meadow and Long Meadow), with Giant Forest having the highest mean TWI of the large groves (9.0).

Similarly, the lowest TWI values were found in seven small, steeper groves, with values below 7.6. Of the larger groves, Black Mountain (8.0 km², 1894 m) had a mean TWI of 8.1 and Evan (12.8 km², 2012 m) had a mean TWI of 8.3. Seventy percent of the groves (49), comprising 82% of the total grove area, had mean TWI values between 6.7 and 8.8. In this range, there was also little difference in the standard deviations, going from a TWI of just under 6 to just over 10. The TWI ranges (Table 1) are skewed much more toward high than low values. Figure 6 depicts the actual distributions of TWI values for three selected categories of groves by area: small (<10 ha), medium (30–100 ha), and large (>500 ha). Analysis shows that smaller groves have the most variability in TWI.

This study also examined within-grove and cross-grove TWI variability from smaller to larger groves; TWI distributions tended to match with the aggregate area. There are both smaller groves and smaller areas within larger groves with low TWI that thus are potentially vulnerable to soil moisture. Further analysis may be necessary at the grove level to identify vulnerable regions because of the larger within-grove variability compared with variability among groves.

The maximum TWI among groves potentially indicated where the wettest areas would be expected. Fewer than 11 small groves had maximum TWI values <15, suggesting that most groves should have some wetter areas (Fig. 7). Further analysis showed that 58% of the grove area had maximum TWI values between 20 and 27. Moreover, a majority of the groves of comparatively larger area (>5 km²) had maximum TWI values >22. This indicates, in general, that larger groves have higher maximum TWI values than smaller groves. For example, Belknap and Redwood Mountain (9.5 and 13.2 km²) had maximum TWI values >26, whereas West Redwood Mountain, Clough, and Douglass (0.01 km²) had maximum TWI values <12.

Comparing all the TWI values in the domain studied, it appears that the groves do generally have higher TWI values than the
Fig. 6. Distribution of topographic wetness index (TWI) values for (a) small groves (<10 ha), (b) medium groves (30–100 ha), and (c) large groves (>500 ha).
surrounding area (Fig. 8). The mean value for the grove area is 8.3 vs. 7.8 for a random sample of pixels in the surrounding area with the same overall elevation distribution as the grove area. Ten random samples were selected from the full non-grove domain, with the same result.

**Elevation, Slope, Aspect, and Topographic Wetness Index**

Figure 9 depicts box plots of mean TWI, slope, and elevation. Results show that medians for TWI, slope, and elevation are 8.5, 22.6°, and 1900 m, respectively. The lower and upper quartiles for TWI, slope, and elevation are 8.35 and 9.0, 17.8 and 27.4°, and 1780 and 1990 m, respectively. Groves with a higher TWI tend to have lower slopes, whereas those with a lower TWI tend to have steeper slopes, as expected from Eq. [1] (Fig. 10). The mean TWI of the total grove area, i.e., aggregating all grove areas together in one analysis, is about 8.3. About 40% of the total grove area is <8.0, but only 10% has a value <7.0. Nearly 70% of the grove area has a TWI >9.0, with 88% having a TWI >10. Some of the high-TWI areas include stream channels and probably also meadows.

Figure 10 compares the mean slope and elevation and TWI maximum values of the 25% smallest and 25% largest sequoia groves ranked by area. Results showed increasing and decreasing trends of
elevation and slope, respectively, with increasing area of sequoia grove. The rate of increment of TWI values and elevation were somewhat consistent with the increasing area of the groves. Analysis showed that not all larger groves are growing only at higher elevations and not all smaller groves are on steeper slopes. For example, Dennison, a smaller grove, grows at a mean elevation of 2345 m, whereas Middle Tule, a larger grove, grows at a mean slope of 21.6°. However, on average, the majority of smaller groves grow along the steep slopes and have lower TWI values, while the majority of larger groves grow at higher elevation with higher TWI values. Further investigation into individual smaller or larger groves is required to understand the vulnerability to soil moisture, but smaller groves growing on steep slopes are probably vulnerable to soil moisture stress.

A general aspect map was derived from a 10-m DEM, which did not provide any relationships or links with TWI values. No relationship was expected. To investigate this further, the aspects were classified into shady slope, sunny slope, and semi-shady and semi-sunny slopes following Ma et al. (2010) (Table 2). There were also no clear patterns of TWI variations on shady slopes vs. sunny slopes. It should be noted that TWI values are based entirely on topography, i.e., converging and diverging areas, and thus are not expected to depend on aspect. However, direct sunlight on south-facing slopes may require more soil water to meet evaporative demands (Anning et al., 2014; Lambers et al., 2008, p. 321–374). Note that sunny and shady slopes refer to more southerly vs. northerly faces, respectively. Moreover, when five smaller and larger groves on sunny vs. shady slopes were compared, the five selected larger groves had more shady areas than sunny areas, whereas four out of the five smaller groves had more sunny areas than shady areas. This is consistent with the previous discussion that smaller groves are more vulnerable to soil moisture stress (Fig. 11).

Although it is not clear how much more moisture is available for plants on north-facing (shady) slopes than south-facing (sunny) slopes, it is clear that south-facing slopes retain less soil moisture than north-facing slopes. These findings are consistent with the work of Dyer (2009), who found the highest rates of evapotranspiration on south-facing slopes, followed by north-facing slopes. South-facing slopes support drought-resistant vegetation, whereas north-facing slopes support moisture-loving plants (Måren et al., 2015). Therefore, slope or aspect has a strong influence on plant diversity and spatial distribution (Zeng et al., 2014).

**Digital-Elevation-Model-Derived Topographic Wetness Index and Snow Cover Persistence**

Figure 12 shows snow cover persistence maps at sequoia groves for a 12-yr period (2000–2011) for the first of each month for March and April along with a map of the maximum TWI values.
Because the TWI is based on topography alone, the derived values are considered static. The TWI is not directly comparable to the dynamic snow cover distributions; however, a dynamic approach can also identify wet and dry locations in the study region. The distribution of TWI maximum values have fair agreement with the snow cover persistence of 1 March (wetter month), which suggests that areas with longer snow cover persistence tend to have a higher TWI, and therefore it is consistent with the statement of Lin et al. (2006) that “topography becomes increasingly important in wet periods, but during dry periods soil moisture patterns depend primarily on soil properties.” This could indicate that a combination of these two factors, snow cover and TWI, may be associated with lower vs. higher vulnerability to soil moisture stress. The majority of the groves consistently have some snow presence on 1 March and 1 April, with differences appearing later in spring.

Figure 13 depicts the mean snow cover persistence for first day of 4 mo: March, April, May, and June. As expected, it was clear that snow persistence decreased from March to June. Snow cover persistence did vary among groves in the same month. When snow started to melt, some groves also started to lose snow cover on the ground, which continued until June. However, some of the groves had snow cover even in June. During the months of March and April, snow cover persistence showed a correlation with elevation above 1800 m or more, whereas little or no correlation was found for elevations lower than 1800 m (Fig. 14). However, factors other than elevation may also influence snow cover persistence, e.g., aspect, canopy cover, and radiation, especially during snowmelt.

Remote Sensed Soil Moisture

Because this study region did not have in situ soil moisture observations, remotely sensed soil moisture was used to compare with snow cover persistence to identify the wet and dry periods of the years and evaluate the DEM-derived TWI values. Figures 15 and 16 show weekly moving average values of AMSR-E soil moisture for 9 yr (1 Jan. 2003–3 Oct. 2011) and SMAP soil moisture for 2015 at four selected meteorological stations. The plots clearly show daily and seasonal variations of wetness and dryness. While the results showed only 8 and 18% ranges in annual soil moisture variations observed by AMSR-E and SMAP, respectively, the observed variations were adequate to identify the timing of relatively high soil moisture. Seasonal trends showed that soil moisture increased from December to late May each year, mainly during the snow season. However, the AMSR-E and SMAP predicted dry periods slightly different from each other, which could be due to different study years or some other factors beyond the scope of this study.

Both AMSR-E and SMAP identified Wolverton meteorological station, which is located in the middle of the sequoia region, as wetter and Shadequarter, which is located out of the sequoia grove, as drier compared with other locations. The

Table 2. The calculated topographic wetness index (TWI) values based on reclassified aspect.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Area (km²)</th>
<th>TWI Min.</th>
<th>TWI Max.</th>
<th>TWI Range</th>
<th>TWI Mean</th>
<th>TWI SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shady slope (0–67.5°)</td>
<td>26</td>
<td>4.33</td>
<td>26.79</td>
<td>22.47</td>
<td>8.43</td>
<td>1.77</td>
</tr>
<tr>
<td>Semi-shady slope (67.5–112.5°)</td>
<td>15</td>
<td>4.38</td>
<td>27.11</td>
<td>22.73</td>
<td>8.45</td>
<td>1.61</td>
</tr>
<tr>
<td>Sunny slope (112.5–247.5°)</td>
<td>45</td>
<td>4.29</td>
<td>27.12</td>
<td>22.83</td>
<td>8.68</td>
<td>1.77</td>
</tr>
<tr>
<td>Semi-sunny slope (247.5–292.5°)</td>
<td>25</td>
<td>4.31</td>
<td>27.12</td>
<td>22.81</td>
<td>8.66</td>
<td>1.74</td>
</tr>
<tr>
<td>Shady slope 1 (292.5–360°)</td>
<td>36</td>
<td>4.29</td>
<td>27.12</td>
<td>22.83</td>
<td>8.44</td>
<td>1.67</td>
</tr>
</tbody>
</table>
rising trend in soil moisture corresponded to periods of snow accumulation and snowmelt in this region. In addition, the observed dry period at each location was slightly different because each location had slightly different snow accumulation and snowmelt periods.

It is important to note that both snow cover persistence and satellite soil moisture distribution analysis showed consistent dry and wet periods in this region. Analysis showed that these findings were consistent with those of Buchanan et al. (2014) and Lin et al. (2006), who compared TWIs with observed soil moisture patterns and found a moderate correlation between them.

Discussion

The primary research objectives were clearly addressed by comparing TWI maps with snow distributions, satellite soil moisture, and topographic features at sequoia groves in the southern Sierra Nevada, California. The TWI can differentiate dry and wet zones, which can directly be linked with the dry and wet areas of sequoia groves. It can also be used to reproduce spatial patterns of wetness areas. However, the TWI alone cannot be used to identify relative water storage in the subsurface. It was found that the TWI is smallest in areas with steep slopes and diverging topography and highest in areas with milder slopes and converging topography. Because water drainage follows topography, each sequoia grove can be less vulnerable to soil moisture stress at converging areas and more vulnerable at diverging areas.
Soil depth does not indicate relative water storage because strata deeper than mapped soils account for a significant fraction of water used by forest vegetation and streamflow in the southern Sierra Nevada mixed-conifer forests (Arkley, 1981; Rossi and Graham, 2010; Bales et al., 2011).

The current analysis did not include the giant sequoia location relative to low vs. high TWI values, but it is apparent that most groves have areas with variable TWIs. While some areas were in or near stream channels and meadows, others were on hillslopes with higher TWIs. It is probable that sequoia groves at lower elevations that lack significant areas with high TWIs are most vulnerable to moisture stress. While steepness is a general indicator, the TWI is expected to be a better indicator of moisture stress. Groves located at higher elevation should be considered less vulnerable, unless the TWI across the groves is low. For the large number of groves with elevations mainly in the 1800- to 2100-m range, the distribution of TWI values, or possibly the mean plus one standard deviation, can serve as a first-order indicator of relative vulnerability.

Snow cover persistence provides added information beyond what a topographic index can provide. It is an index of how late in the year soil moisture will remain high. This is clearly illustrated by Fig. 13, 15, and 16, where soil moisture remains high until snow is melted across the basin, followed by about a 3-mo recession, which is consistent with the findings of Bales et al. (2011). The reduced snowpack means less snowmelt will be available in the summer drought typical of a Mediterranean climate. This will change the hydrology and increase the...
Fig. 15. Weekly moving average values of Advanced Microwave Scanning Radiometer-EOS (AMSR-E) soil moisture at four selected meteorological stations from 2003 to 2011 (inset for 2010).

Fig. 16. Weekly moving average values of Soil Moisture Active and Passive (SMAP) soil moisture at four selected meteorological stations from March to December 2015 (elevations: Johnsondale = 1433 m; Giant Grove = 2012 m; Wolverton = 1597 m; and Shadequarter = 1240 m).
probability that plants will experience water deficit during the growing season.

Interpreting the results of this study with relation to the vulnerability of giant sequoias to moisture stress was difficult because in situ measurements of soil moisture were not available to validate the proxies measured. It is noted here that the TWI is a proxy for actual soil moisture at the landscape scale. Thus, the use of AMSR-E and SMAP time series soil moisture distributions provided some insights on the proxies used and were good indicators of moisture stress in SEKI soils and giant sequoia canopies. However, because satellite soil moisture measurements were available at coarser scales (25–36 km), spatial correlation was not studied. Satellite soil moisture identified the driest and wettest periods of the year that were consistent with the snow accumulation and snowmelt in this region. In the Mediterranean climate of California, there is little rainfall between May and October. Hence the summer is predictably the driest time of the year and sequoias have to cope with soil moisture drops from June through October. Soil moisture during this period is often dependent on melting snow either onsite or uphill. Warmer annual temperatures, including those associated with climate change, reduce the snowpack and lengthen this low soil moisture period.

Overall, the TWI is not directly comparable to dynamic snow cover and satellite soil moisture distributions. However, analysis showed that distribution of TWI maximum values had fair agreement with the snow cover persistence of 1 March (a wetter month). Also, satellite soil moisture and snow cover persistence had good agreement in identifying the driest and the wettest periods of the year. Therefore, it showed fair to good relationships between the static TWI and dynamic snow cover persistence and satellite soil moisture.

Conclusions

This analysis found that the TWI and snow persistence may differ among groves. The TWI also had significant variability within each grove. This distinction provided a basis for identifying potential sequoia groves that were more or less vulnerable to soil moisture stress. This is based on the assumptions that areas with milder slopes and more converging area (higher TWI), plus longer snow persistence, would be less susceptible to low summer soil moisture than areas having steeper slopes and more diverging topography (lower TWI) along with earlier snowmelt.

Snow cover persistence supported by satellite soil moisture was an excellent complement to TWI, as it was a readily available index of dynamic moisture availability. It was most useful at both grove and non-grove areas and should be used in conjunction with regional precipitation and meteorological data. It has a distinct advantage over precipitation data because it is measured on site vs. extrapolated from a measurement site based on topography. It should be emphasized that although topographic water availability and snow persistence supported by satellite soil moisture showed some important distinctions among groves, across the landscape, and among hillslope-scale areas within groves, this study did not validate its ability to predict moisture stress through the use of more-direct measures such as in situ soil moisture, deeper moisture storage, or evapotranspiration. The current analysis can be used to highlight groves potentially more vulnerable, particularly when considering TWI, snow persistence, and satellite soil moisture distribution together, but it should be a starting point, not an ending point for informing resource-management actions to reduce stress in specific areas. Thus, the TWI can help to identify areas potentially vulnerable to moisture stress, although it is not a sufficient indicator of water stress. For example, soil water storage also depends on the depth of properties of the subsurface media.

In continuing this analysis and planning resource-management activities, it should be assumed that lower elevation sequoia groves that lack significant areas with high TWI are most vulnerable to moisture stress. While steepness is a general indicator, the TWI is expected to be a better indicator of moisture stress in this case. Higher elevation groves should be considered less vulnerable unless the TWI across the groves is low. For the large number of groves with elevations mainly in the 1800- to 2100-m range, the distribution of TWI values, or possibly the mean plus one standard deviation, can serve as a first-order indicator of relative vulnerability.

The applied approach has some limitations. Two major limitations of this analysis were a lack of site-specific data for the evaluation of patterns and a lack of detailed within-grove analysis. Because soil moisture was not measured in these groves, only satellite soil moisture and snow cover persistence were used to evaluate the TWI. Detailed within-grove analysis was beyond the scope of this study.

It is also important to mention that the satellite soil moisture products used in this study can be considered a qualitative assessment of soil moisture because satellite soil moisture products still have issues regarding their performance over dense vegetation and steep terrain (Ray et al., 2010; Hain et al., 2011). Finally, hydrologic simulations should be conducted to investigate the vulnerability of giant sequoias to soil moisture stress because of their capacity to estimate the dynamics of soil moisture storage.

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