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Research Article

Evaluation of the Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) Evaporative Stress Index at Micro and Macro Climate Levels Using Field Measurements in the San Francisco Bay Area

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ABSTRACT

Ecosystems in northern California have experienced repeated and prolonged droughts over the past 20 years. To improve predictive capabilities for impending hot and dry periods, the ratio of Actual Evapotranspiration (AET) to Potential Evapotranspiration (PET) has been shown to be a useful index for monitoring the moisture of vegetation. The main objective of this study was to "ground truth" the Evaporative Stress Index (ESI) from NASA's ECOSTRESS sensor across eight different county parks within the San Francisco Bay Area using field measurements of soil moisture and leaf stomatal conductance collected in the summer of 2020. To initially validate ECOSTRESS ESI image data, daily PET rates from stations in the California Irrigation Management Information System (CIMIS) were used for comparison at the meso-climate level of >10 km. Correlation results showed that ESI could accurately track CIMIS PET during both 2019 and 2020. At the micro-climate level of >1 km across the county parks, daily average ECOSTRESS ESI failed to closely track either stomatal conductance or soil moisture content at sampling locations where oak woodland cover was predominant. We hypothesized that this mismatch was due to oak trees' ability to root deep within the soil, allowing it to access water from lower levels not accounted for by ESI surface observations. Sampling sites where oak trees were not the predominant woodland cover showed higher correlation results between ESI and stomatal conductance, however, ESI failed to closely track soil moisture content at the micro climate site level. When all of the study sites were separated between oak-dominated and non-oak-dominated and averaged by county park, there was a significant correlation between soil moisture content and daily average ESI. It was concluded that at sites dominated by a mixture of oak trees and other woodland plant species, ESI is unable to accurately track the differences in each species' stomatal conductance rates measured during the dry summer season.

Keywords: Evaporative stress index; ECOSTRESS; Evapotranspiration; Stomatal conductance; Soil moisture

INTRODUCTION

Vegetation communities growing in the Mediterranean climate of northern California are generally well-adapted to seasonal droughts, when little or no precipitation falls during the hottest months (July to September) of every year [1]. However, since 2001, most of the state has experienced three severe droughts, in 2002-2003, 2007-2009 and 2012-2016 [2]. Multi-year dry periods such as these could be exacerbated by climate change and additional surface warming in the future [3]. To better predict the health of native vegetation communities, there is a need to gain a more complete understanding of the relationship between soil moisture levels and plant water deficits in northern California ecosystems.

For short-term predictive purposes of days to weeks, it has been shown that the ratio of Actual Evapotranspiration (AET) to the atmospheric evaporative demand, also known as Potential Evapotranspiration (PET), provides a useful drought monitoring index [4]. Previous studies have shown that AET derived from thermal satellite remote sensing can be used in combination with

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physically based PET estimates to generate an Evaporative Stress Index (ESI) [5], which may be sensitive to rapid changes in soil moisture conditions.

The Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) was launched to the International Space Station (ISS) in June of 2018. ECOSTRESS is a thermal radiometer that measures Thermal Infrared Radiation (TIR) in five bands from 8 μm to 12.5 μm wavelengths, plus an additional sixth band at 1.6 μm for geolocation and cloud detection [6]. The ESI from ECOSTRESS may be sensitive to rapid changes in soil moisture content and plant water usage, because ECOSTRESS data not only accounts for the impact of rainfall shortages, but also temperature, radiation, and wind anomalies often associated with rapid development of drought conditions [7].

Since it is carried onboard the ISS, which has an irregular orbit (rather than a regular polar or geostationary orbit), ECOSTRESS collects measurements continuously between 52°N and 52°S at different times of day. The overpass return frequency for any same location on Earth is 1-5 days, depending on the latitude. The Priestly-Taylor (PT) model for PET from the NASA Jet Propulsion Laboratory is computed in the derivation of ESI values, often several times on any given overpass day [8]. The PT-JPL algorithm incorporates eco-physiological constraint functions unitless multipliers, scaled 0-1) based on atmospheric moisture (Vapor Pressure Deficit, VPD and, Relative Humidity, RH) and vegetation indices (Normalized Difference and Vegetation Indices, NDVI and Soil Adjusted Vegetation Indices, SAVI, respectively).

NASA's ECOSTRESS science mission aims to reduce uncertainty in plant water use AET and soil water content [6]. Estimations of ET must include both the loss of root zone soil water through transpiration (modulated by stomatal conductance) as well as evaporation from bare soil surfaces. However, there are limited ground-based data sets available in most regions of the world that can be used to confirm these satellite observations of moisture stress and to test hypotheses about the mechanisms controlling variations in soil moisture and plant stomatal conductance on scales ranging from a single site to regional eco-climatic gradients.

It is well established that water transpiration flux from a plant leaf can be computed by algorithms such as the Penman-Monteith equation [9], which combines weather variables with bulk aerodynamic conductance and leaf surface conductance that is in part controlled by stomatal opening levels of the leaves. Transpiration rates are known to be dependent on stomatal conductance levels, which can be controlled in turn by interactions of solar irradiance, air temperature, air saturation deficit, and (root zone) soil water levels [10]. Stomatal conductance is therefore a common indicator of plant water status and drought stress [11].

The main purpose of this study was to "ground truth" all available ECOSTRESS ESI data for detecting plant moisture stress across eight different county parks within the SFBA using field measurements of soil moisture and leaf stomatal conductance collected throughout the summer of 2020 (Figure 1).

MATERIALS AND METHODS

Site description

The San Francisco Bay Area (SFBA) is in an advantageous geographic location to test ESI as an accurate predictor of vegetation moisture stress. At the higher elevations of the Santa Cruz Mountains and the East Bay Diablo Range hills, drought-resistant chaparral vegetation are dominate with a mix of grasses, bay laurel *(Umbellularia californica)*, and several oak species [12].

The average topographic attributes of each county park study site showed that overall slope had little variation among the sites, whereas elevation was consistently higher in the Santa Cruz mountain sites than in the East Bay Diablo Range sites. All the study sites were dominated by evergreen or mixed forest cover (Table 1).

Field data collection

To collect field data that was representative of our study areas, multiple plant and soil water measurement locations were spaced out by approximately 100 meters in a transect to represent an area roughly the size of one ECOSTRESS pixel, which was approximately 70 × 70 m. At each county park study area, we selected 10 different locations along an elevation (lower to higher) transect that represented 10 separated pixels within any ECOSTRESS image. At each sampling location along the transect, we recorded three replicate data points of soil temperature, stomatal conductance from predominant tree species, and volumetric water content, for a total of 30 data points for each study site on each visit date. Each county park was sampled twice from June to August 2020 to allow for a potential increase in drought stress with increasing summer temperatures, all to test ECOSTRESS's ability to track drought stress at various time periods (Table 2).

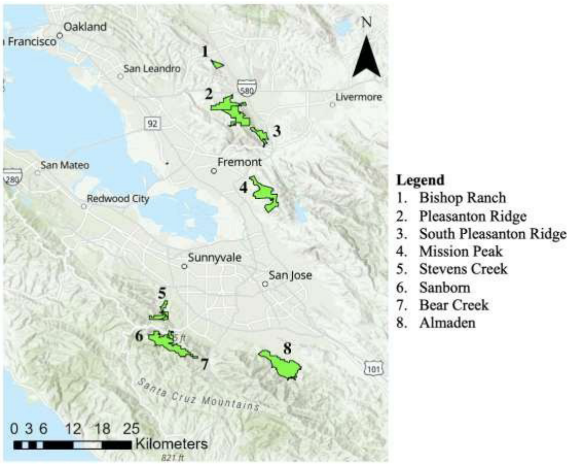

Figure 1: Map locations of the eight county parks selected as study sites within the San Francisco Bay area.

Table 1: Attributes of study sites in the SFBA used for ECOSTRESS ESI ground-truth measurements.

Site name	Primary land cover	Secondary land cover	Elevation (feet)	Average slope (percent)
Almaden	evergreen forest	mixed forest	1334	6.9
Bear Creek	evergreen forest	mixed forest	1176	7.1
Bishop Ranch	mixed forest	developed	568	7
Mission Peak	mixed forest	shrubland	528	6.5
Pleasanton Ridge	mixed forest	grassland	683	7.3
Sanborn	evergreen forest	N/A	1668	7.5
South Pleasanton Ridge	mixed forest	shrubland	566	7
Stevens Creek	evergreen forest	developed	453	6.7

Table 2: Date of each sampling visit per study site. Two visits allowed for a potential increase in drought stress with increasing summer temperatures.

Site name	Visit #1 date	Visit #2 date
Bishop Ranch	09-06-2020	22-07-2020
Pleasaton Ridge	12-06-2020	15-07-2020
South Pleasaton Ridge	26-06-2020	09-08-2020
Mission Peak	01-07-2020	29-07-2020
Stevens Creek	16-06-2020	21-07-2020
Sanborn	09-06-2020	13-07-2020
Bear Creek	23-06-2020	27-07-2020
Almaden	25-06-2020	06-08-2020

Field instruments

The field scout TDR (Time Domain Reflectometry) Model 350 soil moisture meter integrates electrical conductivity and surface temperature measurements to estimate percent Volumetric Water Content (VWC) of surface soil layer (to 4 in depths). The underlying principle of TDR involves measuring the travel time of an electromagnetic wave along the two TDR soil probes. The speed of the wave in soil is dependent on the bulk dielectric permittivity of the soil matrix, and the fact that water has a much higher dielectric constant than air or soil solids is exploited to determine the VWC of the soil. Surface soil temperature was also recorded by the Field Scout instrument.

The METER model SC-1 leaf porometer measures vapor flux from the leaf through the stomata of leaves. The porometer measures stomatal conductance by putting the conductance of a leaf in series with two known conductance chamber elements, and comparing the humidity measurements between them. The SC-1 measurement conductance range is 0-1000 mmol m-2 s-1 with a proven accuracy of 10%.

Evaporative stress index

Evaporative Stress Index (ESI) images from June to August 2020 were obtained from ECOSTRESS, which uses the Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR) to measure drought stress. There are five different wavelengths that represent five levels of intensity of Thermal Infrared Radiation (TIR) and a sixth for geolocation and cloud detection [8]. The spatial resolution of ECOSTRESS is 69 meters cross-track and 38 meters in-track. All ESI images from June to August of 2020 were obtained for our study area, imported into Quantum GIS 3.1 [13], and converted into location time series datasets. Due to limited ECOSTRESS fly-over dates, the fly-over date closest to our sampling date was used for analyses, up to 7 days plus or minus.

By measuring net radiation within an area, ECOSTRESS uses this data in the Priestley-Taylor JPL algorithm to calculate Potential Evapotranspiration (PET) [14]. PT-JPL calculates PET from inputs of atmospheric vapor pressure deficit (Da, kPa), Relative Humidity (RH, percent), and vegetation indices, including Normalized Difference and Soil Adjusted Vegetation Indices (NDVI and SAVI, unitless), and simultaneously reduces PET to an estimate of AET [8].

CIMIS data

To validate the ECOSTRESS PET estimation as a key component of ESI, California Irrigation Management Information System (CIMIS) station records from 2020 were used for their reference Evapotranspiration (ETo) data collection. Using a modified Penman equation [14], ETo is calculated from several measured data sets including relative humidity, solar radiation, and air temperature. The CIMIS meteorological station locations represent daily ETo estimations at a meso-climate level across >10 km of horizontal distance for this study.

CIMIS calculates ETo using a modified version of the Penman equation, driven by hourly meteorology inputs and the fixed parameters associated with a standardized reference plant cover, including stomatal and surface resistance, albedo, and height of vegetation. This hypothetical reference plant cover assumes full shading of the ground, irrigated soils, and is typically used to represent a short green crop cover such as alfalfa (Figure 2).

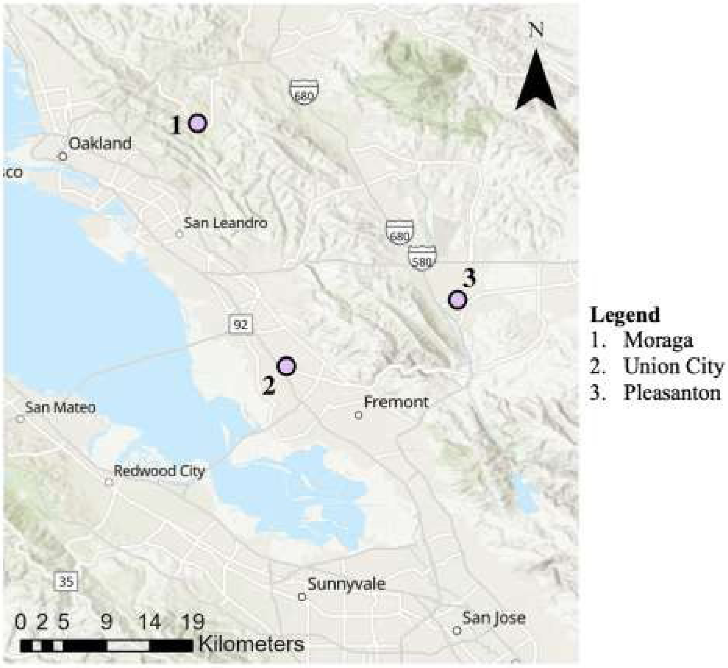

Figure 2: Map locations of three California Irrigation Management Information System (CIMIS) stations used for their reference evapotranspiration (ETo) data collection. Basemap from ESRI, Redlands, CA.

Spatial data analysis

Due to the variance in elevation, tree species, and surrounding understory vegetation, averaging the three data records for each sampling location collected in the field allowed us to match the corresponding ESI values at the micro-climate level of <1 km of horizontal distance. We also averaged ESI to one daily value whenever multiple ESI images were acquired during the same day. To allow us to determine if ECOSTRESS significantly tracked water stress at locations containing a single tree species more accurately than other mixed species locations, the field data were separated into oak-dominated and non-oak-dominated vegetation types. Stomatal conductance datasets separated by tree species were analyzed by visit date and also individually.

To characterize the attributes of the county park study sites, primary and secondary land cover class were determined from the 2016 National Land Cover Dataset [15] at 30-m Landsat pixel resolution, and elevation and slope were derived from digital elevation maps at 30-m spatial resolution from the United States Geological Survey [16].

Statistical tests

Two different tests were used to determine the significance of differences among our datasets. Correlations between daily ESI and VWC or stomatal conductance values were determined by Pearson's linear regression. A resulting correlation coefficient (R^2) value greater than 0.2 was considered significant at $p<0.05$ (95% confidence level) for a two-tailed test [17]. Therefore, any correlation coefficient greater than 0.2 was construed as a meaningful statistical association between daily average ESI and a given soil or plant moisture measurement. The Student's T-test was used to determine differences between visit dates in any of the measured variables at a given study area.

On multiple dates during the months of July and August, 2020, ECOSTRESS recorded an ESI value of greater than 0.75, which is indicative of minimal vegetation moisture stress during the hottest, driest period of the year in the SFBA. CIMIS station records indicated there was no record of precipitation in the SFBA that would have altered the soil moisture availability in the few weeks before or on these same dates, and because of this, we omitted these ESI images as outliers. We know of no explanation for such ESI outliers, although atmospheric anomalies such as low cloud cover could be further investigated as causal factors.

RESULTS

Study area topographic and ESI comparisons

The averages of our measured VWC, stomatal conductance and surface soil temperature for each visit alongside the average ECOSTRESS ESI values for each study site on the days visited were summarized (Table 3a). There were notable decreases the averages for all measurement variables ESI, stomatal conductance, and VWC between the two visits at every study site. Averages of surface soil temperature did not change consistently between the two visit dates at most study sites (Table 3b).

CIMIS ETo versus ESI

To first establish that ECOSTRESS was able to accurately track local PET, we compared daily average CIMIS ETo with ECOSTRESS ESI dates. Assuming that plant-regulated AET at a given CIMIS station location would vary much less than PET over the course of the summer period, because CIMIS stations are largely unvegetated, then ESI and PET are fundamentally the same measurement of water loss at CIMIS station locations. There was a significant negative correlation between ESI and ETo at all three CIMIS stations (R^2>0.44) reporting in the SFBA. This demonstrated that ESI was accurately tracking PET, because as ETo increased, ESI decreased, which is expected from the ESI ratio calculation (Figure 3).

Table 3a: Average measurements on visit dates between June 9 and July 1, 2020 for study sites in the SFBA used for ECOSTRESS ground-truth measurements. Oak-dominated woodland sites were indicated with a *.

Site name	ESI visit #1	StCond visit #1	VWC visit #1	Soil temp visit #1
Mission Peak	0.2	158.67	5.82	26
Bear Creek	0.53	146.57	10.9	29.5
Sanborn	0.55	142.58	7.49	26.55
Almaden*	0.3	191.79	8.84	32.56
Bishop Ranch*	0.69	163.03	14.08	30.51
Pleasanton Ridge*	0.43	235.75	8.08	24.35
South Pleasanton Ridge*	0.17	241.11	5.77	32.77
Stevens Creek*	0.3	260.4	7.9	27.85

Table 3b: Average measurements on visit dates between July 13 and August 9, 2020 for study sites in the SFBA used for ECOSTRESS ground-truth measurements. Oak-dominated woodland sites were indicated with a *.

Site name	ESI visit #2	StCond visit #2	VWC visit #2	Soil temp visit #2
Mission Peak	0.1	121.33	4.88	25.42
Bear Creek	0.34	114.21	7.35	30.07
Sanborn	0.36	131.95	5.25	26.73
Almaden*	0.18	157.79	5.22	26.67
Bishop Ranch*	0.22	149.05	11.37	24.04
Pleasanton Ridge*	0.12	196.62	7.65	29.75
South Pleasanton Ridge*	0.09	134.78	3.77	37.22
Stevens Creek*	0.21	144.78	4.56	25.98

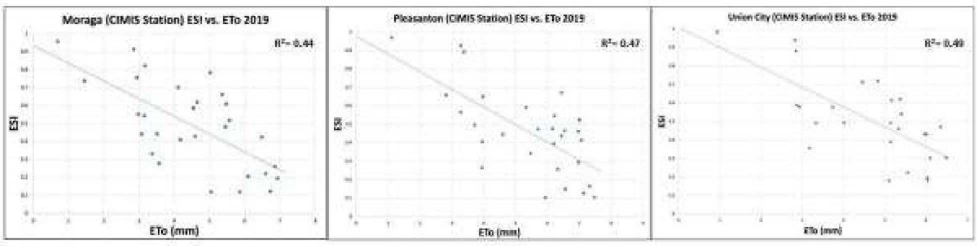

Figure 3: Correlation plots between CIMIS evapotranspiration (mm) and ECOSTRESS ESI for 2019.

Micro-climate level correlations

Out of all eight study sites visited, only two of them, both of which were non-oak dominated, had a significant positive correlation between daily ESI and stomatal conductance measurements on both visit dates. These park sites were Mission Peak and Bear Creek, whose ESI versus stomatal conductance R^2 values were estimated at between 0.33 and 0.45 (Table 4). None of the oak dominated park study sites showed a significant positive correlation between ESI and stomatal conductance. On the contrary, two of the sites, Stevens Creek and South Pleasanton Ridge, had significant negative correlations with R^2 values of 0.27 and 0.54, respectively.

ESI was unable to accurately track VWC within any study site visited on either date in 2020. Moreover, at Mission Peak and Bear Creek, where there were significant positive correlations between ESI and stomatal conductance, we found significant negative correlations between ESI and VWC with R^2 values of 0.51 and 0.44, respectively. The results from the second visit to Mission Peak show that, where there was a positive correlation between ESI and stomatal conductance but a negative correlation between ESI and VWC. In addition, the Sanborn site (R^2=0.23) and Bishop Ranch site (R^2=0.41) showed significant negative correlations between ESI and VWC (Figure 4).

Table 4: Correlation coefficient (R^2) values on visit dates between June 9 and August 9, 2020 within study sites in the SFBA used for ECOSTRESS ground-truth measurements. Significant correlations were shown in bold and negative correlations were shown in italics. Oak-dominated woodland sites were indicated with a *.

Site name	ESI vs. StCond visit #1	ESI vs. StCond visit #2	ESI vs. VWC visit #1	ESI vs. VWC visit #2
Mission Peak	**0.33**	**0.35**	0.04	*0.51*
Bear Creek	**0.45**	**0.42**	0.01	*0.44*
Sanborn	0.02	0.06	*0.23*	0
Almaden*	0	0.01	0.19	0
Bishop Ranch*	0.02	0.1	*0.41*	0.08
Pleasanton Ridge*	0.01	0.08	0.13	0.02
South Pleasanton Ridge*	*0.54*	0.01	0	0.05
Stevens Creek*	0.04	*0.27*	0.13	0.04

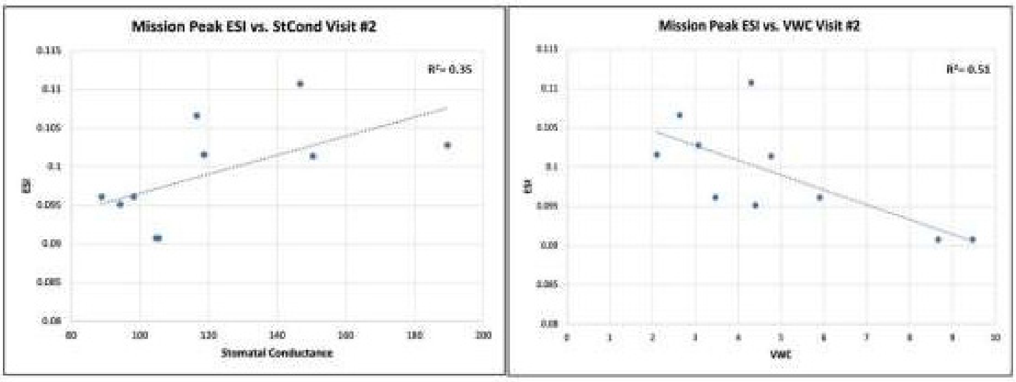

Figure 4: Correlation plots of data sets from the second visit to Mission Peak between ESI and stomatal conductance and between ESI and VWC.

To determine if ESI was able to track differences in VWC and stomatal conductance on the two different dates of sampling, T-test results showed that, at the Sanborn park site, where a significant negative correlation between ESI and VWC was found, there was no significant difference between VWC and stomatal conductance levels between the two visit dates. However, a significant difference ($p<0.05$) in ESI values was found between the two visit dates, which indicated that ESI was not accurately tracking VWC nor stomatal conductance at this site's micro-climate level. Similar results were found at the Mission Peak site, which also showed a significant negative correlation between ESI and VWC. Like Sanborn, there was no significant difference between VWC nor stomatal conductance levels between the two visit dates, yet ESI values did show a significant difference ($p<0.05$) between the two visit dates. Unlike Mission Peak and Sanborn, Stevens Creek did show a significant difference in ESI, VWC, and stomatal conductance levels between the two visit dates. Despite this, however, there were no positive correlations between ESI and neither VWC nor stomatal conductance detected at this study site.

Meso-climate level averages

To analyze any potential correlations between overall VWC data and ESI values, all study site data was averaged and plotted together, which displayed a significant positive correlation between ESI and soil VWC with an R^2 value of 0.50 (Figure 5). To further analyze this relationship, the study sites were separated into oak and non-oak-dominated categories. The averages of both non-oak and oak dominated sites had a positive correlation between ESI and VWC with R^2 values of 0.51 and 0.43, respectively. Neither the averages of all sites, non-oak-dominated nor oak-dominated sites showed a positive correlation between ESI and stomatal conductance, with R^2 values less than 0.1 (Figure 6).

When measurements for non-oak tree species and oak species were separated into individual data sets, only the non-oak group showed a significant positive correlation between ESI and VWC, with an R^2 value of 0.28. Oak-dominated species data had a R^2 value for ESI versus VWC of 0.18 (Figure 7). Neither the non-oak species nor the oak species showed a strong positive correlation between ESI and stomatal conductance, but it is important to note that oak species stomatal conductance data was distributed generally higher levels than non-oak species (Figure 8).

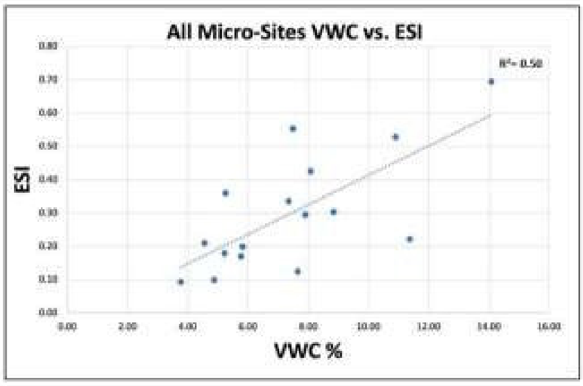

Figure 5: Correlation plots of ESI and soil VWC, for all study site data averaged and plotted together.

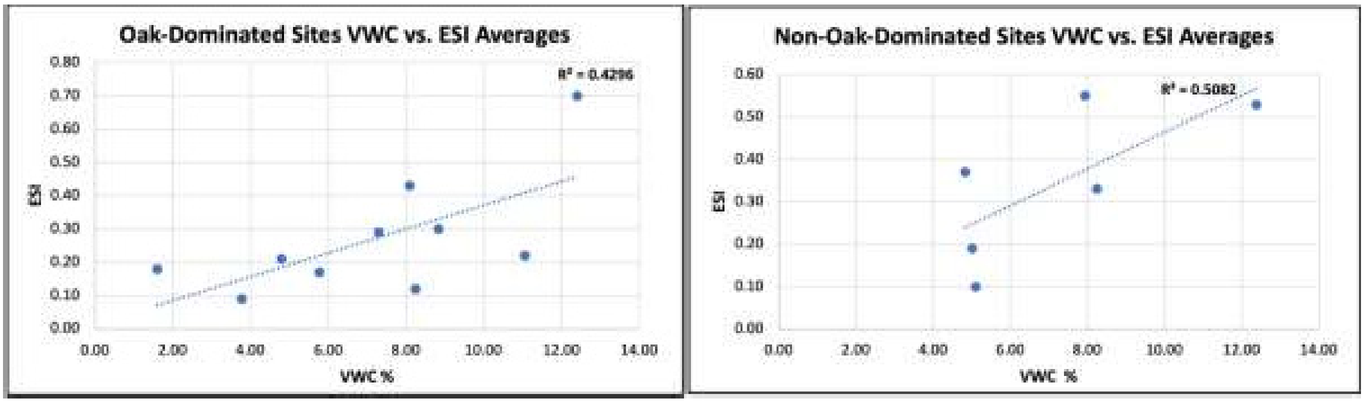

Figure 6: Correlation plots of ESI and soil VWC averaged by study sites and separated into oak- and non oak-dominated categories.

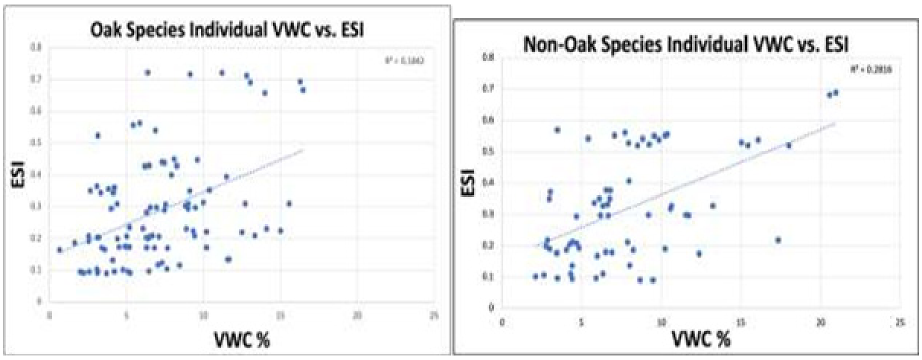

Figure 7: Correlation plots of ESI and soil VWC separated into oak and non-oak dominated categories.

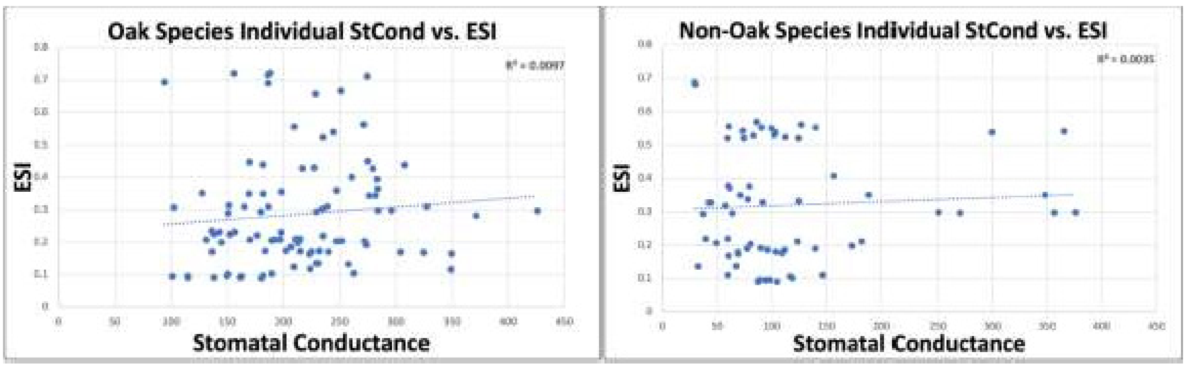

Figure 8: Correlation plots of ESI and stomatal conductance separated into oak and non-oak dominated categories.

DISCUSSION

The main findings from this ground-truth study of ECOSTRESS ESI image datasets were: 1) There was a lack of positive correlation between ESI and VWC at the micro-climate level at any of the county park sites visited in the summer of 2020; 2) When all the study site data were separated between oak-dominated and non-oak-dominated and averaged by county park, there was a significant correlation between soil moisture content (as VWC) and daily average daily ESI at the meso-climate level for non-oak dominated sites; and 3) Where oak woodland cover was not dominant, significant correlation results were found between daily ESI and stomatal conductance measurements at the micro-climate level at a subset of sites.

Our results did show that ECOSTRESS ESI was well correlated with CIMIS ETo at weather station locations in the SFBA. As ground-based ETo increased in the summer of 2020, ESI decreased linearly, which was expected from increasing PET detected by the ECOSTRESS algorithm. Similarly, in a study focused in southern California (Riverside County), researchers compared ECOSTRESS PET and ground-based ETo data sets from July 2018 to June 2020 and concluded that ECOSTRESS could successfully retrieve daily PET estimates that were comparable to average CIMIS station reference ET estimates [13]. Typical linear correlation R^2 values were high at >0.80 and the Root Mean Square Error (RMSE) was reported at 0.11 mm hr^{1}. It was surmised however that one important source of uncertainty in the relationship of ECOSTRESS PET to CIMIS ETo was spatial heterogeneity surrounding the CIMIS stations, introduced by mixed land cover classes and other soil surface properties. Furthermore, ECOSTRESS PET utilizes satellite estimates of albedo of the pixel area of interest, which can be influenced by variable surface reflectance conditions around the station site.

We can hypothesize that, because we intentionally measured soil VWC within tree rooting zones under full foliage cover, the closed tree canopies made it difficult for ESI to differentiate between the more exposed grass-covered soil areas versus the wooded soil moisture levels at many study sites. Because VWC is dependent on soil types and textures, this spatial variable could have played a major role in the unexpected lack of correlation between ESI and VWC measurements along relatively short (<1 km) elevation transects. Further studies may be done to verify that ESI has difficulties differentiating between soil types and therefore cannot often accurately track VWC at the micro-climate level.

To better understand the role of oak tree cover on California woodland water use, researchers reported that stomatal conductance in blue oak (*Quercus douglasii*) seedlings was correlated with percent Extractable Soil Water (ESW) throughout most of the year in central California woodlands, whereas stomatal conductance in adult blue oak trees and saplings was correlated with ESW only between June and September [18]. Furthermore, at a blue oak woodland site in the western Sierra Nevada foothills, where groundwater depth averaged 8 meters, researchers attributed the vast majority of total summer evapotranspiration by oaks to uptake and lift of stored groundwater, after more shallow soil moisture pools became depleted in spring months [19].

Other comparison studies of plant water use in California oak woodlands concluded that measured variations in oak tree production could not be matched closely by ecosystem simulation runs unless soil water availability was modified in the modeling structure [20,21]. The site where this comparison was carried out was a woodland consisting of scattered blue oak trees with occasional gray pine trees (*Pinus sabiniana L.*) surrounded by grazed grassland. Oak trees in this region of central California were able to continue to transpire well into the summer months, albeit at low rates, under very dry surface soil conditions, and to maintain basal levels of carbon metabolism, because tree roots were able to access sources of rainwater deep in the soil profile that is unavailable to grass roots. The necessary adjustment in ecosystem simulation runs required 80% more soil water available for transpiration by shrubs and trees than is commonly set for other moist woodland climate zones of the western United States.

These previous study results help explain our findings that only where non-oak woodland cover was dominant could significant correlation results be detected between ECOSTRESS ESI and stomatal conductance measurements at the micro-climate level. At sites where oak trees were the primary woodland species, ESI was not able to account for the deep soil water storage available for transpiration by oak trees and instead predicted consistently high plant moisture stress all summer at both the micro and meso-climate levels.

Although we measured the stomatal conductance of numerous coast redwood (*Sequoia sempervirens*) tree leaves in our field data from 2020 in the mixed conifer forests of the Sanborn and Bear Creek park sites, there are in fact few previously published studies to draw upon for comparison of evergreen tree water use in or around the Santa Cruz Mountains of the SFBA. In tree farm studies near Chico (farther north of the SFBA in the Central Valley of California), researchers reported that water stress and aboveground growth were significantly lower in coast redwoods than in Douglas-fir (*Pseudotsuga menziesii*) trees [22]. These findings suggested that greater stomatal regulation to conserve water in redwood trees also strongly reduces carbon uptake and growth, compared to weaker stomatal regulation in Douglas-fir trees.

We measured the stomatal conductance of numerous Eucalyptus (*Eucalyptus camaldulensis Dehnh.*) trees at the Mission Peak park site, because this exotic tree species was the most prevalent plant growing (to over 20 m in height) in large sections of the park. However, there have been no published studies on stomatal conductance and soil water used by Eucalyptus trees growing in California to relate directly to our field measurement results. In studies of Eucalyptus trees growing in northern Australia, researchers found that transpiration rates were higher during the dry season than during the wet season, mainly because of higher evaporative demand in the dry season and from the access to groundwater reserves by these deeply rooting trees [23]. Others reported that stomatal conductance and canopy transpiration of mature clonal Eucalyptus grandis trees were mainly related to predawn leaf water potential and, hence, to soil moisture availability [24].

CONCLUSION

ECOSTRESS ESI was not able to accurately track stomatal conductance variations at the micro-climate level in oak-dominated woodland sites and non-oak-dominated park sites to the same degree. Separating plant species into oak and non-oak species categories corroborated our hypothesis that ECOSTRESS cannot account for vegetation moisture stress in woodlands with deep-rooting tree species that can access groundwater sources year-round. We conclude that ECOSTRESS ESI cannot yet be used as an accurate predictor of soil water depletion in oak woodlands of northern California. Improvements in the ET algorithms used by ECOSTRESS are needed to account for the presence of deep-rooting tree species and for soil type variations that influence moisture holding capacity.

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