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Research Article

Can the Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) Satellite Track Soil Moisture at the Macro-Climate Scale Across the Western United States?

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ABSTRACT

The ECOSTRESS satellite uses thermal infrared wavelengths to measure the temperature of the land surface and to calculate an Evaporative Stress Index (ESI). NASA's ECOSTRESS mission was designed to support climate change research, since ESI can be an important indicator of the drought stress in terrestrial plant communities. We evaluated this satellite ESI for its capability to track changes in soil moisture measured at Unites States Department of Agriculture (USDA) stations in the western states. Soil water datasets from 2019 and 2020 from thirty stations in California, seven stations in Utah, three stations in Nevada, and two stations in Idaho were used for comparison of all daily average ESI images from ECOSTRESS. We also evaluated the ESI by comparing it to the reference potential Evapotranspiration (ETo) at the stations operated by CIMIS (California Irrigation Management Information). Correlation results showed that ECOSTRESS ESI can track soil moisture changes most closely at 4 inch, 8 inch, and 20 inch (10 cm, 20 cm, and 50 cm) soil depths for southern California desert station locations, where the predominant land cover was shrubland, and in the Great Basin region at 2 inch and 8 inch soil layers. However, ESI failed to correlate with soil moisture measured at many station locations in the Sierra-Nevada mountain region at any soil depth. ECOSTRESS ESI also failed to reliably track measured PET at any CIMIS stations. Several explanations were explored for this lack of predictive capacity of ECOSTRESS ESI as a drought indicator in the western United States.

Keywords: Evaporative stress index; ECOSTRESS; Drought; Evapotranspiration; Soil moisture; Snow cover

INTRODUCTION

Drought events in the western United States often have adverse effects on society, primarily through loss of agricultural production, degradation of rangelands, and depletion of water resources affecting streamflow levels and reservoir water storage [1]. The relatively rapid onset of damaging drought conditions has been termed "flash drought" [2]. Sudden dry periods such as these could be exacerbated by climate change and additional surface warming in the future [3]. Consequently, there is a pressing need to test improved physically based drought metrics, especially those that can accurately capture land surface-atmosphere feedbacks based on the relationship between Actual Evapotranspiration (AET) and atmospheric evaporative demand, also known as Potential Evapotranspiration (PET) [4]. Any evapotranspiration demand that is higher than the PET can result in plants undergoing physiological changes to conserve water. Therefore, the ratio of AET: PET can be a key indicator of the water stress that plants are experiencing [5].

Previous studies have shown that AET derived from thermal satellite remote sensing can be used in combination with physically based PET estimates to generate an Evaporative Stress Index – ESI, which may be sensitive to rapid changes in soil moisture conditions [4,6]. The Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) was launched to the International Space Station (ISS) in June of 2018 [7,8]. 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 [9]. 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

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temperature, radiation, and wind anomalies often associated with rapid development of drought conditions [6].

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 to 5 days, depending on the latitude. The Priestley-Taylor (PT) model for PET from the NASA Jet Propulsion Laboratory (JPL) is computed in the derivation of ESI values, often several times on any given overpass day [5]. 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 NDVI and SAVI.

The ECOSTRESS satellite uses thermal wavelengths to measure the temperature of the land surface to better understand how much water plants need and how they respond to stress. The purpose of the ECOSTRESS mission is to address three overarching science questions: “How is the terrestrial biosphere responding to changes in water availability? How do changes in diurnal vegetation water stress impact the global carbon cycle? Can agricultural vulnerability be reduced through advanced monitoring of agricultural water consumptive use and improved drought estimation?” [9]. We note that volumetric soil moisture content below 10% is the permanent wilting point for plants growing in most soils (NRCS, 1997), which will induce plant moisture stress under any climate scenario.

NASA’s ECOSTRESS science mission aims to reduce uncertainty in plant water use and soil water content [9]. Estimations of AET must include loss of root zone soil water through transpiration, together with evaporation from bare soil surfaces. The purpose of this study was to use all available ground stations measuring soil moisture profiles in the western states of California, Nevada, Utah, and Idaho (USA) to evaluate ECOSTRESS satellite observations of moisture stress, and to test our understanding of the mechanisms controlling daily variations in soil moisture over regional eco-climatic gradients. We also evaluated the ESI by comparing it to reference evapotranspiration (ETo) at stations operated by CIMIS (California Irrigation Management Information). The water loss rate that CIMIS measures as ETo is equivalent to PET.

Study area

The study area included 30 USDA stations in California, 7 USDA stations in Utah, 3 USDA stations in Nevada, and 2 USDA in Idaho. These stations were grouped into three main eco-climatic regions: Sierra-Nevada mountains, southern California deserts, and the Great Basin (Figure 1).

Sierra-Nevada vegetation communities commonly consist of white fir (*Abies concolor*, Gordon & Glend.), ponderosa pine (*Pinus ponderosa*, Lawson & C. Lawson), Jeffrey pine (*Pinus jeffreyi, Balf.*), sugar pine (*Pinus lambertiana, Douglas*), black oak (*Quercus kelloggii, Newb.*), and incense cedar (*Calocedrus decurrens, Torr.Florin*) [10]. Dominant plant species of the Mojave desert regions of California include creosote bush (*Larrea tridentata*), saltbush (*Atriplex polycarpa*), brittlebush (*Encelia farinosa*), desert holly (*Atriplex hymenelytra*), white burrobush (*Hymenoclea salsola*), and Joshua tree (*Yucca brevifolia*). The Mojave is bounded to the north by the Great Basin shrubland region. Dominant species in the Great Basin of Nevada and Utah include sagebrushes (*Artemisia* sp.), saltbrushes (*Atriple* sp.), rabbitbrush (*Chrysothamnus* sp.), blackbrush (*Coleogyne* sp.) (Table 1).

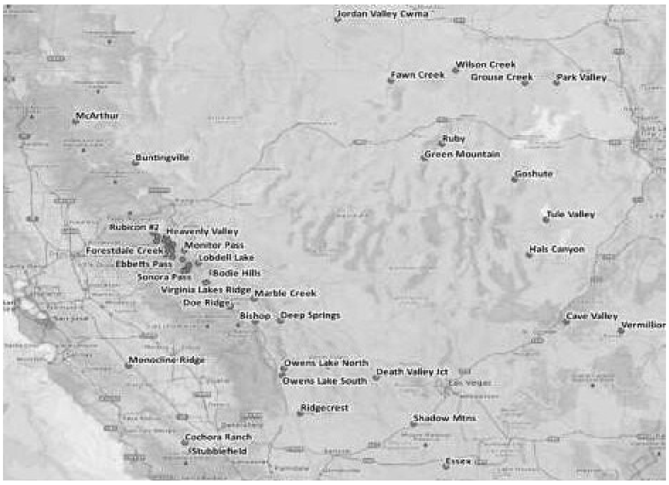

Figure 1: Map of USDA station study locations in the western United States.

Table 1: USDA station study locations in California.

Site Name	Elevation (ft)	latitude	longitude	Predominant land cover	Secondary land cover
Rubicon #2	7619	38.99927	-120.13139	Evergreen Forest	Evergreen Forest
Fallen leaf	6242	38.934-03	-120.05450	Shrubland	Evergreen Forest
Heavenly Valley	8534	38.92431	-119.91641	Shrubland	Evergreen Forest
Hagans Meadow	7742	38.85190	-119.93740	Evergreen Forest	Shrubland
Echo Peak	7653	38.84900	-120.07950	Shrubland	Evergreen Forest

Horse Meadow	8557	38.83652	-119.88732	Shrubland	Evergreen Forest
Burnside lake	8129	38.71943	-119.89420	Evergreen Forest	Shrubland
Carson Pass	8360	38.69270	-120.00220	Evergreen Forest	N/A
Forestdale Creek	8017	38.68245	-119.95970	Evergreen Forest	Shrubland
Monitor Pass	8306	38.66830	-119.60870	Grassland/Pasture	N/A
Spratt Creek	6063	38.66627	-119.81741	Shrubland	Evergreen Forest
Blue Lakes	8067	38.60800	-119.92437	Evergreen Forest	Evergreen Forest
Ebbetts Pass	8661	38.54970	-119.80468	Evergreen Forest	Shrubland
Poison Flat	7736	38.50576	-119.62624	Evergreen Forest	N/A
Lobdell Lake	9249	38.43745	-119.36572	Shrubland	N A
Summit Meadow	9313	38.39747	-119.53522	Shrubland	Evergreen Forest
Sonora Pass	8770	38.31021	-119.60030	Evergreen Forest	N/A
Leavitt Meadows	7198	38.30367	-119.55111	Shrubland	N/A
Leavitt Lake	9604	38.27594	-119.61281	Evergreen Forest	Shrubland
Bodie Hills	7825	38.26477	-119.12645	Shrubland	N/A
Virginia Lakes Ridge	9400	38.07298	-119.23433	Shrubland	N/A
Marble Creek	6183	37.77767	-118.42090	Shrubland	N/A
Doe Ridge	7340	37.63423	-118.82643	Shrubland	N/A
Deep Springs	5399	37.37222	-117.97383	Shrubland	N/A
Monocline Ridge	875	36.54417	-120.55463	Grassland/Pasture	N A
Death Valley Jct	2062	36.32502	-116.35132	Shrubland	Barren
Shadow Mtns	3643	35.46607	-115.71510	Shrubland	N/A
Cochora Ranch	2697	35.11807	-119.59608	Shrubland	N/A
Stubblefield	2995	34.97018	-119.47831	Shrubland	N/A
Essex	2644	34.67235	-115.16693	Shrubland	N/A

MATERIALS AND METHODS

USDA soil moisture data

Our analysis started with locating and downloading Volumetric Water Content (VWC, percent) datasets at various soil depths, as well as data for daily precipitation and air temperature from the United States Department of Agriculture (USDA) online portals for the years 2019 and 2020. The USDA compiles daily weather and soil moisture data from the station SNOTEL and SCAN networks (available online at https://www.wcc.nrcs.usda.gov/).

These SCAN and SNOTEL stations both use Hydra Probe Digital Sdi-12 sensors (Stevens Water Monitoring Systems Inc.) to measure soil VWC. The sensors are inserted horizontally into the soil at various depths. SNOTEL stations measure soil moisture only at the 2 inch, 8 inch, and 20 inch depth. The accuracy of these sensors is ± 0.01 WFV (Water Fraction by Volume) for most soils. SNOTEL stations are located in the Sierra-Nevada region and in northern Utah. SCAN stations located in Southern California measure soil moisture at 2 inch, 4 inch, 8 inch, 20 inch, and 40 inch depth.

CIMIS evapotranspiration data

To validate the ECOSTRESS PET estimations, California Irrigation Management Information System (CIMIS) station records from 2019 and 2020 were obtained for their reference Evapotranspiration (ETo) data collection. CIMIS weather station locations and represent daily PET estimations.

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 [9]. 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. 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 ETo/PET are fundamentally the same measurement of water loss at CIMIS station locations.

ECOSTRESS ESI data

All ECOSTRESS images from 2019 and 2020 were obtained for our study areas, imported into Quantum GIS 3.1 and converted into station-location time series datasets [11]. ECOSTRESS 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 [5]. The spatial resolution of ECOSTRESS is 69 meters cross-track and 38 meters in-track.

By measuring net radiation within an area, ECOSTRESS uses this data in the Priestley–Taylor JPL algorithm to calculate Potential Evapotranspiration (PET) [9]. 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 [5].

Land cover classes

To characterize the land cover attributes of the USDA station sites, primary and secondary land cover classes were determined from the 2016 National Land Cover Dataset (NLCD); at 30 m Landsat pixel resolution [12]. The predominant land cover at each station was summarized in QGIS (2020) to identify any important relationships between the specific land cover and ESI correlations with measured VWC (Table 1 and Table 2).

Data analysis and statistical tests

Daily ESI values and precipitation amounts for each station were compared for the years of 2019 and 2020 to identify anomalies in the ESI values recorded by ECOSTRESS. Such anomalies were categorized as abrupt increases in the ESI with no associated precipitation recorded in the five days prior. Anomalous ESI values that were not supported by corresponding precipitation events were removed from the dataset that was used to evaluate a potential correlation with soil moisture data. We have no explanation for such ESI outliers, although atmospheric anomalies such as high, thin cloud cover could be further investigated as a causal factor. Any ESI values that were reported on the same day were averaged together, since the ECOSTRESS satellite measures ESI during some periods multiple times in a day.

Linear regressions were used to determine if there was a significant correlation between daily ESI and VWC at the various soil depths. Values of Pearson's correlation coefficient (R^2) greater than 0.2 were considered significant at $p<0.05$ (95% confidence level) for a two-tailed test [13]. Therefore, any correlation coefficient greater than 0.2 was construed as a meaningful statistical association between daily average ESI and a given soil moisture measurement.

Each USDA station's latitude, longitude, elevation, and predominant land cover class, along with the R^2 value for ESI correlations at the measured soil depths, were organized into a database for further analysis of associations between land cover and soil moisture variations. Linear regressions results were also used to validate how well ECOSTRESS ESI corresponded with ETo from the CIMIS stations.

To further understand the differences that were observed between precipitation in 2019 and 2020 at the three study regions, two-tail equal variance t-tests were performed. A histogram inspection of the average monthly precipitation at each of the study sites showed that using an equal variance t-test was justified. The monthly precipitation for 2019 was averaged at each of the sites. The average precipitation for each of the sites in the specific region was compared to the averages obtained from 2020.

RESULTS AND DISCUSSION

Soil moisture variations

In the Sierra Nevada mountain region, 8 inch and the 20 inch soil depths showed higher soil moisture for 2019 and 2020 in comparison to the other regions (Figure 2). The soil moisture at the various depths in the Sierra Nevada region increased the most during the months of mid-April to mid-June. In contrast, in the Southern California desert region, soil moisture fluctuated the most from January to March and peaked during January, while in the Great Basin region, soil moisture fluctuated the most from January to mid-May and peaked in May. In both the Great Basin region and the Southern California region, the 20 inch and 40 inch the soil moisture remained low and consistent, especially in 2020. In contrast, in the Sierra Nevada region, the 20 inch depth had the highest soil moisture and increased during the spring months. Overall, the soil moisture for all three regions was higher at most soil depths in 2019 than in 2020 (Figure 3).

Table 2: USDA station study locations in Utah, Nevada, and Idaho.

Site Name	Elevation (ft)	Latitude	Longitude	Predoiminant Land Cover	Secondary Land Cover
Grouse Creek, UT	5835	41.78	-113.82	Shrubland	N/A
Park Valley, UT	5098	41.77	-113.29	Shrubland	Grassland/Pasture
Goshute, UT	5487	39.99	-114.00	Shrubland	N/A
Tule Valley, UT	4592	39.24	-113.46	Shrubland	N/A
Hals Canyon, UT	5260	38.59	-113.75	Shrubland	N/A
Cave Valley, UT	6273	37.36	-113.12	Shrubland	N/A
Vermillion, UT	6392	37.19	-112.19	Shrubland	N/A
Green Mountain, NV	8185	40.38	-115.53	Shrubland	N/A
Fawn Creek, NV	7031	41.82	-116.1	Evergreen Forest	N/A
Ruby, NV	6000	40.64	-115.23	Shrubland	N/A
Wilson Creek, ID	7120	42.01	-115.00	Shrubland	N/A
Jordan Valley, ID	4508	42.95	-117.01	Shrubland	N/A

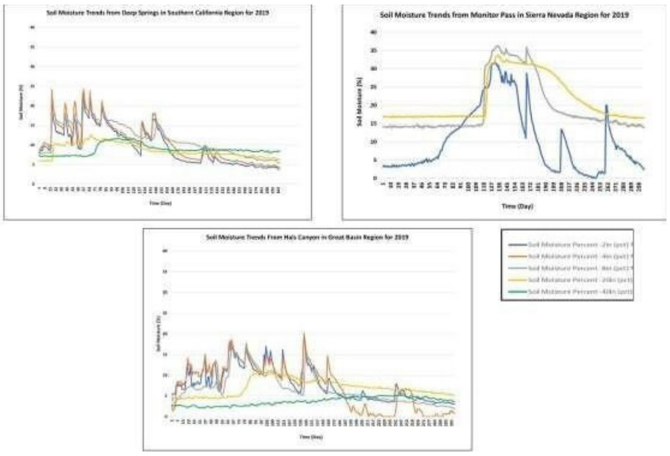

Figure 2: Variation of soil moisture at various soil depths for the months of January to October of 2019 from representative stations in the regions of Southern California, Sierra Nevada, and Great Basin.

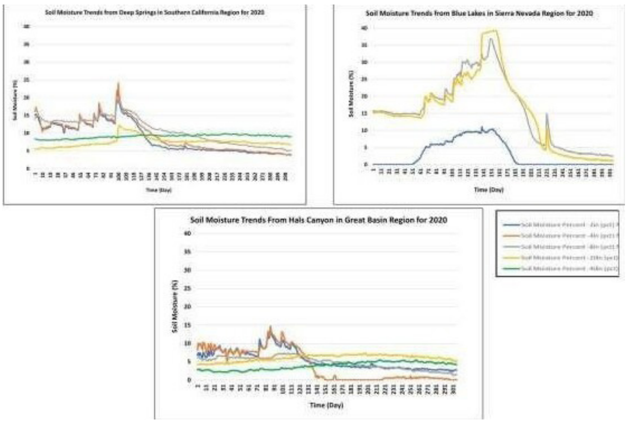

Figure 3: Variation of soil moisture at various soil depths for the months of January to October of 2020 from representative stations in the regions of Southern California, Sierra Nevada, and Great Basin.

California Desert ESI-VWC correlations

The datasets from USDA station records from 2020 analyzed for the California desert study area showed that 4 out of the 9 stations showed a significant positive correlation ($p<0.05$) between ECOSTRESS ESI and VWC at the 2 inch soil depth. There were 5 stations out of 9 with VWC measured at the 4 inch depth that showed a positive correlation between ESI and VWC, and 1 out of 9 stations with VWC measured at the 8 inch depth that showed a positive correlation with ESI.

In contrast, the correlations for the California desert USDA station data from 2019 showed fewer stations where ESI tracked closely with daily measured VWC. The data from only three stations had a significant correlation ($p<0.05$) between ESI and VWC at either 4 inch depth or the 8 inch depth in 2019.

In a closer examination of California desert station data from 2019, Marble Creek, Deep Springs, Death Valley, and Cochora Ranch showed no significant correlation between ESI and VWC at any soil depth. Two stations, Shadow Mountain and Stubblefield were missing the daily measured VWC to compare to the ECOSTRESS ESI measurements recorded. However, at Essex, ESI tracked closely with VWC at the 4 inch depth with a R^2 value of 0.56. At Doe Ridge and Monocline Ridge, ESI tracked closely with VWC at the 8 inch depth. At Doe Ridge, ESI also tracked closely with VWC at the 20 inch depth and (Figure 4).

In contrast to the correlation results from 2019 for California Desert study sites, 8 sites out of the 9 stations had significant positive correlation ($p<0.05$) between ECOSTRESS ESI and VWC in at least one soil depth in 2020. Doe Ridge, Deep Springs, Monocline Ridge, and Cochora Ranch showed a significant positive correlation between ESI and VWC at the 2 inch and 4 inch depths in 2020. Monocline Ridge was the only site that also showed a correlation between ESI and VWC at the 8 inch depth with a R^2 value of 0.42. Essex showed a significant positive correlation between ESI and VWC at the 4 inch depth with a R^2 value of 0.37 and at the 20 inch depth. Death Valley showed an anomaly between ESI and VWC at the 2 inch depth as a negative correlation between ESI and soil moisture with a R^2 value of 0.20 in 2020 (Figure 5).

Sierra-Nevada ESI-VWC correlations

The USDA station data from 2019 analyzed from Sierra California study sites showed that only 2 out of 21 stations had a positive correlation ESI and VWC ($R^2>0.20$) at least one soil depth. Blue Lakes showed a positive correlation ESI and VWC at the 2 inch depth with a R^2 value of 0.23 and Lobdell Lakes showed a positive correlation ESI and VWC at the 20 inch depth with a R^2 value of 0.22 (Table 3).

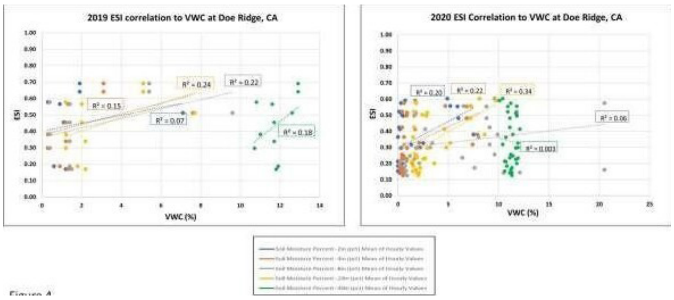

Figure 4: ESI correlation to VWC at Doe Ridge, California for 2019-2020. There was a significant correlation between ESI and VWC at 2 inch, 4 inch, 8 inch, and 20 inch soil depths for both 2019-2020 with $R^2>0.20$.

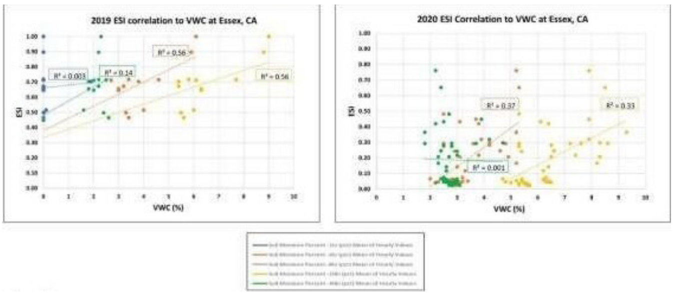

Figure 5: ESI correlation to VWC at Essex, California for 2019-2020. There was a significant correlation between ESI and VWC at 4 inch and 20 inch soil depths for both 2019-2020 with $R^2 >0.20$.

Table 3: Correlation coefficient (R^2) values between ESI and VWC at the 2 inch, 4 inch, 8 inch, 20 inch, and 40 inch depths for the study sites in Sierra Nevada Region in California to evaluate ECOSTRESS ESI's ability to track VWC for 2019.

Site Name	Predominant Land Cover	Secondary Land Cover	R^2 -value ESI vs. VWC at 2 inch depth	R^2-value ESI vs. VWC at 4 inch depth	R^2-value ESI vs. VWC at 8 inch depth	R^2-value ESI vs. VWC at 20 inch depth	R^2-value ESI vs. VWC at 40 inch depth
Rubicon #2	Evergreen Forest	Evergreen Forest	0.01	NM	0.08	0.10	NM
Fallen leaf	Shrubland	Evergreen Forest	0.10	NM	0.10	0.00	NM
Heavenly Valley	Shrubland	Evergreen Forest	0.10	NM	0.10	0.11	NM
Hagans Meadow	Evergreen Forest	Shrubland	0.00	NM	0.06	0.12	NM
Echo Peak	Shrubland	Evergreen Forest	0.03	NM	0.00	0.00	NM
Horse Meadow	Shrubland	Evergreen Forest	0.01	NM	0.01	0.01	NM
Burnside Lake	Evergreen Forest	Shrubland	0.02	NM	0.04	0.04	NM
Carson Pass	Evergreen Forest	N/A	0.11	NM	0.11	0.12	NM
Forestdale Creek	Evergreen Forest	Shrubland	0.01	NM	0.03	0.16	NM
Monitor Pass	Grassland/ Pasture	N/A	0.01	NM	0.13	0.18	NM
Spratt Creek	Shrubland	Evergreen Forest	0.15	NM	0.07	0.03	NM
Blue Lakes	Evergreen Forest	Evergreen Forest	0.23*	NM	0.18	0.14	NM
Ebbetts Pass	Evergreen Forest	Shrubland	0.00	NM	0.00	0.01	NM
Poison Flat	Evergreen Forest	N/A	0.01	NM	0.01	0.00	NM
Lobdell Lake	Shrubland	N/A	0.14	NM	0.19	0.22*	NM
Summit Meadow	Shrubland	Evergreen Forest	0.00	NM	0.00	0.00	NM
Sonora Pass	Evergreen Forest	N/A	0.09	NM	0.07	0.10	NM
Leavitt Meadows	Shrubland	N/A	0.04	NM	0.05	0.14	NM
Leavitt Lake	Evergreen Forest	Shrubland	0.00	NM	0.01	0.01	NM
Bodie Hills	Shrubland	N/A	0.04	0.04	0.12	0.15	0.19
Virginia Lakes Ridge	Shrubland	N/A	0.18	NM	0.17	0.14	NM

Note: *$R^2>0.20$,there is a significant positive correlation relationship between ESI and VWC
N/A-not applicable
ND- no data collected
NM- not measured by the station

In contrast to the 2019 data, the 2020 data analysis showed that 6 out of the 21 stations had positive correlation ESI and VWC ($R^2 > 0.20$) for at least one soil depth. Nonetheless, most of the stations that showed no significant correlation between ESI and VWC for 2019 also showed a similar result for 2020. The stations at Rubicon, Fallen Leaf, Hagan Meadow, Echo Peak, Horse Meadow, Burnside Lake, Carson Pass, Monitor Pass, Spratt Creek, Summit Meadow, Sonora Pass, Leavitt Meadows, and Virginia Lake Ridge showed no significant correlation between ESI and VWC for both 2019 and 2020 (Table 4).

In a closer examination of Sierra-Nevada California station data from 2020, Heavenly Valley, Forestdale Creek, Poison Flat, and Leavitt Lake showed a positive correlation between ESI and VWC at the 20 inch depth. Poison Flat also showed positive correlation between ESI and VWC at the 2 inch and 8 inch depth. Ebbetts Pass showed a positive correlation between ESI and VWC at the 2 inch depth. Bodie Hills showed ESI tracked closely with VWC at the 2 inch and 4 inch depth (Table 5). However, Bodie Hills also showed an anomaly between ESI and VWC at the 40 inch depth as a negative correlation between ESI and soil moisture with a R^2 value of 0.38 in 2020 (Figure 6).

Great basin ESI-VWC correlations

The USDA station data from 2020 analyzed from the Great Basin study area showed that 9 out of the 12 stations had a significant positive correlation ($p < 0.05$) between ECOSTRESS ESI and VWC at the 2 inch soil depth. There were 6 stations out of 8 with VWC measured at the 4 inch depth that showed a positive correlation between ESI and VWC, and 7 out of 11 stations with VWC measured at the 8 inch depth that showed a positive correlation between ESI (Table 6).

In contrast, the correlations with USDA station data from 2019 showed fewer stations where ESI tracked closely with daily measured VWC. The results from only two stations had a significant correlation between ESI and VWC at the 2 inch depth and at the 4 inch depth in 2019. At the 8 inch depth, only one station had a significant correlation ($p < 0.05$) between ESI and VWC in 2019 (Figure 7).

In a closer examination of Utah station data from 2019, Grouse Creek, Park Valley, Goshute, and Cave Valley showed no significant correlation between ESI and VWC at any soil depth. However, at Tule Valley, ESI tracked closely with VWC at the 4 inch depth. Tule Valley also showed an anomaly between ESI and VWC at the 8 inch depth as a negative correlation between ESI and soil moisture with a R^2 value of 0.65 in 2019. Vermillion showed a similar negative anomaly at the 2 inch depth with a R^2 value of 0.33. At Hals Canyon, ESI tracked closely with VWC at the 2 inch and 4 inch depths. In Nevada, the Green Mountain, Fawn Creek, and Rudy Ridge Valley stations showed no significant correlations between ESI and VWC at any soil depth in 2019. In addition, the Wilson Creek and Jordan Valley stations in Idaho showed no significant correlations between ESI and VWC at any soil depth (Table 7).

In contrast to the correlation results from Utah stations in 2019, at Park Valley and Cave Valley in 2020, there were significant positive correlations between ESI and VWC at the 2 inch, 4 inch, and 8 inch depths. At Goshute, ESI tracked with VWC at the 2 inch depth in 2020. At Tule Valley, ESI correlated positively with soil moisture in 2020 at the 2 inch and 4 inch depths. The correlation between ESI and VWC at the 4 inch depth was consistent with what was determined in 2019. At Hals Canyon, ESI tracked closely with VWC at the 8 inch depth in 2020 as well. At Vermillion, there was a significant positive correlation between ESI and VWC at the 2 inch and 8 inch depths in 2020, unlike the non-significant results from 2019.

For the 2020 ESI correlations at the Nevada and Idaho stations, Fawn Creek, Nevada and Wilson Creek, Idaho showed a positive significant correlation between ESI and VWC at the 2 inch and 8 inch depths. At Ruby, Nevada, ESI tracked VWC at the 2 inch and 4 inch depths in 2020. At Jordan Valley, Idaho, ESI tracked VWC in 2020 at the 4 inch and 8 inch depths; however at the 2 inch depth, there was a negative correlation in 2020 (Table 8).

CIMIS ETo-ESI correlations

Only three CIMIS stations had enough data values to compare ESI to daily PET (Potential Evapotranspiration). In 2019, the Bishop station showed no significant relationship between ESI and ETo. However, in 2020, Bishop did show a significant positive correlation between ESI and ETo R^2 value of 0.21, which is not what was expected, based on the AET: PET ratio of ESI. Ridgecrest showed no significant correlation between ESI and ETo for 2019 and 2020. Markleeville did not have ESI data for 2019 to compare. In 2020, there was both ESI and ETo data at Markleeville from May until October, but no significant correlation with CIMIS ETo was detected (Figure 8).

Table 4: Correlation coefficient (R^2) values between ESI and VWC at the 2 inch, 4 inch, 8 inch, 20 inch, and 40 inch depths for the study sites in Southern California to evaluate ECOSTRESS ESI's ability to track VWC for 2019.

Site Name	Predominant Land Cover	Secondary Land Cover	R^2 -value ESI vs. VWC at 2 inch depth	R^2-value ESI vs. VWC at 4 inch depth	R^2-value ESI vs. VWC at 8 inch depth	R^2-value ESI vs. VWC at 20 inch depth	R^2-value ESI vs. VWC at 40 inch depth
Marble Creek	Shrubland	N/A	0.08	0.07	0.07	0.05	0.06
Doe Ridge	Shrubland	N/A	0.07	0.15	0.22*	0.24*	0.18
Deep Springs	Shrubland	N/A	0.01	0.03	0.04	0.03	0.04
Monocline Ridge	Grassland/ Pasture	N/A	0.6	0.13	0.66*	ND	ND
Death Valley Jct	Shrubland	Barren	ND	ND	ND	ND	ND
Shadow Mtns	Shrubland	N/A	ND	ND	ND	ND	ND
Cochora Ranch	Shrubland	N/A	0.08	0.09	0.11	0.12	ND

Stubble field	Shrubland	N/A	ND	ND	ND	ND	ND
Essex	Shrubland	N/A	0.00	0.56*	ND	0.56*	0.14

Note: *R^2>0.20,there is a significant positive correlation relationship between ESI and VWC
N/A-not applicable
ND-no data collected
NM-not measured by the station

Table 5: Correlation coefficient (R^2) values between ESI and VWC at the 2 inch, 4 inch, 8 inch, 20 inch, and 40 inch depths for the study sites in Sierra Nevada Region in California to evaluate ECOSTRESS ESI's ability to track VWC for 2020.

Site Name	Predominant Land Cover	Secondary Land Cover	R^2 value ESI vs. VWC at 2 inch depth	R^2 value ESI vs. at 4 inch depth	R^2-value ESI vs. VWC at 8 inch depth	R^2-value ESI vs. VWC at 20 inch depth	R^2-value ESI vs. VWC at 40 inch depth
Rubicon #2	Evergreen Forest	Evergreen Forest	0.00	NM	0.14	0.06	NM
Fallen Leaf	Shrubland	Evergreen Forest	0.02	NM	0.02	0.01	NM
Heavenly Valley	Shrubland	Evergreen Forest	0.16	NM	0.11	0.21*	NM
Hagans Meadow	Evergreen Forest	Shrubland	0.00	NM	0.08	0.09	NM
Echo Peak	Shrubland	Evergreen Forest	0.06	NM	0.11	0.12	NM
Horse Meadow	Shrubland	Evergreen Forest	0.07	NM	0.13	0.04	NM
Burnside Lake	Evergreen Forest	Shrubland	0.11	NM	0.12	0.19	NM
Carson Pass	Evergreen Forest	N/A	0.01	NM	0.02	0.04	NM
Forestdale Creek	Evergreen Forest	Shrubland	0.05	NM	0.11	0.34*	NM
Monitor Pass	Grassland/ Pasture	N/A	0.01	NM	0.03	0.03	NM
Spratt Creek	Shrubland	Evergreen Forest	0.01	NM	0.13	0.16	NM
Blue Lakes	Evergreen Forest	Evergreen Forest	0.04	NM	0.01	0.01	NM
Ebbetts Pass	Evergreen Forest	Shrubland	0.16	NM	0.37*	0.03	NM
Poison Flat	Evergreen Forest	N/A	0.23*	NM	0.23*	0.25*	NM
Lobdell Lake	Shrubland	N/A	0.02	NM	0.02	0.04	NM
Summit Meadow	Shrubland	Evergreen Forest	0.00	NM	0.01	0.03	NM
Sonora Pass	Evergreen Forest	N/A	0.00	NM	0.00	0.01	NM
Leavitt Meadows	Shrubland	N/A	0.01	NM	0.00	0.02	NM
Leavitt Lake	Evergreen Forest	Shrubland	0.06	NM	0.07	0.42*	NM
Bodie Hills	Shrubland	N/A	0.30*	0.21*	0.12	0.09	0.38**
Virginia Lakes Ridge	Shrubland	N/A	0.09	NM	0.09	0.18	NM

Note: *R^2>0.20, there is a significant positive correlation relationship between ESI and VWC
N/A not applicable
ND- no data Collected
NM-not measured by the station

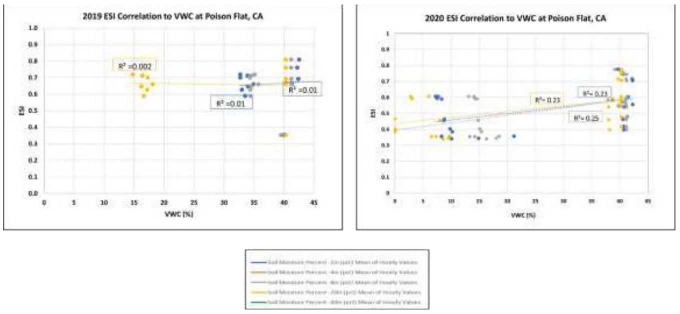

Figure 6: ESI correlation to VWC at Poison Flat, California for 2019-2020. There was a significant correlation between ESI and VWC at 2 inch, 8 inch, and 20 inch soil depths for both 2019-2020 with R^2>0.20.

Table 6: Correlation coefficient (R^2) values between ESI and VWC at the 2 inch, 4 inch, 8 inch, 20 inch, and 40 inch depths for the study sites in Southern California to evaluate ECOSTRESS ESI's ability to track VWC for 2020.

Site Name	Predominant Land Cover	Secondary Land Cover	R^2 value ESI vs. VWC at 2 inch depth	R^2 value ESI vs. at 4 inch depth	R^2-value ESI vs. VWC at 8 inch depth	R^2-value ESI vs. VWC at 20 inch depth	R^2-value ESI vs. VWC at 40 inch depth
Marble Creek	Shrubland	N/A	0.13	0.02	0.03	0.06	ND
Doe Ridge	Shrubland	N/A	0.20*	0.22*	0.06	0.34*	ND
Deep Springs	Shrubland	N/A	0.44*	0.46*	0.42*	0.16	ND
Monocline Ridge	Grassland/ Pasture	N/A	0.52*	0.40*	0.05	ND	ND
DeathValley Jct	Shrubland	Barren	0.20**	0.05	ND	ND	0.15
Shadow Mtns	Shrubland	N/A	ND	ND	ND	ND	ND
Cochora Ranch	Shrubland	N/A	0.25*	0.23*	0.16	0.05	0.02
Stubblefield	Shrubland	N/A	ND	ND	ND	ND	ND
Essex	Shrubland	N/A	ND	0.37*	ND	0.33*	ND

Note: *R^2>0.20,there is a significant positive correlation relationship between ESI and VWC
N/A- not applicable
ND- no data collected
NM- not measured by the station

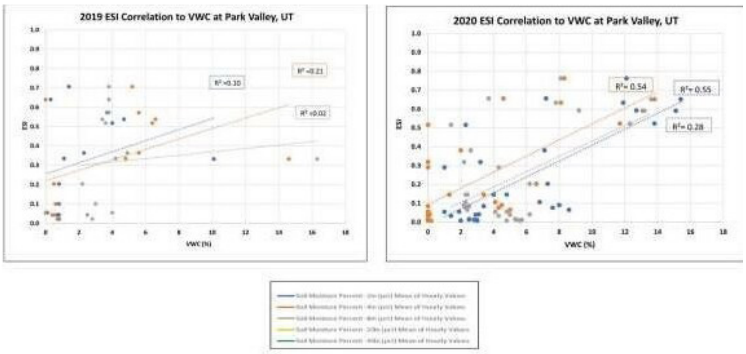

Figure 7: ESI correlation to VWC at Park Valley, UT for 2019-2020. There was a significant correlation between ESI and VWC at 2 inch, 4 inch, and 8 inch soil depths for both 2019-2020 with R^2>0.20.

Table 7: Correlation coefficient (R^2) values between ESI and VWC at the 2 inch, 4 inch, and 8 inch depths for the study sites in Utah, Nevada, and Idaho to evaluate ECOSTRESS ESI's ability to track VWC for 2019.

Site Name	Site Name	Secondary Land Cover	R^2 value ESI vs. VWC at 2 inch depth	R^2 yalue ESI vs. VWC at 4 inch depth	R^2-value ESI vs. VWC at 8 inch depth
Grouse Creek,UT	Shrubland	N/A	0.02	0.01	0.07
Park Vallev, UT	Shrubland	Grassland/pasture	0.01	0.21	0.02
Goshute,UT	Shrubland	N/A	0.21	ND	ND
Tule Valley,UT	Shrubland	N/A	0.00	0.40*	0.65**
Hals Canyon,UT	Shrubland	N/A	0.31*	0.47*	0.09
Cave Valley,UT	Shrubland	N/A	0.10	0.18	0.05
Vermillion,UT	Shrubland	N/A	0.33**	0.00	0.00
Green Mountain,NV	Shrubland	N/A	0.00	NM	0.00
Fawn Creek,NV	Evergreen	0.33*	0.33*	0.33*	0.33*
Forest	N/A	0.01	NM	0.06	0.33*

Ruby,NV	Shrubland	N/A	ND	ND	ND
Wilson Creek,ID	Shrubland	N/A	0.17	NM	0.01
Jordan Valley,ID	Shrubland	N/A	0.13	0.15	0.12

Note: *R^2>0.20,there is a significant positive correlation relationship between ESI and VWC
N/A- not applicable
ND- no data collected
NM-not measured by the station

Table 8: Correlation coefficient (R2) values between ESI and VWC at the 2 inch, 4 inch, and 8 inch depths for the study sites in Utah, Nevada, and Idaho to evaluate ECOSTRESS ESI's ability to track VWC for 2020.

Site Name	Predominant Land Cover	Secondary Land Cover	R^2 value ESI vs. VWC at 2 inch depth	R^2 value ESI vs. VWC at 4 inch depth	R^2-value ESI vs. VWC at 8 inch depth
Grouse Creek, UT	Shrubland	N/A	0.15	0.13	0.15
Park Valley, UT	Shrubland	Grassland/pasture	0.55*	0.54*	0.28*
Goshute, UT	Shrubland	N/A	0.62*	ND	ND
Tule Valley, UT	Shrubland	N/A	0.67*	0.55*	0.00
Hals canyon, UT	Shrubland	N/A	0.68*	0.65*	0.46*
Cave Valley, UT	Shrubland	N/A	0.29*	0.29*	0.40*
Vermillion, UT	Shrubland	N/A	0.21*	0.12	0.26*
Green Mountain, NV	Shrubland	N/A	0.19	NM	0.18
Fawn Creek, NV	Evergreen	0.33*	0.33*	0.33*	0.33*
Forest	N/A	0.29*	NM	037*	0.33*
Ruby, NV	Shrubland	N/A	0.51*	0.54*	0.06
Wilson Creek, ID	Shrubland	N/A	0.35*	NM	0.70*
Jordan Valley, ID	Shrubland	N/A	0.36**	0.47*	0.56*

Note: *R^2>0.20, there is a significant positive correlation relationship between ESI and VWC
N/A- not applicable
ND- no data collected
NM- not measured by the station

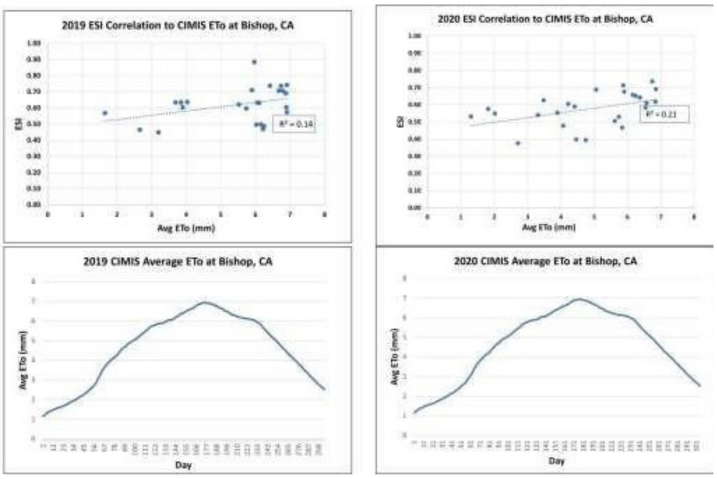

Figure 8: ESI correlation to daily ETo (Potential Evapotranspiration) at Bishop, California for 2019-2020.

Annual precipitation comparisons

The number of stations that showed a significant correlation between ESI and measured VWC in 2019 compared to 2020 was significantly different. To further analyze and explain these differences in precipitation between the two years, a two-tail t-test of equal variance was performed at each of the study regions. The results for the Great Basin region showed that the precipitation for 2019 was significantly greater among the study sites in comparison to precipitation in 2020, with a p-value<0.001. The Sierra Nevada region showed that the precipitation as well as the snow water equivalent for 2019 was significantly greater among the study sites in comparison to totals in 2020, with a p-value<0.05. Results for the Southern California desert region showed that the precipitation total for 2019 was significantly greater among the study sites in comparison to precipitation in 2020, with a p-value<0.001.

DISCUSSION

The main findings from this evaluation study of ECOSTRESS ESI image datasets were as follows: (1) ESI tracked soil moisture most closely at the 4 inch, 8 inch, and 20 inch soil depths in southern California desert locations where the land cover is predominantly shrubland, (2) in the forested Sierra-Nevada mountain region of California, ESI could not reliably track changes in soil moisture. This failure may be attributed to persistent snow cover and snow melt impacting the accuracy of ECOSTRESS surface temperatures that are related to vegetation moisture availability, and (3) in the Great Basin region, ESI could track soil moisture most closely at shallow soil layers <8-inch depth.

A common explanation for the lack of ESI correlations with VWC is that evapotranspiration rates in semiarid regions of the western United States are typically low throughout summer months, such that small variations in ET lead to large changes in the satellite-estimated ESI [4]. Who pointed out that this level of sensitivity in the satellite thermal measurements can lead to poor correlations of daily ESI with other drought indicators that are based on localized weather data inputs, like the Evaporative Demand Drought Index. It was also noted by these authors that ESI data derived from remote sensing instruments like ECOSTRESS are frequently missing for snow-covered mountainous regions of the western states, also presumably due to persistent cloud cover.

From studies of soil moisture, snowmelt and rainfall in a southern Sierra-Nevada mixed-conifer forest, others have reported that, below an elevation of 2000 m, soils have contact with weathered saprolite that can extend beyond a depth of 1.5 m, creating pathways for deep soil water percolation of rainwater [10]. Based on data from two snowmelt seasons, it was further reported that Sierra-Nevada forest soils dry out following snowmelt at relatively uniform rates. However, the timing of soil drying at a given site may be offset by up to four weeks, due to differences in snowmelt rates at different elevations and aspects.

It has been further reported that spring and summer rainfall most strongly impacted soil water changes at Sierra-Nevada sites with sparse vegetation cover [10]. Soil drying rates after a single rain event were found to be faster than following the principal snowmelt period of each year, but that soil water changes during the snowmelt season resulted from a combination of evapotranspiration and deep drainage. About one-third of annual evapotranspiration came from water storage below 1 m soil depth. Some drainage water was stored in the deeper regolith during periods of high rainfall. This reserve was available for tree transpiration during summer and fall months when shallow soil water storage was limited.

We found that ECOSTRESS ESI was able to track variations in VWC levels during the summer months of 2019 and 2020 at only 6 out of 21 Sierra-Nevada weather station sites. At the station sites where there was a significant correlation, results showed ECOSTRESS ESI was best able to track with VWC at the 20 inch soil depth. However, overall, ECOSTRESS ESI failed to consistently track with VWC in the forested weather stations sites in this forested mountain region.

One soil moisture dataset in the Sierra-Nevada region merited special consideration as an example of localized topography influencing VWC variations, namely the Poison Flat SNOTEL station. This station was located on the edge of a wet meadow that can remain saturated below-ground into the summer season, especially after high snowfall seasons (J. Anderson, USDA, personal communication). The USDA soil water sensors and snow pillow are located slightly out of the meadow near an area of forest cover, where the water table is still elevated. This explains why all soil depths at this site remained at around 40% VWC throughout the year, and the daily measured VWC was not correlated strongly with ECOSTRESS ESI variations. Consequently, the Poison Flat dataset cannot be considered representative of upslope sites away from wetter meadow sites.

Upon further analysis, the t-tests performed showed a significant difference in precipitation and snow cover between 2019 and 2020 in the Sierra-Nevada region. It is plausible to conclude that some of the differences in correlation results among the various study regions can be attributed to differences in precipitation and snow cover from year-to-year. ECOSTRESS PET utilizes satellite estimates of albedo for the pixels of interest, which can be influenced by cloud cover and snow cover, since it uses thermal-infrared wavelengths to estimate the temperature of the land surface. In 2019, there was significantly more rainfall and snow cover in all the study regions when compared to 2020. There were also fewer ESI values recorded by ECOSTRESS in 2019 compared to 2020.

We found that ECOSTRESS ESI was able to track rapid changes in VWC levels during the summer months of 2019 and 2020 at 10 out of 12 Great Basin stations. Great Basin station data showed that ESI was able to track with VWC at the 2 inch soil depth most consistently. However, it was also able to track VWC well at the 4 inch and 8 inch soil depths. The negative correlation at the 2 inch depth in Ruby Ridge Valley, Nevada was attributed to missing VWC data for half of the corresponding dates for which ESI was recorded.

Based on field studies in the northern Great Basin (around Reno, Nevada), it was reported that abundant spring precipitation in most years contributed to relatively high rates of ET water flux early in the yearly growing season [14]. The depletion of soil moisture during the hot summer months caused reductions in sagebrush vegetation cover and in plant ET fluxes. In areas infested with cheatgrass (*Bromus tectorum* L), steep declines in ET levels during the summer months were commonly measured, as rapid senescence of this invasive annual grass was associated with a 60% decline in ET fluxes by July.

Several soil moisture datasets in the Great Basin region merited special attention as examples of macro-climate patterns influencing VWC variations, namely Tule Valley and Hals Canyon, UT and Ruby, NV, where soil water levels did not change at 20 inch and 40 inch depths even with high rainfall events. It was surmised that rain storm amounts at these sites were generally insufficient to infiltrate and wet-up the 20 inch and 40 inch sensors during periods outside of the winter snowmelt season (USDA, personal communication). Two other USDA station datasets, at Vermillion, UT and Jordan Valley, ID, showed that VWC often dried down to near 0% at the 2 inch depth, which suggested that the soils at these sites had extremely low water holding capacity under hot summer climate conditions.

Similar patterns in soil moisture measurements were observed at several Mojave Desert USDA stations, including Bodie Hills, Marble Creek, Deep Springs, and Death Valley, CA. In this extremely arid region, it is unusual to experience a series of summer rain events of sufficient duration and intensity to move the wetting front to soil depths greater than 4 inch (K. Sutcliffe, USDA, personal communication). Additionally, many Mojave Desert soils have diagnostic soil horizons of accumulated clay or calcium carbonate. These horizons create a barrier to unsaturated flow and typically form at the average depth of the wetting front (M. Cole, USDA, personal communication).

To better understand patterns of soil water use in the Mojave Desert, it was reported that, early in the growing season, extraction of water from beneath plant canopies was slightly greater than from shrub interspaces, but that on an annual basis, soil water extraction from beneath plant canopies was not significantly different than that from shrub interspaces [15]. The lower limit of soil water extraction varied from 4 to 10 percent VWC, depending on soil texture. This study concluded that annual ET in the Mojave Desert is dependent largely on winter precipitation rather than on shrub species composition.

From other studies of Mojave Desert soils, it was reported that intermittent increases in water potentials in the upper 0.75 m of a soil indicated that percolation of precipitation was effectively impeded by the natural capillary break in the desert soil profile (with loamy sand layer above a gravelly coarse sand layer) [16]. At these site studies, all of the water that accumulated annually in the uppermost soil layer was used by desert plant cover to meet the high ET demand. In another study of the downward movement of water and chemical tracers in the Mojave Desert, it was found that shrub roots act to increase downward rainwater flux into desert soils via root channel preferential flow pathways [17]. Previous studies have established that vegetation cover in deserts of the southwestern U.S. positively affected infiltration rates of precipitation by altering bulk density and organic matter content under the plant cover compared to open interspaces [18,19].

If the phenomenon of preferential flow of precipitation along desert vegetation root channels was a common process at the USDA stations located in the southern California deserts, this could help explain why we found that 5 out of 9 sites in 2019 and 2020 showed a positive correlation between ESI and VWC at 4 inch and 8 inch depths, but not at the deeper soil layers [20]. The 20 inch and 40 inch soil depths at these Southern California stations showed that VWC did not fluctuate as expected. Soil moisture at these depths remained at a constant level, while ESI decreased. This trend can help explain the negative correlations between ESI and VWC at the 20 inch and 40 inch depths. The rapid absorption of rainwater by the deep-rooted shrubs located at the 20 inch and 40 inch depths help to explain why the shallow depths were drying as expected and correlating closely with ESI, but not at the 20 inch and 40 inch layers [21]. During intervals when ESI was decreasing, precipitation could be removed from the shallow soil depths, due to the root channel preferential flow pathways which also helps maintain a relatively constant VWC at the deeper soil layers.

Our results further indicated that ECOSTRESS ESI could not track CIMIS station ETo estimated in California study areas. As was expected, CIMIS ETo decreased during the summer months as temperatures increased. As the CIMIS ground-based ETo flux estimates increased in the summer months of 2019 and 2020, ESI did not decrease linearly, which would have been expected from increasing PET detected by the ECOSTRESS algorithm. Since ESI is the ratio of AET to PET, the correlation between ESI and ETo should have shown an inverse relationship. However, ESI did not change as expected, instead increasing during the hot and dry summer months, while decreasing during the first months of the year.

On the contrary, a study focused in southern California (Riverside County) 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 ETo estimates [9]. Typical linear correlation R^2 values were high at >0.80 and the root mean square error (RMSE) were 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 pixels area of interest, which can be influenced by variable surface reflectance conditions around the station site. It is plausible that such complex surface reflectance conditions around the station sites in our study area undermined the ECOSTRESS PET calculations in a similar manner [22].

An alternative explanation would be the inability of ECOSTRESS to produce regular ESI images constantly throughout the year. For instance, at the Markleeville CIMIS for 2019, there was no recorded ESI data, while there was sufficient ETo reported by the CIMIS stations. However, in 2020, Markleeville CIMIS provided ETo data for only the months of May to October, while North Owens Lake and South Owens Lake were missing ETo data for the entire period of 2019-2020. This lack of consistent data reported by both CIMIS and ECOSTRESS made it difficult to determine a correlation between satellite ESI and ground-based ETo.

CONCLUSION

We conclude that ECOSTRESS ESI cannot consistently and closely track daily soil moisture variations and serve as a reliable drought indicator at the macro-climate scale (>100 km) across major eco-regions of the western United States. ESI was able to track soil moisture most closely at the 4 inch, 8 inch, and 20 inch soil depths in southern California desert locations, and in the Great Basin region at 2 inch and 8 inch soil layers. However, in the forested Sierra-Nevada mountain region of California, ESI cannot reliably track changes in soil moisture. This failure may be attributed to persistent snow cover and snow melt impacting the accuracy of ECOSTRESS surface temperature detections.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY STATEMENT

Any data used in this study may be obtained upon request to chris.potter@nasa.gov.

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