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Source: Rangelands, 38(4) : 183-190

Published By: Society for Range Management

URL: https://doi.org/10.1016/j.rala.2016.06.002

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Evaluating New SMAP Soil Moisture for Drought Monitoring in the Rangelands of the US High Plains

By Naga Manohar Velpuri, Gabriel B. Senay, and Jeffrey T. Morisette

On the Ground

- Level 3 soil moisture datasets from the recently launched Soil Moisture Active Passive (SMAP) satellite are evaluated for drought monitoring in rangelands.
- Validation of SMAP soil moisture (SSM) with *in situ* and modeled estimates showed high level of agreement.
- SSM showed the highest correlation with surface soil moisture (0-5 cm) and a strong correlation to depths up to 20 cm.
- SSM showed a reliable and expected response of capturing seasonal dynamics in relation to precipitation, land surface temperature, and evapotranspiration.
- Further evaluation using multi-year SMAP datasets is necessary to quantify the full benefits and limitations for drought monitoring in rangelands.

Keywords: drought monitoring, remote sensing, SMAP, soil moisture, rangelands.

Rangelands 38(4):183–190

doi: 10.1016/j.rala.2016.06.002

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Droughts are one of the costliest natural disasters and globally affect a large number of people and their livelihoods every year. In the United States, droughts, on average, cause financial damage of $6 to $8 billion per year.[1] The 1996 drought resulted in estimated loss of about $6 billion for the state of Texas alone[1] and had the greatest negative impact on rangeland ecosystems. Gathering knowledge of the onset, duration, and severity of prior droughts is important for efficient planning of drought mitigation strategies. In order to minimize losses due to droughts and to manage the impact of water scarcities, it is essential to develop scientifically-based drought monitoring tools and early warning systems.[2]

Understanding the hydrologic cycle and its parameters is of paramount importance to identify the nature and characteristics of droughts. Precipitation is one of the most important parameters that provides information on the availability of water and potential occurrence of drought. Although precipitation is the best observed hydrologic variable, it alone cannot adequately characterize a drought. Nevertheless, several widely used drought monitoring indices have been developed based on the information obtained from precipitation data.[3] Other agro-hydrologic parameters such as land surface temperature, normalized difference vegetation index (NDVI), and evapotranspiration (ET) have also been used in several standard drought indices.[4] While each of these standard indices used for drought monitoring has its own advantages and disadvantages, all of them are expressions of the key hydrologic variable, i.e., soil moisture. It may be worth considering a multi-sensor approach that would look for a convergence of evidence, which would allow for as many of the agro-hydrologic variables as possible when trying to derive a reliable drought product that can be used consistently over space and time.[2]

Of all the hydrologic variables, soil moisture is one of the least measured variables for understanding droughts at large spatial scales. Because of the lack of large-scale and long-term observations of soil moisture in the United States and elsewhere, the use of simulated soil moisture fields from land surface models, forced with observed precipitation and near surface meteorology, has been a viable aproach.[2] Soil moisture combines the response from recent precipitation, antecedent moisture, and the soil and vegetation characteristics. The amount of water in the top layers of the soil is correlated with shorter-term precipitation and atmospheric demand. This governs the amount of water available to meet the demands of evapotranspiration and, in turn, plant growth. In water-limited ecosystems such as semi-arid rangelands, soil

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water content in the root zone is a strong predictor of future vegetation condition. Therefore, characterizing soil moisture plays a critical role for drought monitoring in general but becomes a critical parameter for water-limited rangeland ecosystems.

The goal of this study is to evaluate the capability of level 3 soil moisture estimates obtained from the Soil Moisture Active Passive (SMAP) mission particularly for drought monitoring over rangelands. However, due to the limited (nine months) and preliminary nature of the SMAP data, this paper focuses on *in situ* validation as well as a comparison of SMAP soil moisture (SSM) with other currently available drought monitoring data. The results should be considered a demonstration of the reliability and usefulness of SSM but not an exhaustive synthesis on its application for drought monitoring, which would require multi-year time series evaluation of the product over diverse ecosystems.

Need for Satellite-Based Estimates of Soil Moisture

Soil moisture may be measured by a variety of methods, but unfortunately, there is no comprehensive, national network of soil moisture monitoring instruments[3] that can provide us with seamless information on soil moisture status across the nation. Although there are few national networks available, the density of observations does not provide a comprehensive understanding of change in soil moisture conditions nationally. Hence, soil moisture is generally modeled over large areas using precipitation and temperature, or through root-zone water balance modeling. The SMAP mission is one of the first Earth observation satellites built by the National Aeronautics and Space Administration (NASA) in response to the National Research Council's Decadal Survey to provide global measurements of soil moisture in the top 5 cm of the soil and freeze/thaw state.[5] The passive radiometer onboard SMAP measures naturally emitted microwave radiation at 1.4 GHz. The radiometer detects the minute differences in microwave signals caused by the presence of moisture on the land surface. In general, a dry surface (such as desert sand) emits larger amounts of microwave radiation whereas surface water features emit very low amounts of radiation. Using satellite-based soil moisture estimates for drought monitoring has several advantages: 1) global coverage enables monitoring of large areas; 2) daily coverage improves the ability to monitor the onset of drought-related events; 3) the application of consistent data and algorithms enables inter-comparison of SMAP data over time; 4) lower frequency of microwave (e.g., L-band) enables all-weather (that is, cloud-penetrating) monitoring; 5) soil moisture observations are made even when sparse and moderate vegetation is present on the soil surface; and 6) unlike other visible/near-infrared sensors, SMAP measurements are independent of solar illumination which allows for day and night observations. On the other hand, these soil moisture estimates for drought monitoring have some limitations: 1) soil moisture estimates that can have higher uncertainties or be unavailable over regions with dense vegetation, 2) the SSM estimates have coarse resolution (36 km), and 3) validation needs to be performed using *in situ* observations.

Evaluation of SSM Using *In Situ* and Modeled Datasets

During August 2015, NASA released the first calibrated level 1 data from SMAP.[i] By January 2016, all radiometer data products from the SMAP were available. At the time of the writing of this paper, SMAP level 3 data products[6] available for April to December of 2015 were obtained from the National Snow and Ice Data Center (NSIDC) website.[ii] These preliminary beta-quality data are generated using preliminary algorithms that are not yet validated and, hence, subject to some degree of uncertainties and improvements.

In this study, we validated the performance of the early access SSM product available at 36 km spatial resolution equal area scalable Earth-2 (EASE2) grids covering rangeland regions in the states of Texas and Oklahoma, USA. First, we validated SSM against *in situ* soil moisture observations obtained from eight United States Climate Reference Network (USCRN) sites[7] (see Fig. 1 for locations). *In situ* soil moisture measurements are publicly available online.[iii] We also performed basin-scale validation using modeled soil moisture obtained from the VegET agro-hydrologic model.[8] Because SMAP data products and validation data used in this study are available at different spatial resolutions, we summarized both input SMAP and validation data at a watershed scale. We identified hydrologic units (HUC8 watersheds, HUC) that are dominated by grasslands and shrublands. We used 0.5-km land cover climatology products[iv] obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) data[9] to compute the percentage of grasslands and shrublands for each HUC (Fig. 1). Then, we selected HUCs with grassland and shrublands cover greater than 70%. Fig. 1 shows grasslands- and shrublands-dominated watersheds across the United States. However, in this study, we used HUCs covering the USCRN sites in Texas and Oklahoma. The SMAP level 3 soil moisture is summarized (spatial average) for eight HUCs and temporally aggregated over an 8-day time period for comparison with validation products. The list of all the datasets and their characteristics are presented in the appendix, Table A1.

Point and Basin-Scale Validation of SSM

Retrieval of soil moisture from brightness temperature observations is based on the radiative transfer equation, commonly known in the passive microwave soil moisture community as the tau-omega model.[10] Allowing for spatial heterogeneity and scaling issues, soil moisture measurements from SSM should be comparable to *in situ* measurements or modeled soil moisture estimates. Twofold validation of SSM was conducted in this study. First, SSM estimates (cm^3/cm^3) were validated using *in situ* soil moisture observations (m^3/m^3) obtained from eight USCRN sites. Second, basin-scale

[i] Read about this release at http://smap.jpl.nasa.gov/news/1246/.

[ii] Available at http://nsidc.org/data/docs/daac/smap/sp_l3_smp/.

[iii] Available at https://www.ncdc.noaa.gov/crn/.

[iv] Available at http://landcover.usgs.gov/global_climatology.php.

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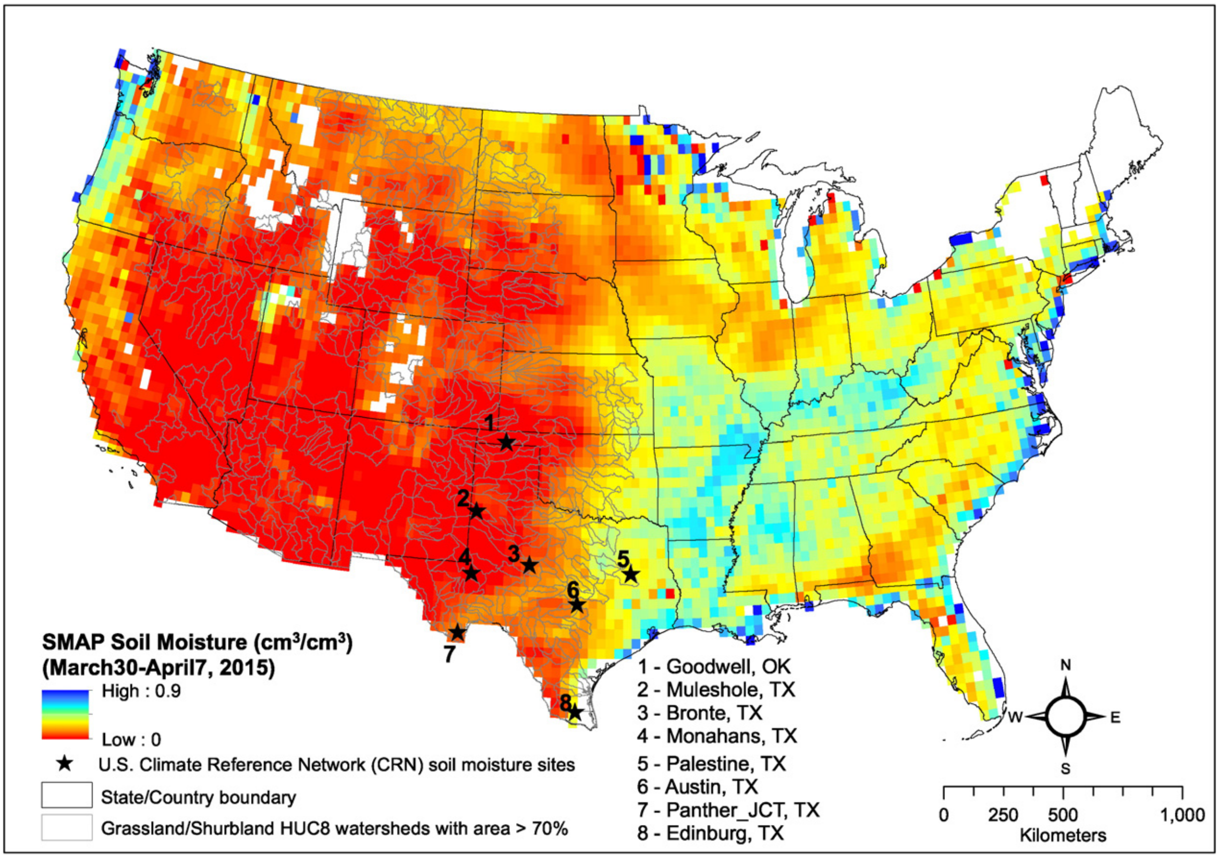

Figure 1. Study area showing hydrologic units (HUC8 watersheds) that are dominated by grasslands and shrublands (area > 70%). Stars represent locations of United States Climate Reference Network (USCRN) soil moisture observation sites used in this study. The background image is the sample image of average SMAP Soil Moisture fields summarized for 30 March to 7 April 2015.

validation was performed using modeled soil moisture estimates (mm) obtained from the VegET agro-hydrologic model, which produces daily estimates of root-zone soil moisture by computing soil water balance driven by NEXRAD precipitation (next generation radar)[v] and land surface phenology obtained from remote sensing datasets.[8] Daily modeled soil moisture estimates were further aggregated to 8-day and summarized for 8 HUCs corresponding to USCRN sites. Validation results are presented in Fig. 2 for eight USCRN sites. Point-based validation results (Fig. 2A) indicate a high level of agreement with *in situ* soil moisture sites with the Pearson's correlation coefficient "r" ranging from a low of 0.53 (Panther Junction, TX) to a high of 0.95 (Austin, TX). Similarly, good agreement was found for basin-scale validation with r ranging from a low of 0.48 (Muleshole, TX) to a high of 0.96 (Palestine, TX) (Fig. 2B). It is clear from the validation results that SSM was able to capture day-to-day variability in observed as well as modeled soil moisture. However, there seem to be inconsistent magnitude discrepancies among SSM, *in situ*, and modeled SM in some sites. Hence, it is important to identify and understand the nature and source of systematic and random errors in diverse ecosystems before integrating SSM with drought monitoring tools and procedures.

[v] View the NEXRAD precipitation analysis at http://www.srh.noaa.gov/rfcshare/precip_about.php.

Root Zone SM vs. SSM

Optimally, the SMAP radiometer can measure soil moisture up to 5 cm depth. However, understanding the amount of moisture available in the root zone would provide an accurate assessment of drought on rangeland vegetation. To understand the impact of depth on SSM, we compared SSM with *in situ* measurements made at different depths (5, 10, 20, 50, and 100 cm) obtained from USCRN sites.[7] Comparison results (r) presented in Fig. 3 indicate that SSM showed the highest correlation with *in situ* measurements at 5 cm for all the sites, and correlation decreased in the deeper layers of soil. Although, for two sites (Goodwell, OK, and Palestine, TX) SSM compared well with *in situ* measurements made at all depths. The variability in soil moisture observations over April–December is shown as shaded regions in Fig. 3. The relationship could change depending on the rain event, vegetation, and soil characteristics at a given location. However, results from this analysis indicated that SSM shows a relatively strong relationship with most SM measurements made up to 20 cm, which is important for understanding the impact of drought in rangeland ecosystems.

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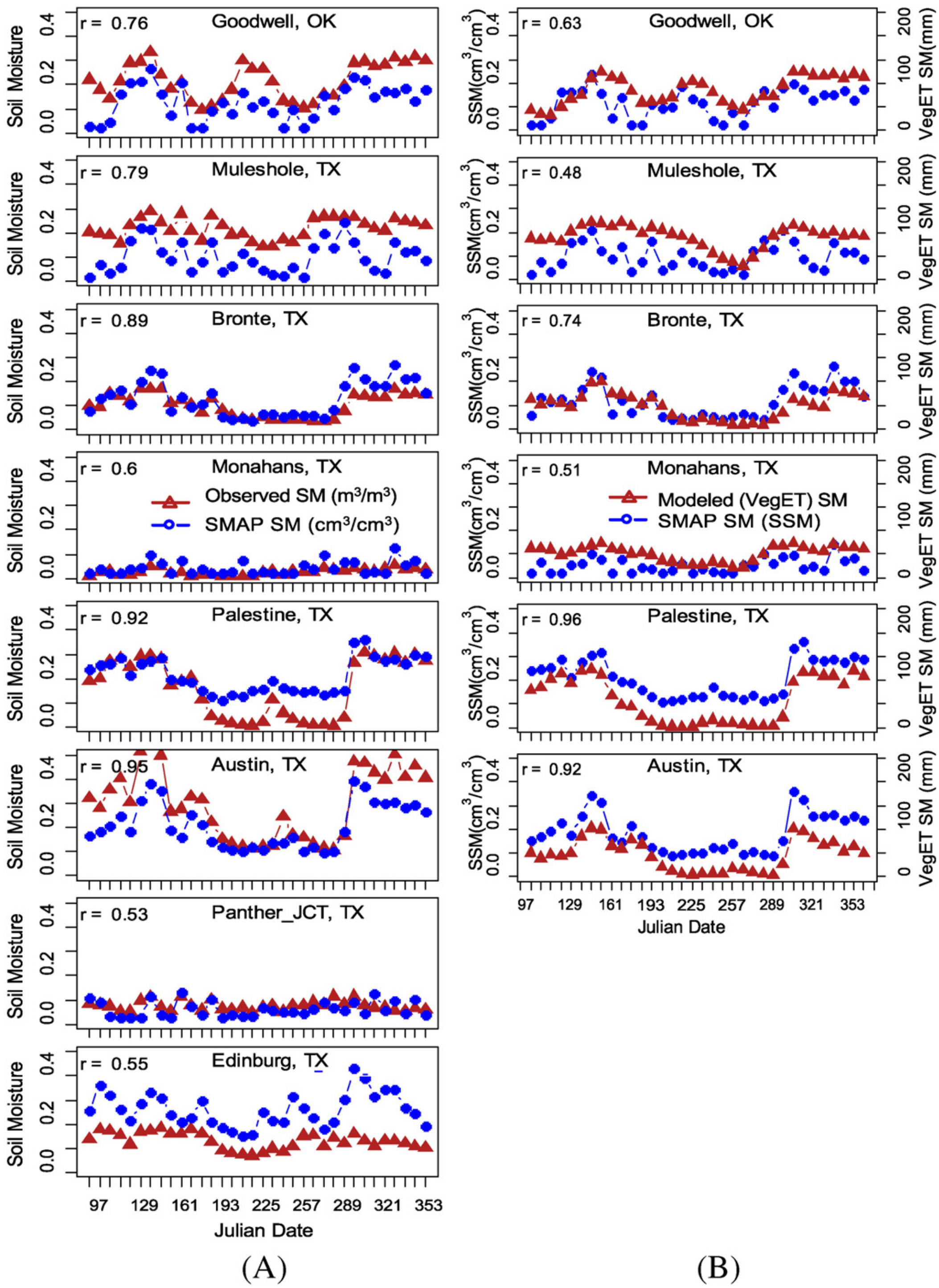

Figure 2. Validation of SMAP soil moisture in Texas and Oklahoma. (A) Point validation of SMAP soil moisture vs. observed soil moisture from eight USCRN sites (see Fig. 1). (B) Basin validation of SMAP HUC8 soil moisture vs. modeled HUC8 soil moisture obtained from the VegET model. Note: Modeled estimates of soil moisture (VegET SM) are not available for Panther Junction, TX, and Edinburg, TX. The data used to generate this figure are available at https://www.sciencebase.gov/catalog/item/5769847ae4b07657d1a05fb2.

Comparison of SSM with Other Agro-Hydrologic Variables

Some of the key agro-hydrologic variables that are most commonly used to generate drought indices include precipitation, normalized differential vegetation index, land surface temperature, and ET. It is important to determine if the SMAP radiometer responds to some of these drivers and response variables. First, to understand how well the SMAP radiometer is responding to the increase or decrease in soil moisture content due to a rain event (or lack thereof), we tested SSM against

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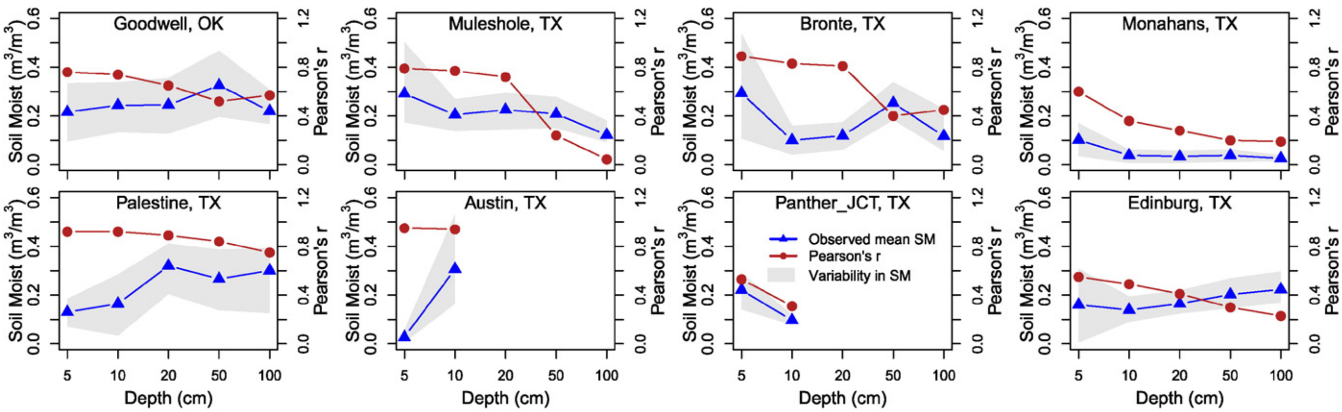

Figure 3. Comparison of SMAP soil moisture against *in situ* soil moisture measurements (made at different soil depths) obtained from USCRN sites. The shaded area represents soil moisture variability (max-min) for each station. Note: Austin and Panther Junction sites do not have soil moisture observations for depths more than 20 cm. The data used to generate this figure are available at https://www.sciencebase.gov/catalog/item/576986e3e4b07657d1a05fc0.

precipitation data. Eight-day precipitation totals for the eight HUCs covering USCRN sites were summarized from 4-km Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation datasets[11] obtained from the PRISM Climate Group website.[vi] Fig. 4 (top row) shows the comparison results of SSM plotted with PRISM precipitation. Comparison results with PRISM precipitation showed reasonable agreement with rainfall (r values ranging from 0.56–0.71).

Second, to determine if SSM shows response to changes in land surface temperature (LST), we plotted the MODIS LST (MOD11A2) 8-day average obtained from MODIS onboard the Terra satellite (because overpass times from Terra are closer to SMAP overpass times than those of the Aqua satellite). MODIS LST, derived from MODIS thermal bands, is an important parameter, closely linked to soil moisture and widely used to estimate ET. MODIS products are available on a near-daily basis and available freely via the Land Processes Distributed Active Archive Center (LPDAAC) web page.[vii] Results indicate (Fig. 4, middle row) that, on average, SSM showed an expected negative relation with MODIS LST with a wide range of r values from -0.25 for Muleshole and Panther Junction, TX, to -0.79 for Palestine, TX. Low correlations resulted from the lack of range in soil moisture estimates in some HUCs.

In general, SSM and modeled actual ET estimates cannot be directly compared (as ET is driven by both available energy and soil moisture). However, under non-energy limiting environments, ET is expected to respond positively to the available soil moisture. Hence, in this study we produced normalized ET (ETn) by creating a ratio between actual ET (ETa) obtained from the VegET model[8] with potential ET (PET) estimates (obtained from University of Idaho website[viii]) to exclude seasonality (energy component) of ET, thus making ETn more comparable to soil moisture. Therefore, comparisons between ETn and SSM would provide insights into a potential convergence of evidence approach for drought monitoring. Comparison results of ETn with SSM are presented for 6 HUCs in Fig. 4 (bottom row). On average, SSM showed a strong positive relation with ETn with r values ranging from a low of 0.29 for Muleshole, TX, to a high of 0.94 for Palestine, TX. Comparison results from Fig. 4 reinforce the fact that SSM can complement and validate other agro-hydrologic variables used in drought monitoring in rangeland ecosystems with a potential of being used as an input to developing a robust multi-index drought monitoring system.

Drought Monitoring Using SSM

Drought monitoring is a complex process and depends on a variety of complex hydrological and physiological factors that are challenging to monitor consistently and exhaustively in space and time.[1] Currently, the US Drought Monitor (USDM) offers weekly data on the occurrence and severity/intensity of drought in the United States. The USDM provides a consistent and usable drought product generated by combining information from a variety of factors and drought indices. In this study, we directly (qualitatively) compared drought severity images for parts of the southern United States obtained from the USDM with the SSM summaries for the grassland HUCS over Texas and Oklahoma watersheds (Fig. 4).

Qualitative comparison of SMAP soil moisture and drought images from USDM are shown in Fig. 5. Drought graphics obtained from USDM indicate that regions were abnormally dry during early September 2015 and that drought severity increased from dry to moderate to severe and extreme drought in just a few weeks. By 20 October 2015, several regions in Texas were showing exceptional drought intensity. However, short duration rains that started just after 20 October 2015 provided relief from the exceptional drought conditions. SSM images for the same region indicate a similar

vi View the PRISM group website at http://www.prism.oregonstate.edu/.

vii View the LP-DAAC website at https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod11a2.

viii Available at http://metdata.northwestknowledge.net/.

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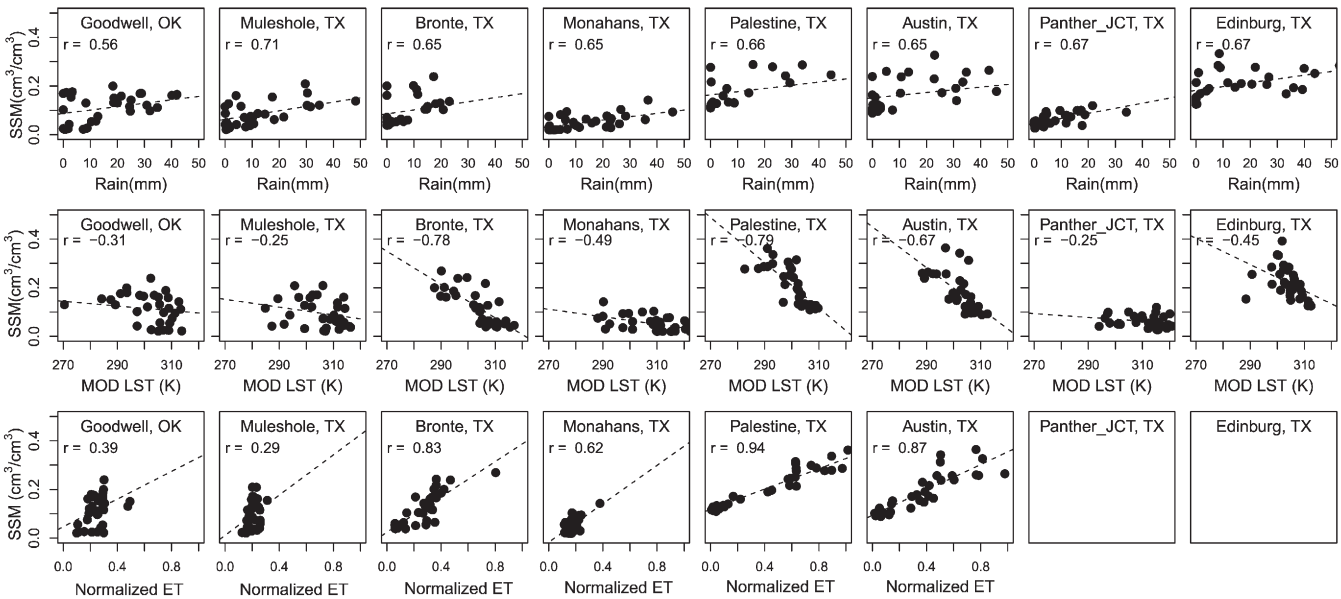

Figure 4. Scatterplots showing comparison of SMAP soil moisture (SSM) with other agro-hydrologic (drives and response) variables for the eight HUCs covering the USCRN soil moisture observation sites. *Top row:* SSM vs. PRISM precipitation data; *Middle row:* SSM vs. MODIS land surface temperature; *Bottom row*: SSM vs. normalized modeled evapotranspiration (ETa/PET) obtained from the VegET model. The data used to generate this figure are available at https://www.sciencebase.gov/catalog/item/57699ebfe4b07657d1a05feb. Note: Modeled ET estimates for Panther Junction, TX, and Edinburg, TX, were not available.

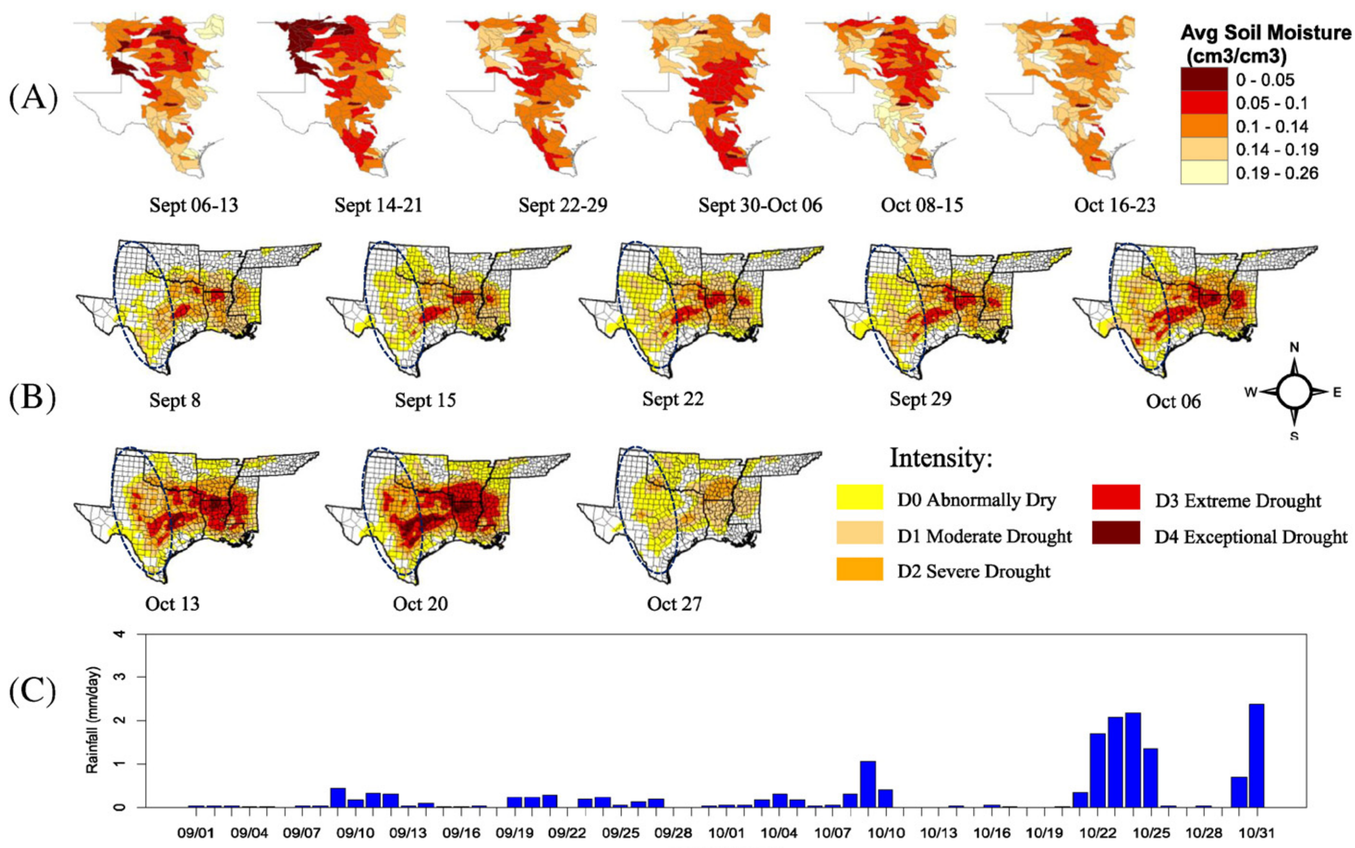

Figure 5. Drought representation in the rangelands of Texas (SeptemberOctober 2015). (A) SMAP soil moisture for Julian dates 249289. (B) Weekly drought images obtained from the US Drought Monitor. (C) Mean daily precipitation from Texas and Oklahoma grassland-dominant HUC8 polygons.

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improving trend in soil moisture status. SSM data indicated that during the early part of September 2015 (Julian dates 249, 257, and 265) through mid-October 2015 (Julian dates 273 and 281) soil moisture levels declined substantially from 0.3 to 0.0 cm^3/cm^3 over some regions of Texas and Oklahoma. However, rain events that occurred after 20 October 2015 improved the soil moisture level back to early September 2015 levels as corroborated by data obtained from the USDM. This finding indicates that soil moisture images obtained from SMAP are consistent with, and could potentially be incorporated into, drought monitoring tools such as the USDM. Although only a qualitative comparison between SSM and USDM is made, understanding the differences in these two datasets will help us develop a more quantitative analysis and integration. The SSM provides information on soil moisture or the amount of soil moisture deficit, whereas the USDM provides information on drought severity classification based on a multitude of inputs.

This study presented initial insights and demonstrated the potential of using SSM for drought monitoring studies in the rangeland ecosystems. The SMAP satellite is providing, for the first time, spatially explicit, global observations of soil moisture at 36-km spatial resolution. This initial investigation indicates that there is potential for SMAP data to contribute to existing drought monitoring tools and procedures. This is a step forward towards building a national soil moisture monitoring system, without which, quantitative measures of drought will remain difficult to judge.[3]

It must be stressed, however, that this study used only 9 months (April–December 2015) of beta quality, early release data with preliminary algorithms and are subject to uncertainties. This study is based on the early adopter data to determine initial accuracy and usefulness of the SSM product. Hence, care should be taken in generalizing results from this study. As more data become available, comprehensive evaluations of SSM over longer time periods and larger areas will be necessary to understand the full benefits and limitations of using SMAP data for drought monitoring. Improved understanding can benefit from additional studies that include multi-year time series of SMAP data and studies that focus on comprehensive evaluations of SSM at a) field or pixel scale, b) regional scale/watershed scale, and c) global scale. Furthermore, studies integrating field soil moisture measurements wherever available with SSM for monitoring drought and its severity according to soil types and hydro-climatic regions can advance our knowledge of using SMAP data for drought monitoring. Studies that work to understand the relationships between available soil moisture and changes in rangeland biomass, drought onset, frequency, and severity in rangeland ecosystems will be needed as well. Because the SMAP data are independent of solar illumination and unique from the primary data used in other drought indices, studies that explore how these data complement (as opposed to replace) existing monitoring tools and procedures will be important as we work toward building an integrated drought monitoring approach that takes advantage of all available data to help decision makers mitigate the impact of drought in a timely manner.

Acknowledgements

This work was performed under US Geological Survey (USGS) contract G13PC00028 in support of the Water-SMART program. Partial funding for this research was provided by the USGS through the North Central Climate Science Center. We gratefully thank the NASA Early Adaptor Program for making SMAP data available for this study. All the data used in this study are publicly available and links to download data are provided in the manuscript. Also data that support results (figures) produced in this study are available on ScienceBase (links provided for each figure). We thank and express our sincere appreciation to two anonymous reviewers for their constructive comments and suggestions to improve the manuscript. We also thank Dr. Shahriar Pervez, Tom Adamson, and Sandra Cooper for their comments and review. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Appendix A

Table A1. Characteristics and source of input and validation data used in this study

No.	Dataset	Source/ Satellite/ Sensor	Time period	Resolution	Reference
1	SMAP Level 3 soil moisture	SMAP Radiometer	Apr-Dec 2015 (daily swaths)	36 km	6
2	PRISM Rainfall	PRISM model	Apr-Dec 2015 (daily aggregated to 8-day)	4 km	11

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Table A1 (*continued*)

No.	Dataset	Source/ Satellite/ Sensor	Time period	Resolution	Reference
3	MODIS land surface temp (LST)	MODIS Terra (MOD11A2.005)	Apr-Dec 2015 (8-day composites)	1 km	-
4	Modeled soil moisture	VegET Model	Apr-Dec 2015 (8-day composites)	5 km	8
5	Actual evapotranspiration	VegET Model	Apr-Dec 2015 (8-day composites)	5 km	8
6	*In situ* soil moisture	US Climate Reference Network Stations	Apr-Dec 2015 (daily aggregated to 8-day)	-	7
7	Hydrologic units for CONUS	USGS	-	-	-
8	Global Land cover climatology	MODIS (MCD12Q1)	-	0.5 km	9

References

1. Wilhite, DA 2000. Drought as a natural hazard: Concepts and definitions. In: Drought: A Global Assessment, edited by D.A. Wilhite, London: Routledge. p. 3-18.
2. Sheffield, J, G Goteti, F Wen, and EF Wood. 2004. A simulated soil moisture based drought analysis for the United States. *J Geophys Res Atmos* 109(D24).
3. Keyantash, J, and JA Dracup. 2002. The quantification of drought: An evaluation of drought indices. *Bull Am Meteorol Soc* 83:1167-1180.
4. Senay, GB, NM Velpuri, S Bohms, M Budde, C Young, J Rowland, and JP Verdin. 2014. Drought monitoring and assessment: remote sensing and modeling approaches for the famine early warning systems network. In: Paolo P, & Baldassarre GD, editors. Book on Hydro-Meteorological Hazards, Risks, and Disasters. Elsevier.
5. Entekhabi, D, EG Njoku, PE Neill, KH Kellogg, WT Crow, WN Edelstein, and JV Zyl. 2010. The soil moisture active passive (SMAP) mission. *Proc IEEE* 98:704-716.
6. O'Neill, PE, S Chan, EG Njoku, T Jackson, and R Bindlish. 2015. SMAP L3 Radiometer Global Daily 36 km EASE-Grid Soil Moisture, Version 1. Boulder, Colorado USA: NASA National Snow and Ice Data Center Distributed Active Archive Center [Available at: http://dx.doi.org/10.5067/HF1KOE0Q85V7].
7. Bell, JE, MA Palecki, CB Baker, WG Collins, JH Lawrimore, RD Leeper, ME Hall, J Kochendorfer, TP Meyers, T Wilson, and HJ Diamond. 2013. U.S. Climate Reference Network soil moisture and temperature observations. *J Hydrometeorol* 14:977-988.
8. Senay, GB 2008. Modeling landscape evapotranspiration by integrating land surface phenology and water balance algorithm. *Algorithms* 1:52-68.
9. Broxton, PD, X Zeng, D Sulla-Menashe, and PA Troch. 2014. A global land cover climatology using MODIS data. *J Appl Meteorol Climatol* 53:1593-1605.
10. Mo, T, BJ Choudhury, TJ Schmugge, JR Wang, and TJ Jackson. 1982. A model for microwave emission from vegetation-covered fields. *J Geophys Res Oceans* 87:11229-11237.
11. Daly, C, JW Smith, JI Smith, and RB McKane. 2007. High-resolution spatial modeling of daily weather elements for a catchment in the Oregon Cascade Mountains, United States. *J Appl Meteorol Climatol* 46:1565-1586.

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This work was performed under the United States Geological Survey (USGS) contracts G13PC00028 in support of the WaterSMART program. Partial funding for this research was provided by the USGS through the North Central Climate Science Center. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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