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Idaho Water Resources

Estimating Soil Moisture in Semiarid Sagebrush Steppe Utilizing NASA Satellite Imagery

DEVELOP Technical Report

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1. Abstract

Soil moisture is a critical component of ecosystem health, particularly in semi-arid landscapes where seasonal and infrequent precipitation is one of the primary controls on vegetation health and productivity. Current land management practices for soil moisture data collection rely on costly and time-consuming field sampling or extensive modeling. The introduction of remotely sensed soil moisture measurements from NASA Earth observations (EO) will provide low-effort, high spatio-temporal coverage datasets for management agencies, such as our primary partners at the U.S. Fish and Wildlife Service (USFWS). Validating remotely sensed data with field observations from Reynolds Creek Experimental Watershed (RCEW) in Idaho will increase the confidence in remotely sensed soil moisture data. This project evaluated methods for monitoring soil moisture in semi-arid ecosystems using data from NASA Soil Moisture Active Passive (SMAP) sharpened with European Space Agency (ESA) Sentinel-1 C-Band Synthetic Aperture Radar (C-SAR) backscatter, Global Precipitation Measurement (GPM), and Terra Moderate Resolution Imaging Spectroradiometer (MODIS) derived Normalized Difference Vegetation Index (NDVI) for the period between December 2016 to July 2018. The Idaho NASA DEVELOP team created useful maps and established a workflow to allow land managers to easily access and visualize soil moisture in their area of interest. Linear regression analysis was used to quantify correlations between soil moisture, precipitation, and vegetation health. Preliminary correlation between SMAP and *in situ* soil moisture were positive at all sites, and results fell into the following categories: 53% had a moderate to high correlation at high confidence, 30% had a low to moderate correlation high confidence, and 27% of sites were excluded for having low confidence, $p>0.05$.

Keywords

SMAP, soil moisture, NDVI, GPM, MODIS, Sentinel-1 C-SAR, Google Earth Engine API, Reynolds Creek

2. Introduction

2.1 Background Information

Water availability in semi-arid landscapes is vital to the survival of natural flora and fauna. Consequently, research concerning localized water availability is a critical component of land management. Ongoing research focused on soil moisture and water storage within the water-energy nexus aims to investigate the interdependence between water resources and biological productivity (Schnur, Xie, & Wang, 2010). The relationship between rainfall intensity and soil moisture content also has crucial impacts on land degradation in semi-arid environments (Sridhar & Nayak, 2010; Ziadat & Taimeh, 2013). Previous soil moisture studies conducted on a regional scale have resampled gridded surface meteorological data to address spatial and temporal variability within these datasets (Abatzaglou, 2011). However, because gridded data is interpolated, this process does not always accurately predict actual values. Land management agencies have struggled to adopt satellite data as a means of estimating soil moisture due to coarse spatial resolutions, a lack of regionally-calibrated, ground-based validation sites, as well as a predilection for studies concerning agricultural land over natural cover. Thus, direct field measurements remain the standard for soil moisture data collection (Marks, Seyfried, Flerchinger, & Winstral, 2007; Sridhar & Nayak, 2010).

In situ methods are both costly and time-intensive, particularly when calculating water storage over large areas. Soil Moisture Active Passive (SMAP) is a satellite platform developed to provide critical data on the spatial and temporal distribution of soil moisture at local to global scale. With the failure of the satellite's active radar sensor in mid-2015, the remaining passive sensor has a spatial resolution of 36 kilometers (Chan et al, 2016). Recent work conducted at NASA's Jet Propulsion Laboratory (JPL) has utilized backscatter from Sentinel-1's radiometer to complement the passive sensor, allowing combined images to be sharpened to 1 and 3 km resolution soil moisture data products (Das & Dunbar, 2017; Das et al., 2017). These recently developed products are in the beta-testing stage, but preliminary studies report promising results (El Hajj et al., 2018). The validation of these data products against *in situ* measurements in our study area will help inform further product development at JPL and may encourage further testing and use by local agencies and land managers.

The study area for this project was Idaho's Reynolds Creek Experimental Watershed (RCEW), which is characteristic of the sagebrush-steppe ecosystems of the Intermountain West (Figure 1). Designated as a Critical Zone Observatory in 1959, RCEW is used as a laboratory for the holistic study of biologic and hydrologic processes, with near-continuous data collection occurring for the past sixty years (Slaughter, Marks, Flerchinger, Van Vector, & Burgess, 2001). The site contains 29 stations of ground-based soil moisture and precipitation observations distributed across the watershed. These measurements provide *in situ* baselines for a comparative analysis of various remotely-sensed data sets, including SMAP/Sentinel-1, GPM, and MODIS observations. Located in the Owyhee Mountains southwest of Boise, the watershed drains into the Snake River to the north and spans a vertical relief of over one kilometer (1101 to 2241 meters). The RCEW is dominated by sagebrush shrub-steppe at lower elevations and transitions to mountain sagebrush, juniper, aspen, and conifer forest at higher elevations. Research scientists at the U.S. Department of Agriculture's (USDA) Agricultural Research Service (ARS) currently work in and monitor the area. These project partners provided soil moisture and precipitation measurements for the duration of the study period, which is restricted by available images from the enhanced SMAP dataset, which ranged from December 2016 to July 2018.

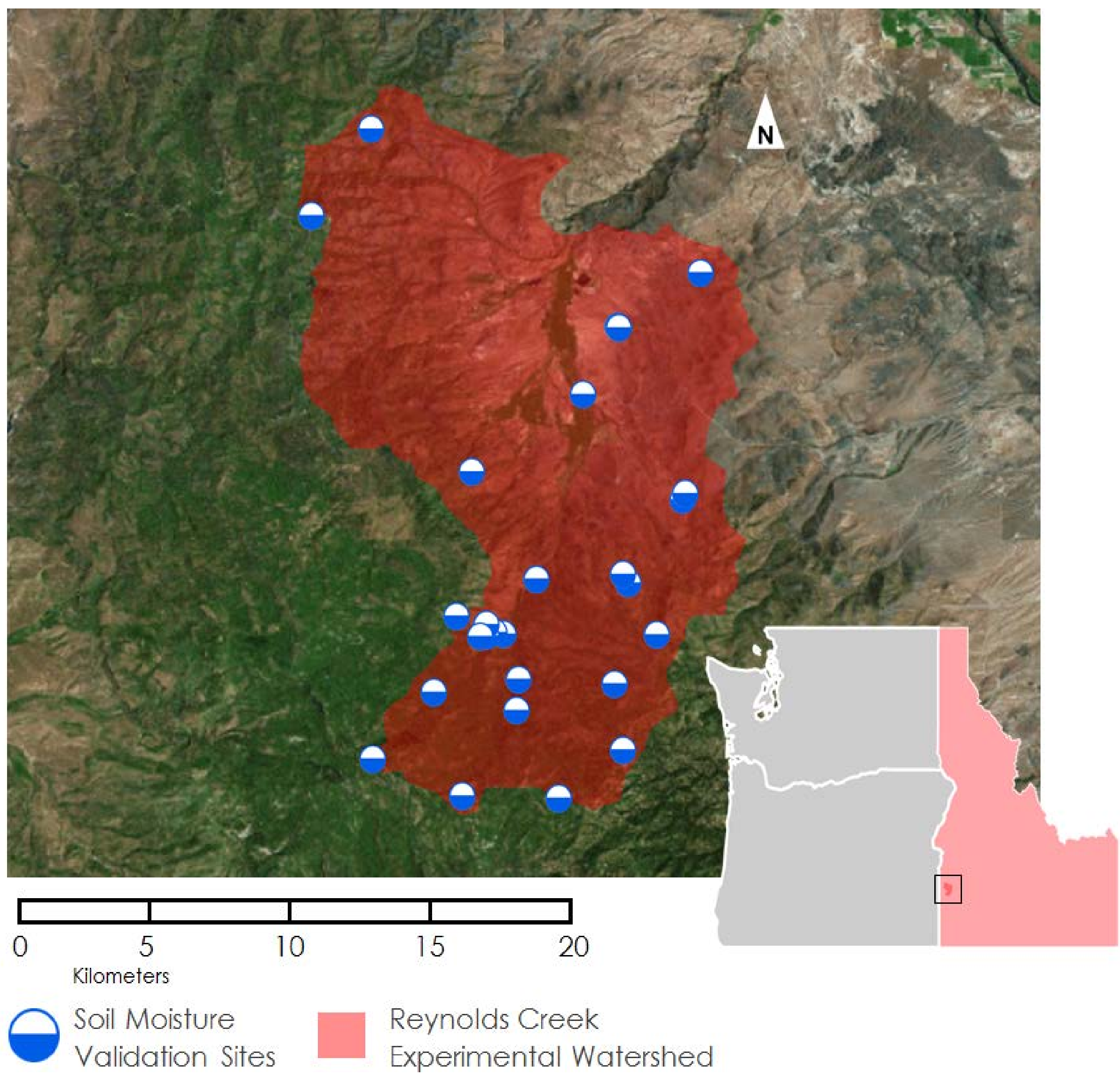

Figure 1 – The Reynolds Creek Experimental Watershed (RCEW) in southwest Idaho was the study area for this research.

2.2 Project Partners & Objectives

The partners for this project were the U.S. Fish and Wildlife Service (USFWS), Idaho Department of Fish and Game (IDFG), USDA Agricultural Research Service (ARS), National Resource Conservation Service (NRCS), and DOE Idaho National Laboratory (INL). The USFWS Eastern Idaho Field Office is the primary end-user and boundary organization for data dissemination between project stakeholders. The USFWS facilitates state and private partnerships as well as consults with other agencies under the Department of the Interior to protect endangered and threatened species. Thus, the agency has a vested interest in increasing the quality and quantity of environmental measurements, such as soil moisture, that impact habitat suitability and available forage. The IDFG, another project end-user, also manages native animal populations within the state and is interested in increasing their use of NASA Earth observations to monitor vegetation phenology and water distribution for habitat assessments. Project collaborators from the USDA ARS and NRCS provided unpublished *in situ* data from the RCEW. These organizations are interested in high-resolution soil moisture estimates to improve hydrologic and carbon cycling models. The Idaho National Laboratory, another project collaborator, have a vested interest in the hydrological cycles across the Snake River Plain, with dedicated funding for water balance research projects.

The primary objective of this research was to compare soil moisture estimates from SMAP/Sentinel-1 enhanced satellite imagery with *in situ* measurements in southern Idaho. This comparison served to assess the product's accuracy in estimating soil moisture values in the semi-arid sagebrush steppe covering much of the Intermountain West. To complete this objective, these values were compared against a variety of topographic and vegetative variables to assess if these factors impacted satellite measurements. Finally, soil moisture estimates were compared to measurements of precipitation from GPM and *in situ* measurements and to vegetative health indicators from MODIS-derived NDVI. These comparisons were conducted in order to evaluate if SMAP soil moisture estimates can approximate aspects of the natural water cycle within semi-arid ecosystems.

3. Methodology

3.1 Data Acquisition

The team collected Level-2 Soil Moisture Active Passive (SMAP) radiometer soil moisture data products from NASA EARTHDATA in GeoTIFF format for the period of December 2016 to June 2018. This product, SMAP/Sentinel-1, is enhanced with the ESA Sentinel-1A and -1B C-band radar backscatter data and resampled at a spatial resolution of 1 km (Das & Dunbar, 2017). The original temporal resolution of SMAP was approximately 3 days, but the SMAP/Sentinel-1 product is reduced to coincident timing with Sentinel imagery, at a new coarser resolution of 3-6 days with occasional gaps up to 14 days. In addition, temporal coverage is limited in winter months when pixels with significant snow coverage are excluded from processing. SMAP/Sentinel-1 tiles 117W42N, 117W43N, and 115W43N were chosen for optimal coverage of the study area.

Remotely-sensed precipitation measurements were retrieved from Level-3 Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for Global Precipitation Measurement (GPM IMERG), a combined microwave precipitation and microwave-calibrated infrared satellite product. Only the infrared precipitation band was utilized, which has a half-hour temporal resolution and a ~11 km spatial resolution (Huffman, 2017). The GPM IMERG product was called with the ImageCollection ID 'NASA/GPM_L3/IMERG_V05' in the Google Earth Engine (GEE) Advanced Programming Interface (API). Pre-processed, atmospherically corrected Normalized Difference Vegetation Index (NDVI) images were sourced from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) and represent 16-day mean value composites at 250 m spatial resolution (Didan, 2015). Terra Vegetation Indices (MODIS) were imported via GEE API with the ImageCollection ID 'MODIS/006/MOD13Q1. MOD13Q1.006'. The SMAP L3 Radiometer Global Daily 36 km EASE-Grid Soil Moisture Version 5 soil moisture data products

(SPL3SMP) were retrieved through NASA EARTHDATA as GeoTIFFs and were used as a comparison to SMAP/Sentinel-1 products (Appendix A, Table A1).

In addition to NASA EO's, a variety of ground-based datasets were analyzed. *In situ*, quarter-hourly soil moisture and precipitation measurements were acquired from project partners at the USDA ARS for 29 monitoring sites distributed across RCEW (Seyfried, 2018). Additionally, RCEW geology, soil, vegetation, and GIS shapefiles were downloaded from the RCEW website (Stephenson, 1960; USDA-ARS, ISU, BSU, 2014). Digital elevation models (DEM) were acquired from the USGS National Elevation Dataset (NED).

3.2 Data Processing

Initial data processing was split between two programs: Esri ArcGIS Pro and GEE API. First, ArcGIS Pro was used to combine two RCEW geospatial files with other geospatial datasets. The combined RCEW dataset included shapefiles for watershed delineation, instrument locations, soil type, and vegetation classification. Raster images of SMAP/Sentinel-1 soil moisture (SMAP/Sentinel-1), and USGS NED DEM were combined with the RCEW datasets and clipped to the watershed boundary shapefile. SMAP soil moisture values were filtered to a viable range of 0.02 to 0.6 mm^3/mm^3 according to specification from the data authors (Das and Dunbar, 2017). Aspect and slope were calculated from the DEM with ArcGIS Slope and Aspect tools. Then, soil moisture, vegetation type, soil type, slope, aspect, and elevation were sampled at each of the 29 monitoring station using the ArcGIS Sample tool and then exported to comma-separated value (CSV) files for further analysis.

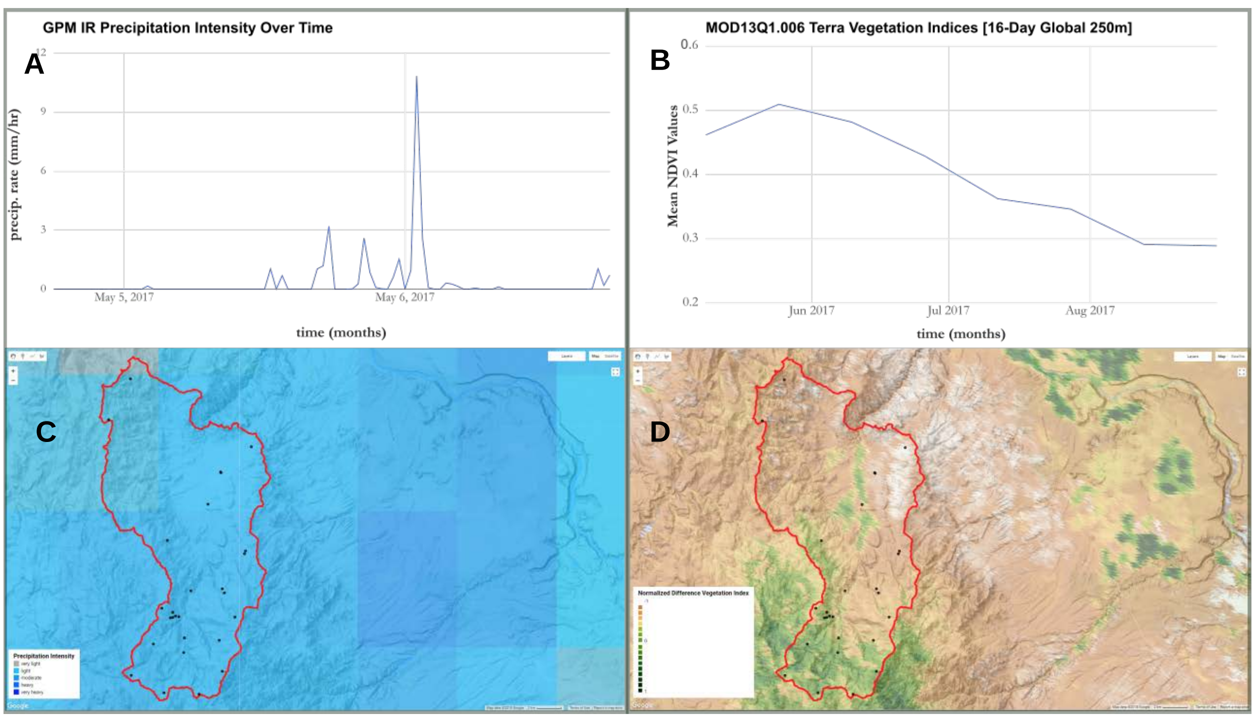

Figure 2 - Precipitation estimates from GPM IMERG (A) were extracted for each RCEW probe site from the 'IRprecipitation' band of the GPM IMERG data product (B). These methods were replicated to extract 16-day mean NDVI values (C) from MODIS data products (D).

GEE API was used to sample two NASA satellite datasets: GPM IMERG and Terra/MODIS Vegetation Indices (Appendix A, Table A1). Imagery was imported, organized, and values were extracted in a CSV format using methodology previously developed by Coats, Condo, Crawford, Kucera, & Sforzo (2018). First, the GPM IMERG product was called in the GEE Code Editor. Next, the RCEW site stations and boundary datasets were uploaded from shapefiles, converted to table features, and imported to the working script. Filter functions reduced the 'IMERG_V05' image collection to the study period (2016-2018) and to boundary features, with the merged IRprecipitation band selected for precipitation measurements (Coats et al., 2018) (Figure 2.A). Unique 'IMERG_V05' values were used to extract values coincident with RCEW station sample sites, and were exported as a time-series CSV (Figure 2.B). This methodology was replicated for the MODIS data products, substituting the NDVI band for IRprecipitation to assess vegetation health (Figure 2.A) and create a time-series CSV of unique 'MOD13Q1' values (Figure 2.B). All CSV files were processed in MATLAB to standardize time, date, and value formatting between platforms. Microsoft Excel was used to calculate average daily soil moisture values from quarter hourly RCEW *in situ* probe measurements.

3.3 Data Analysis
To determine potential relationships between soil moisture estimates and other environmental factors, the team performed two types of correlation analyses. SMAP/Sentinel-1 soil moisture estimates were run against precipitation measurements, vegetative health estimates (NDVI), land cover types, and topographic variation (slope, aspect, elevation) using the Microsoft Excel regression tool. These regressions were run on a site-by-site basis, producing regression coefficients (r^2 values) quantifying the relationship between satellite-derived and *in situ* measurements. Correlation strength, r^2 values, were interpreted to be weak at values 0.3 or less, moderate at values from 0.3-0.5, and strong >0.5. Statistical validity of regression coefficients were determined by p-values, with values above 0.05 indicating correlations occurred by random chance and are thus statistically invalid, given small sample sizes. MATLAB's native cross-correlation function, xcorr, was used to quantify time lag and correlations between paired daily *in situ* precipitation and soil moisture datasets.

4. Results & Discussion
4.1 Analysis of Results
Initial analysis of the SMAP/Sentinel-1 1 km products for our study area suggests the new product offers a significant improvement over SMAP 36 km and 9 km products for watershed-level/local scale research, and moderate correlation of SMAP/Sentinel-1 to *in situ* soil moisture measurements is promising for continued use. Figure 3 contrasts an unsharpened SMAP 36 km resolution image from May 2017 to a sharpened SMAP/Sentinel-1 1 km image from the same time. In the unsharpened image, one pixel covers nearly the entire study area of Reynold's Creek, producing a single soil moisture value for all 29 instrument sites. The sharpened product is comprised of over 300 pixels, resulting in a unique values for most of the ground validation sites and which have moderate to strong correlation with the *in situ* measures.

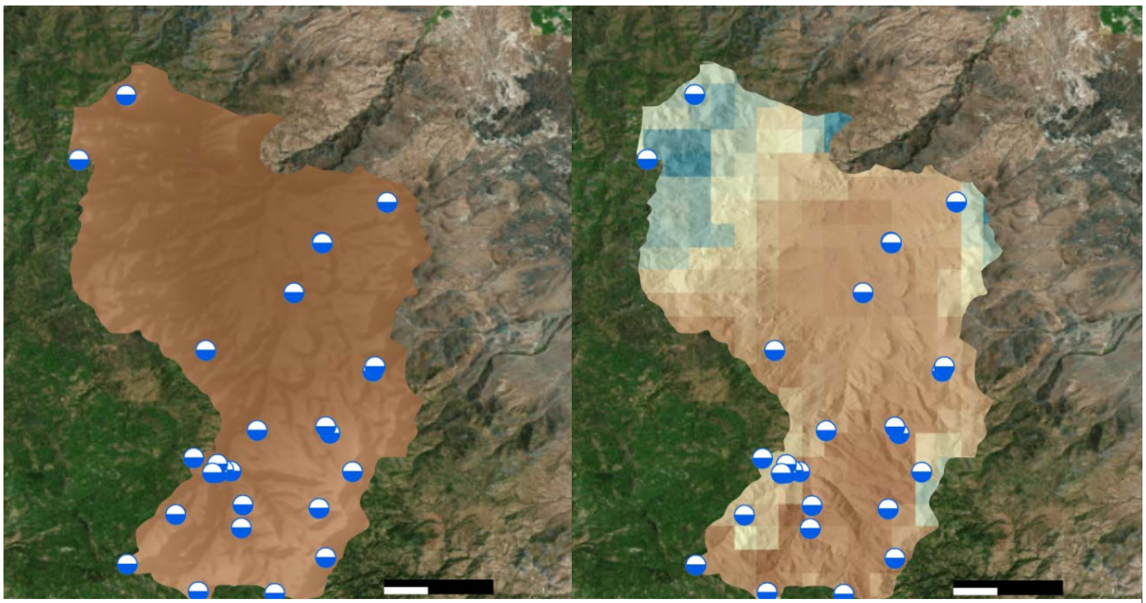

Figure 3 - The SMAP/Sentinel-1 1km product (left) has significantly better spatial resolution than the original SMAP 36km product (right), increasing its potential for watershed to regional scale applications

The analysis exhibited moderate positive correlations between SMAP/Sentinel-1 soil moisture values and *in situ* soil moisture measurements for 53% of stations (Table 1). Values ranged from r^2 values of 0.12 to 0.51, with a mean r^2 value of 0.31 and at a significance of $p=0.05$. Nine of the twenty nine stations were excluded from the above mean statistics for demonstrating a p-value of greater than 0.05. Sites with low-confidence can be explained by either low sample sizes or seemingly exceedingly low *in situ* soil moisture values.

Several time-series graphs of SMAP/Sentinel-1 and paired *in situ* soil moisture measurements were created for each sample site. Figure 4 shows site 057; regression on this series of data produced an $r^2 = 0.4121$, a moderately strong correlation value. Low correlative values with good p-values from SMAP/Sentinel-1 and *in situ* may also be due to intra-pixel variability. SMAP/Sentinel-1 tended to report higher soil moisture values than the *in situ* measurements, which may be due to a variety of causes including radio frequency interference (RFI), simple sensor bias, meteorological interference (El Hajj et al., 2018). Further investigation may differentiate factors contributing to this bias.

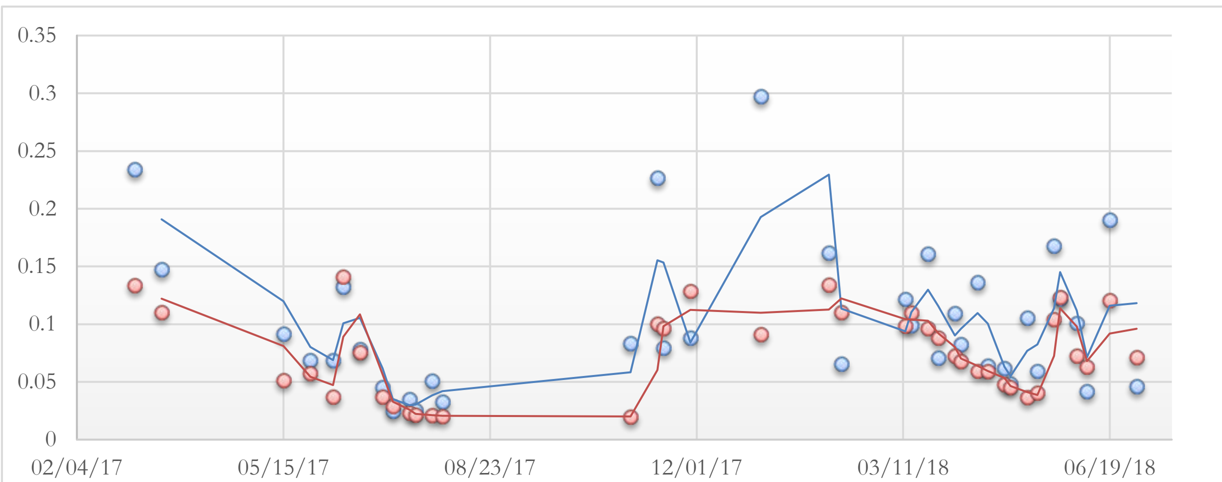

Figure 4 - An example time series of soil-moisture from Site 057. Note SMAP/Sentinel-1 and *in situ* soil moisture estimates are strongly correlated at $R^2=0.74$ and that SMAP/Sentinel-1 has greater variation in measurements.

The association between GPM IMERG and both *in situ* and SMAP/Sentinel-1 soil moisture estimates is weak and thus inconclusive. Additionally, satellite-derived precipitation from GPM IMERG did not correlate well to RCEW precipitation data. This dissimilarity could be explained by the relatively coarse spatial resolution of GPM IMERG, at 11.132 kilometers per pixel. GPM IMERG products could be more suited for larger-scale analysis, in areas where data availability is sparse, or leveraged for its finer temporal coverage (Coats et al., 2018), with smaller scales requiring more localized rain gauge monitoring. Cross-correlation analysis between *in situ* precipitation and *in situ* soil moisture measurements yielded a moderate, positive correlation with a mean r value of 0.44 at a 2.5 day lag. NDVI and SMAP/Sentinel-1 soil moisture had low associations (r^2 value) likely due to the complexity of their relationship and time scale variability. MOD13Q1.006 NDVI used a 16 day aggregate with max value for each pixel to eliminate clouds, which obfuscates the date a specific pixel is from. Furthermore, the time lag between these two factors may be much longer than with precipitation and soil moisture, due to complex factors which affect vegetation health. Finally we compared TOPOFIRE soil moisture, which is a gridded interpolation using incoming precipitation, Soil Survey Geographic Database (SSURGO) and evapotranspiration models. The number of sample values were limited by the overlap between the two datasets, which severely affected the calculated p-values (Table 2). Future work may better constrain correlation between the two datasets. Poor correlation between the datasets may also reflect fundamental differences between measured and modeled soil moistures.

4.2 Future Work

Further use of the SMAP/Sentinel-1 data product will rely on future work validating the imagery across land cover types and seasons. A major constraint on current studies is the lack of temporal coverage for SMAP, with the enhanced SMAP/Sentinel-1 dataset available from late 2016 onward. Ongoing research with feedback from validation studies can provide valuable information to improve the algorithm for the data product. At present, there are several ongoing studies with promising results that show moderate positive correlations similar to what we see in our results (Hajj et al, 2018). We see a bias for SMAP/Sentinel-1 to overestimate soil moisture by a small amount, and teasing out the reasons for that bias is important. Further investigation of correlations with interdependent variables over longer time frames may also yield unique or interesting relationships. An important component of understand the timing of the water budget for the RCEW would be determining the temporal correlation of the response between soil moisture and NDVI values (Nicholson & Farrar, 1994).

Using data collected from NASA Earth observing satellites Aqua and Terra, the Idaho Water Resource II project this fall will compare methods of estimating seasonal ET in Idaho's natural landscapes using MODIS-derived model products. The NASA Modern-Era Retrospective Analysis for Research and Applications Reanalysis Model (MERRA-2), which uses GPM IMERG precipitation inputs to model soil moisture at a 50 km resolution and Terra (MODIS/MOD16) could prove to be a useful ET data source. Integration of land-surface models (LSM) like NLDAS-2, VIC, and Mosaic with evapotranspiration-focused products could better quantify water distribution and flow within the environment. Previous landscape-scale soil moisture studies have resampled gridded surface meteorological data to address spatial and temporal variability within these datasets (Abatzaglou, 2011; Cooke, 2012; IDWR, 2002; Schaake et al., 2004). End products will be assessed against SMAP, field-based soil measurements, and other methods of estimating soil moisture to determine which methodologies correlate best with limited available ground-based measurements.

Future modeling efforts should incorporate the precipitation, vegetation health, and soil moisture inputs investigated in this study with ET outputs derived from NASA satellite platforms and modelled datasets (i.e. MOD16, GRIDMET, NLDAS-2, etc.) in order to provide a more holistic picture of water movements in the system related to biological productivity.

5. Conclusions

This research investigated using NASA EOs to estimate soil moisture within the semi-arid landscape of Idaho at the watershed scale. Specifically, this project aimed to compare new soil moisture products from NASA's SMAP mission combined with ESA's Sentinel-1 with ground-based RCEW soil moisture station measurements. This study highlights the capacity to use satellite-based soil moisture estimates to facilitate decision-making processes by land management agencies.

Through simple regression analyses, satellite platforms for soil moisture were validated with ground-based data. The SMAP/Sentinel-1 soil moisture products had moderate to strong positive correlations with *in situ* soil moisture sites at high confidence levels. Correlation testing between SMAP/Sentinel-1 data and satellite-estimated precipitation (GPM IMERG) and vegetation health (MODIS) resulted in a very low association between GPM IMERG and SMAP/Sentinel-1 products, and therefore the relationship between them remains inclusive. Analysis between MODIS and the SMAP/Sentinel-1 products also had very low association. Therefore, further work is needed to draw conclusions between SMAP/Sentinel-1 and GPM IMERG and MODIS. The team tested variability between soil moisture estimates based on topographic or vegetative controls, and found low variability--indicating soil moisture estimates were generally robust over sagebrush steppe as well as the other cover types present in the Reynolds Creek Experimental Watershed.

Ultimately, this research highlights the advantages of using sharpened SMAP/Sentinel-1 products via soil moisture validation with ground-based measurements. Using other precipitation and vegetation health indices from satellite-based systems to correlate with *in situ* data could be more effective when integrated into a LSM.

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7. Glossary

BSU - Boise State University
C-SAR - Sentinel-1 C-Band Synthetic Aperture Radar
CZO - Reynolds Creek Critical Zone Observatory
ET - Evapotranspiration
EOS - NASA Earth Observing System
EOSDIS - NASA Earth Observing System Data and Information System
GIS TReC - Geographic Information Systems Training and Research Center
GEE - Google Earth Engine
GES DISC - Goddard Earth Sciences Data and Information Services Center
GPM - Global Precipitation Measurement
GPM_3IMERGHH_05 - GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V05
GPM GMI - Global Precipitation Measurement, Global Microwave Imager
GPM IMERG - Integrated Multi-satellite Retrievals for Global Precipitation Measurement

IDFG - Idaho Department of Fish and Game
IDWR - Idaho Department of Water Resources
INL - Idaho National Laboratory
ISU - Idaho State University
JPL - Jet Propulsion Laboratory
L2_SM_SP - SMAP-Sentinel Level 2 Soil Moisture Active-Passive (L2SMSP) product
LFM - Live Fuel Moisture
LP DAAC - Land Processes Distributed Active Archive Center
MERRA-2 - NASA Modern-Era Retrospective Analysis for Research and Applications Reanalysis Model
MOD13Q1.006 - MODIS/Terra Vegetation Indices 16-Day L3 Global 250 m SIN Grid V006
MODIS - Terra MODerate resolution Imaging Spectroradiometer
NDVI - Normalized Difference Vegetation Index
NED - National Elevation Dataset
NLDAS-2 - North American Land Data Assimilation System
NSDIC DAAC - National Snow and Ice Data Center Distributed Active Archive Center
PRISM - Parameter-elevation Relationships on Independent Slopes Model
RCEW - Reynolds Creek Experimental Watershed
SMAP - Soil Moisture Active Passive
SPL2SMAP_S - Data Set ID for SMAP/Sentinel-1 L2 Radiometer/Radar 30-Second Scene 3 km EASE - Grid Soil Moisture, Version 2
SSURGO - Soil Survey Geographic Database
USDA ARS - United States Department of Agriculture, Agricultural Research Service
USDA NRCS - United States Department of Agriculture, Natural Resources Conservation Service
USFW - Department of Interior, United States Fish and Wildlife Service
USGS - United States Geological Survey

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9. Appendices

Table 1 – Chart showing correlation between *in situ* and SMAP/Sentinel-1 organized by site. R is the correlation coefficient and demonstrates strength of correlation, R^2 represents how well correlation can be explained by single variable, P-values represent likelihood correlation could occur by chance.

SMAP/Sentinel-1 vs *in situ* soil moist							
Site	**012**	**031**	**049**	**057**	**057b-g**	**057b-n**	**076**
R^2	0.1058	0.3679	0.3652	0.4121	0.5097	0.5157	0.2335
R	0.3252	0.6066	0.6043	0.6419	0.7140	0.7181	0.4832
P-value	0.0693	0.0006	0.0001	1.40E-05	7.00E-07	5.63E-07	0.0068
N Sample	32	28	38	38	37	37	30
Site	**127d-n**	**144**	**145**	**147**	**155**	**163**	**167**
R^2	0.1181	0.3467	0.0703	0.1021	0.0928	0.0917	0.0257
R	0.3437	0.5888	0.2652	0.3195	0.3046	0.3028	0.1603
P-value	0.0466	0.0002	0.2105	0.0911	0.1224	0.0646	0.3730
N Sample	34	36	24	29	27	38	33
Site	**098c**	**098d-g**	**098d-n**	**116c**	**124b-a**	**124b-s**	**127**
R^2	0.3003	0.2340	0.2232	0.4595	0.7367	0.4258	0.2243
R	0.5480	0.4837	0.4724	0.6779	0.8583	0.6525	0.4736
P-value	0.0004	0.0024	0.0032	2.93E-06	0.0626	0.0001	0.0041
N Sample	38	37	37	38	5	30	35
Site	**176**	**13803**	**jdt1**	**jdt2**	**jdt2b**	**jdt3**	**jdt3b**
R^2	0.2337	0.3267	0.3047	0.1406	0.4661	0.2739	0.2628
R	0.4834	0.5716	0.5520	0.3749	0.6827	0.5234	0.5126
P-value	0.0051	0.0010	0.0007	0.0289	0.0101	0.0021	0.0507
N Sample	32	30	34	34	13	32	15
Site	**jdt4b**	**095b**	**174**	**127d-g**	**jbt4**		
R^2	0.3840	0.2856	0.2126	0.2490	0.1916		
R	0.6197	0.5344	0.4611	0.4990	0.4378		
P-value	0.0560	0.0005	0.0118	0.0027	0.0122		
N Sample	10	38	29	34	32		

Table 2 – Comparison of TOPOFIRE Soil Moisture and SMAP/Sentinel-1

TOPOFIRE vs SMAP/Sentinel					**N =13**		
Site	**012**	**031**	**049**	**057**	**076**	**095b**	**098c**	**098d-g**
R^2	0.2031	0.2876	0.3346	0.2339	0.2018	0.4742	0.4416	0.4868
P-value	0.1222	0.0589	0.0384	0.0941	0.1236	0.0093	0.0132	0.0080
Site	**116c**	**124b**	**127**	**127d-g**	**13803**	**144**	**145**	**147**
R^2	0.5632	0.4147	0.2216	0.0107	0.0002	0.0586	0.2675	0.0364
P-value	0.0031	0.0175	0.1045	0.7367	0.9662	0.4255	0.0703	0.5326
Site	**163**	**167**	**jdt1**	**jdt2**	**jdt3**	**jdt3b**	**jdt4**	
R^2	0.2699	0.4702	0.0287	0.0814	0.0154	0.0004	0.0097	
P-value	0.0688	0.0097	0.5804	0.3448	0.6865	0.9500	0.7489	

Table A1. Primary Datasets

Dataset	**Date**	**Use**	**Acquired From**	**Level**	**DOI**
SMAP/Sentinel-1 L2 Radiometer/Radar 30-Second Scene 3 km EASE-Grid Soil Moisture V002 (SPL2SMAP_S)	2016 - 2018	Soil Moisture	NASA EARTHDATA	Level 2	10.5067/KE1CSVXMI95Y
GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V05 (GPM_3IMERGHH_05)	2015 - 2018	Precipitation	Google Earth Engine	Level 3	10.5067/GPM/IMERG/3B-HH/05
MOD13Q1.006 Terra Vegetation Indices 16-Day Global 250m (MOD13Q1.006)	2015 - 2018	Vegetation Indices NDVI	Google Earth Engine	Level 2	10.5067/MODIS/MOD13Q1.006
SMAP L3 Radiometer Global Daily 36 km EASE-Grid Soil Moisture, Version 5, NASA_USDA SMAP Global Soil Moisture Data (SPL3SMP)	2015 - 2018	Soil Moisture	NASA EARTHDATA	Level 3	10.5067/ZX7YX2Y2LHEB

Table A2. Ancillary Datasets

Dataset	Date	Use	Acquired From	Level	DOI
RCEW Soil Moisture	2015-2018	Soil Moisture	USDA-ARS	NA	NA
RCEW Precipitation	2017	Precipitation	USDA-ARS	NA	NA
Reynolds Creek - Soils, Vegetation, and Geology	1960-1970	Vegetation	Critical Zone Observatory - Reynolds Creek Experimental Watershed	NA	http://criticalzone.org/reynolds/data/dataset/3722/#policy
Reynolds Creek - Instrumentation, Regions, and Boundaries	2014	Boundaries and Instrument Locations	Critical Zone Observatory - Reynolds Creek Experimental Watershed	NA	http://criticalzone.org/reynolds/data/dataset/3934/#citation
USGS NED 1/3 arc-second	2013	Elevation	eological Survey	NA	https://catalog.data.gov/dataset/national-elevation-dataset-ned-1-3-arc-second-downloadable-data-collection-national-geospatial