Core ideas

- Soil moisture is a critical, yet under-represented land surface variable
- Soil moisture data collection is undergoing rapid growth and innovation
- We present a strategy for a nationally coordinated monitoring network

Developing a Strategy for the National Coordinated Soil Moisture Monitoring Network

Michael H. Cosh[1], Todd Caldwell[2], Bruce Baker[3], John D. Bolten[4], Nathan Edwards[5], Peter Goble[6], Heather Hofman[7], Tyson E. Ochsner[8], Steven Quiring[9], Charles Schalk[10], Marina Skumanich[11], Mark Svoboda[12], and Molly Woloszyn[11]

[1]U.S. Department of Agriculture, Agricultural Research Service, Beltsville Agricultural Research Center, Hydrology and Remote Sensing laboratory, 10300 Baltimore Ave, Beltsville, MD 20705

[2]U.S. Geological Survey, Nevada Water Science Center, 2730 N. Deer Run Rd., Carson City, NV 89701

[3]National Oceanic and Atmospheric Administration, Air Resources Laboratory, 456 South Illinois Avenue Oak Ridge, TN 37830

[4]Hydrological Sciences Laboratory, Code 617, NASA Goddard Space Flight Center, Greenbelt , MD 20771

[5]South Dakota State University, 13 2nd Ave SE, Aberdeen, SD 57401

[6]Colorado State University, Colorado Climate Center, 1371 Campus Delivery, Fort Collins, CO 80523

[7]U.S. Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center, 1201 NE Lloyd Blvd, Suite 802 Portland, OR 97232

[8]Oklahoma State University, Department of Plant and Soil Sciences, 371 Agricultural Hall, Stillwater, OK 74078

[9]Ohio State University, Department of Geography, 154 North Oval Mall, Columbus, OH 4321

[10]U.S. Geological Survey, Hydrologic Networks Branch, 196 Whitten Road, Augusta, ME 04330

[11]National Oceanic and Atmospheric Administration, National Integrated Drought Information System,

[12]University of Nebraska-Lincoln, National Drought Mitigation Center, 3310 Holdrege Street, Lincoln, NE 68583

Abbreviations CEOS, Committee on Earth Observation Satellites; IWAA, Integrated Water Availability Assessments; IWP, Integrated Water Prediction; LSM, land surface model; MOISST, Marena, Oklahoma In Situ Sensor Testbed; NCSMMN, National Coordinated Soil Moisture Monitoring Network; NGWMN, National Ground Water Monitoring Network; NGWOS, Next Generation Water Observing Systems; NIDIS, National Integrated Drought Information System; NOAA, National Oceanic and Atmospheric Administration; SAR, synthetic aperture radar; SCAN, Soil Climate Analysis Network; SWC, soil water content; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey.

ABSTRACT

Soil moisture is a critical land surface variable, impacting a wide variety of climatological, agricultural, and hydrological processes. Determining the current soil moisture status is possible via a variety of methods, including in situ monitoring, remote sensing, and numerical modeling. While all of these approaches are rapidly evolving, there is no cohesive strategy or framework to integrate these diverse information sources to develop and disseminate coordinated national soil moisture products that will improve our ability to understand climate variability. The National Coordinated Soil Moisture Monitoring Network initiative has developed a national strategy for network coordination with NOAA's National Integrated Drought Information System. The strategy is currently in review within NOAA, and work is underway to implement the initial milestones of the strategy. This update reviews the goals and steps being taken to establish this national scale coordination for soil moisture monitoring in the United States.

1 Introduction

Soil moisture is a critical land surface variable affecting a wide variety of economically and environmentally important processes. From agricultural monitoring, to weather prediction, to drought and flood mitigation, the value of soil moisture metrics is undeniable [*Vereecken et al.*, 2008]. Most ground-based networks employ in situ sensors measuring at high temporal resolution and multiple soil depths, but the volume of measurement is typically small. Remote sensing platforms have much larger spatial footprints (10-40 km) but only sense shallow soil moisture (<5 cm) with return periods every 2-3 days. Lastly, land surface models can estimate soil moisture with high spatial and temporal resolution, but they are imperfect approximations of the real-world physics that rely on meteorological data and underlying parameterizations. In fact, both space-borne and land surface model estimates of soil moisture require calibration and validation to in situ, ground validation data. Thus, these three sources of data are required to work in concert to produce a temporally and spatially continuous soil moisture product at the relevant scale needed.

The United States has a prolific, but uncoordinated, collection of in situ monitoring networks at the national, state, and local levels (**Figure 1**). However, there is currently no national strategy for the development, deployment, and maintenance of these soil moisture monitoring networks, nor for their coordination and data integration. The absence of such a strategy leads to a host of problems including inadequate monitoring in many states, inconsistent data collection practices between networks, and no cohesive plan to improve the overall infrastructure. Here, we summarize a coherent strategy for the National Coordinated Soil Moisture Monitoring Network (NCSMMN), developed for the National Integrated Drought Information System (NIDIS) under the National Oceanic and Atmospheric Administration (NOAA), the entity tasked by Congress to manage this initiative. This update presents the key components of this strategy, results from the associated 2020 National Soil Moisture Workshop, and a path forward for the NCSMMN.

2 Available Soil Moisture Technologies

2.1 In situ soil moisture sensors

Soil moisture is usually measured as volumetric soil water content (SWC) or the volume of liquid water within a given volume of soil (m^3 m^{-3}). Soil water content can range from oven-dry (0 m^3m^{-3}) to the water-filled porosity of a saturated soil, typically <0.60 m^3m^{-3}. Most soil moisture sensors infer SWC from either thermal or electrical properties of the bulk soil; the latter tends to be more popular due to the wider availability of commercial sensors and perceived simplicity of the measurement. Most electrical SWC sensors are based on the propagation of an electromagnetic wave within a porous medium. These fall into many different classes including time domain reflectometry, time domain transmissometry, transmission line oscillators, capacitance sensors, and impedance sensors [*Vaz et al.*, 2013].

Measurement errors estimated by manufacturers under carefully controlled conditions are often 0.02-0.03 m^3m^{-3}, but errors estimated by researchers in field and laboratory experiments are often substantially higher (**Table 1**). However, these measurement errors can be reduced through improved, and often site-specific field or laboratory calibrations. Ultimately, the soil moisture measurements from in situ networks should be validated using volumetric soil sampling at each station to determine the ground validation values and network level measurement error, but few in situ networks have been validated to date [*Scott et al.*, 2013; *Coopersmith et al.*, 2015; *Caldwell et al.*, 2019; *Zhang et al.*, 2019]. Currently, there are no standard or widely-accepted methods for installation, calibration, validation, and quality control for SWC sensors. This lack of standardization and general guidance has made it challenging for some monitoring networks, like state Mesonets, to add soil moisture measurements.

2.2 Remote Sensing Platforms

Spaceborne microwave soil moisture sensors can either be passive (receive energy) or active (transmit and receive energy). Passive remote sensors (radiometers) measure brightness temperature emissions from microwave radiation originating from the Earth's surface. The frequency and intensity of emitted radiation depends on the dielectric properties of the near-surface, which for soil are a function of the amount of water present and its temperature. Active remote sensors (or radars) provide their own illumination source, sending out a transmitted wave and measuring the received reflection back to determine its backscatter cross-section. Synthetic aperture radars employ processing that provides higher spatial resolution, allowing finer scale features of the surface to be observed. Measurements of emissivity and backscatter cross-section (or simply backscatter) provide complementary information on the soil moisture, surface roughness, and vegetation characteristics of the land surface (see **Table 2**). Reviews of various satellite-based soil moisture platforms and related issues can be found in *Mohanty et al.* [2017] and *Babaeian et al.* [2019]. An ultimate goal of NCSMMN would be to have quality standards that are comparable to the Fiducial Reference Measurement (FRM) standard, as implemented at https://qa4sm.eu/.

2.3 Land Surface Models

Land surface models (LSM) are systems of equations designed to simulate the flow of mass, water, and energy within the soil-vegetation-atmosphere continuum. The water balance approach applied by LSM calculates a change in soil water storage as the difference between incoming (e.g., precipitation) and outgoing (e.g., evapotranspiration, runoff, and groundwater recharge) fluxes of water. LSM differ widely with regards to their complexity, assumptions, and atmospheric forcing requirements. Model-based soil moisture datasets are easily accessible and provide temporal continuity (i.e., no missing data) and continuous spatial coverage within their simulation domain. However, LSM have several key limitations for soil moisture including simplified physics [*Or*, 2020] and inadequate parameterization schemes for soil properties [*Fatichi et al.*, 2020]. In addition, LSM performance and accuracy are highly susceptible to the quality of the forcing data, including precipitation, temperature, net radiation, humidity, and wind. The large availability of routinely delivered forcing data, along with the long-term trend in computational power, has substantially reduced obstacles for operational, large-scale soil moisture products derived from LSM (**Table 2**). For a review of regional and global land data assimilation systems, see *Xia et al.* [2019].

3 Current State of Soil Moisture Monitoring in the U.S.

The number of in situ soil moisture monitoring stations has increased substantially in recent decades. In the United States, most long-term soil moisture monitoring networks are operated by federal and state agencies. These networks have continued to expand and infill at both regional and national scales. **Figure 1** provides an overview of key federal, state, and university-sponsored networks currently in operation with data transmitted in near real-time. Some of these networks have a period of record beyond 20 years; however, there is also a substantial variability in soil depths monitored and type of sensors used (**Table 3**). As of 2021, there are approximately 2,000 soil moisture monitoring stations producing publicly-available data in the United States.

4 Developing a Strategy for the National Coordinated Soil Moisture Monitoring Network

In 2013, NIDIS and partners began an initiative to work towards a coordinated national soil moisture monitoring network. A meeting to clarify the vision for this effort was held in November 2013 in Kansas City, Missouri, with federal, state, and academic experts participating [McNutt et al., 2013]. A second workshop in 2016 in Boulder, CO, focused on three core elements of a coordinated and integrated national soil moisture network [*McNutt et al.*, 2016]. A third workshop was held in 2017 in conjunction with the

Marena, OK, In Situ Sensor Testbed (MOISST, [*Cosh et al.*, 2016]) workshop. Following a fourth planning meeting in Lincoln, NE, in 2018 (again in conjunction with the MOISST workshop), an Executive Committee was formed, which included leaders from federal agencies and academic institutions, and was charged with clearly defining the goals and framework to bring the NCSMMN concept to fruition [*Clayton et al.*, 2019]. Drawing on knowledge and data generated from this series of meetings and associated research projects, the Executive Committee, working with other partners, prepared a "A Strategy for the National Coordinated Soil Moisture Monitoring Network", which is summarized below.

5 Overview of the NCSMMN Strategy

The NCSMMN is a multi-institutional national effort with the mission to provide **"coordinated, high-quality, nationwide, soil moisture information for the public good."** At the highest level, the NCSMMN seeks to:

- Establish a national "network of networks" that effectively demonstrates data and operational coordination of in situ networks and addresses gaps in coverage;
- Support research and development of innovative techniques to merge in situ soil moisture data with remotely-sensed and modeled hydrologic data to create near-real-time, gridded, user-friendly soil moisture maps and associated tools; and
- Build a community of practice and expertise around measuring soil moisture and developing new ways to use soil moisture information—a "network of people" that links data providers, researchers, and the user community.

The Strategy Document for the NCSMMN presents several recommendations and next steps for moving these goals forward. The recommendations are summarized in **Table 4** and listed in a logical flow of activities, but many steps are intended to be taken in parallel. The first group of recommendations address NCSMMN operations and support activities, including determining a formal institutional “home” for the NCSMMN and engaging in communication and outreach. Currently, NIDIS is serving as the lead agency for the NCSMMN, and has developed an initial NCSMMN webpage on its drought portal (link). An NCSMMN e-mail listserv has also been established, and we invite interested individuals to sign-up using information provided on the webpage. Other outreach activities include a series of workshops and seminars planned for the coming year, including a Mesonet operators’ workshop to provide peer-to-peer networking (See NCSMMN webpage for more details on outreach activities).

A second area of focus in the NCSMMN Strategy is on developing the appropriate infrastructure for high-quality data integration. Accordingly, recommendations in the Strategy aim to formalize and codify partnerships with existing state Mesonets as well as to develop quality criteria for data inclusion. Another recommendation is to increase the density of networks nationwide through targeted build-outs, and by exploring potential new partnerships, including private sector and citizen science efforts.

The final area of focus in the NCSMMN Strategy is on product development. To deliver the intended products to support public decision-making, the Strategy recommends supporting research to develop or improve methodologies for soil moisture data collection, standardization, integration, blending, and validation. One example is the issue of how best to perform interpolation (horizontal, vertical, temporal) of point source data into meaningful gridded information. The final recommendation is to develop products that meet the needs of diverse end-user groups, and that support crucial applications such as drought and flood monitoring, fire danger ratings, and streamflow forecasting.

6 Community input on the NCSMMN Strategy

The 2020 National Soil Moisture Workshop was held online August 12-13, with 182 attendees from federal, state, and local agencies; universities; and the private sector. This annual workshop provides a unique opportunity for leaders in soil moisture research and development to come together in an interactive format to exchange ideas and develop collaborations. This was the tenth consecutive year for this workshop. One objective of this year's workshop was to gather additional community input on the NCSMMN strategy and to stimulate progress towards realizing the vision of the NCSMMN.

Participants were assigned breakout groups to give feedback on the NCSMMN Strategy through a series of three overarching topics summarized in **Figure 2** and elaborated upon here. Because a "network of networks" requires some assessment of data quality from each provider to properly assign weight to that data in generated products, our first topic focused on establishing data quality criteria. We asked – *What criteria should be used to assess "high-quality" (or Tier 1) versus "moderate-quality" (Tier 2) data?* Metadata, the data behind the data, was considered to be of particular importance, and in fact has been a recurring theme in NCSMMN discussions. Different types of metadata are listed in **Figure 3**. One key type of metadata is soil characterization for each location and measurement depth. Tier 1 data providers should also provide raw data values along with sensor calibrations, some measure of network error and uncertainty, and have documented quality assurance/quality control ideally with redundancy in measurements. A basic requirement for a NCSMMN provider is access to data with minimal latency, which necessitates automated QA flagging to assess abrupt changes or steps. Most modern soiil moisture sensors also collect temperature and bulk electrical conductivity data. These data, along with ancillary time series data from meteorological sensors, and site cameras, would also improve the overall quality and confidence in the data provided. It should be noted that network quality may not be constant in either space or time due to factors such as: discontinuity in funding and locations subjected to deposition, erosion, biota, and expansive soils, all of which can change readings.

Our second breakout topic was an exploration of impediments to and user needs for data quality: *What are the technical or other (e.g., organizational) impediments to generating high-quality data? And what technical assistance is needed to help data providers deliver high-quality data?* The foremost response was financial support. In most organizations, it is easier to acquire initial funds to purchase equipment or install a network than long-term funds for operations and maintenance. Second was technical support. Given a general absence of standards, limited number of qualified staff, and lack of institutional expertise, training programs, and working groups are needed to assist network operators with installation, maintenance, data transmission, and quality control. Data management and dissemination at some final repository is needed, perhaps along the lines of the National Ground Water Monitoring Network (NGWMN), which is a compilation of selected groundwater monitoring wells from federal, state, and local groundwater monitoring network [*SOGW*, 2013]. Data ownership and network identity were also noted as impediments since many data producers are required to show usage and benefits to justify their costs.

In regard to NCSMMN data outputs, we asked *What are the most important data attributes or products to meet user needs*? The community responses highlighted data availability, focusing on gap-filled time series data for a uniform set of measurement depths in a consistent format, along with interactive charts and web applications. For spatially interpolated (i.e., gridded) data, color-indexed maps with daily, weekly, or monthly summaries (not raw data) were requested. The requested data formats included time synched, station time series data and GeoTIFF or netCDF for gridded products which tend to be cloud-friendly, as file become large. Some decision making requires near real-time data for emergency management, flood forecasting, agricultural applications (irrigation requirements, fertilizer and pesticide applications, harvesting and planting decisions), wildfire potential and fuel moisture estimation. The requested products favored maps and visualizations over tables of data. Lastly, many users do not have technical expertise interpreting soil conditions, so some level of education and outreach is required. Technical workshops on topics such as data use, products, and the latest technologies in sensors would improve usage of any of these products.

The final breakout sessions focused on NCSMMN research priorities and products in the near- and long-term. The immediate needs included an effective Data Management Plan; developing a repository of data processing scripts; conducting a national assessment of networks to determine where spatial coverage is either lacking or redundant; advancing approaches to soil moisture measurement in more complex terrains such as forests, alpine terrain of varied aspect/slope, and under rainfed and irrigated crops, and convening a steering committee. Many of these near-term priorities are currently being addressed as noted in Section 7. In the long-term, it was stated that the NCSMMN should prioritize network expansion to increase the overall density of data. The last major priority is to expand the soil moisture community to include other sciences such as social sciences and economics, human health, soil health, etc., and continue to improve collaboration between data providers, researchers, and non-research data users through webinars and workshops.

7 Moving Forward

7.1 National Soil Survey Participation

It has been recognized that information about the soil (<2 m) and vadose zone (the entire unsaturated zone) is critical to the interpretation of any remote sensing or LSM product. To support this crucial collateral information, the Kellogg Soil Survey Laboratory in Lincoln, NE, is eager to support the analysis and archiving of soil samples collected at monitoring station locations to improve their soil archive, as well as to provide the necessary metadata for each station. A minimum set of soil parameters are to be determined for each soil moisture station by providing soil cores to the Kellogg Laboratory for analysis.

7.2 Installation Guidance

As noted above, there is a need for formal guidance on site selection and soil moisture sensor installation. Building off of the *IAEA* [2008] Training Course Series, the USGS plans to produce a collaborative Techniques and Methods (T&M) guide on soil moisture data collection. The USGS T&M series compiles the description of procedures for the collection, analysis, or interpretation of scientific data. It includes selected scripts, manuals, and documentation that represent major methodology or techniques of data collection. In conjunction with USDA-ARS, the USGS is updating a former T&M on soil moisture by *Johnson* [1962] to serve as a hands-on installation guide for field technicians. Drawing off this work, the NCSMMN Executive Committee is planning to develop a video guide for sensor installation along the lines of the *Lawrence et al.* [2016] approach to sampling forest soils.

7.3 NCSMMN Web Presence

As mentioned, NIDIS has developed an initial web-presence for NCSMMN communication and public outreach, with plans to broaden this platform over time as the NCSMMN organizational alignment becomes more settled. In addition, an Open Science Framework project has been established (https://osf.io/56gsj/) to serve as a resource for the Executive Committee and for community interaction. This site provides a repository for committee deliberations and includes various background documents related to the NCSMMN.

7.4 Upcoming Workshops

One of the primary purposes of the NCSMMN is to provide engagement across the many different groups using or generating soil moisture data. As such, a critical method of engagement is workshops and seminars to promote conversations and sharing of knowledge. A sequence of workshops and seminars are now in the planning stages. The Soil Moisture Network Operators Workshop (SM-NOW) will serve as a data provider support forum for peer-to-peer sharing of techniques and experiences to help improve the installation, maintenance, and data delivery from soil moisture networks. This community is expected to benefit from internal discussions of siting strategies, management protocols, and other challenges faced by network operators and managers. A series of Soil Moisture End Users Workshops are being planned to provide an opportunity for different soil moisture data end user sectors (such as state climatologists, water basin managers, drought monitor authors, weather forecasters, etc.) to provide specific ideas and needs they have for useful soil moisture products. The objective is to create a more tailored and detailed set of user needs, to better inform and orient research and product development efforts. For example, a workshop focused on the relationships between soil moisture and wildfire danger is being planned for spring 2021. A seminar series is also being organized to provide more regular, less time-demanding updates for the soil moisture community on new research and project developments. This is currently planned for quarterly calls (4/year) with one being synchronous with the National Soil Moisture Workshop. For more information on any of these workshops or seminars, contact the corresponding author.

8 Other Related Activities

The validation of global coarse satellite soil moisture products requires a community-based effort to implement best practices [*Gruber et al.*, 2020]. The Committee on Earth Observation Satellites (CEOS) has the goal of ensuring international coordination of civil space-based Earth observation programs, promoting exchange of data to optimize societal benefit and to inform decision making for securing a prosperous and sustainable future for humankind. The mission of the Working Group on Calibration and Validation is to ensure the accuracy and quality of Earth Observation data and products. The CEOS Land Product Validation Soil Moisture Subgroup recently authored the Soil Moisture Product Validation Good Practices Protocol [*Montzka et al.*, 2020] to provide, analyze, and improve high quality Earth Observation results; to evaluate the long-term quality of soil moisture products; to give advice on how to handle temporal and spatial mismatch; and to provide guidance on effectively reporting validation results.

As mentioned previously, the U.S. Army Corps of Engineers has begun the process of awarding contracts to state and federal agencies, as well as private firms, to expand the monitoring of soil moisture and snowpack in the Upper Missouri River Basin [*USACE*, 2021]. These contracts are expected to increase the number of public monitoring stations in the basin by approximately 540 sites and will take 5-7 years to complete. It is anticipated that this expansion will provide better input data for basin runoff models and better inform decision making for hydrologic concerns in the basin as well as downstream. More generally, data from the expansion will be integrated into the overall NCSMMN initiative and support a broad range of research efforts and decision-making applications related to flooding, drought, water and weather forecasting.

Recently, the U.S. Geological Survey (USGS) has begun integrating its water science programs to better address the nation's greatest water resource challenges now and into the future by advancing data collection in 10 prioritized basins [Va*n Metre et al.,* 2020]. Three new programs instrumental in launching this basin selection effort are the Next Generation Water Observing Systems (NGWOS), Integrated Water Availability Assessments (IWAA), and Integrated Water Prediction (IWP). Under NGWOS, traditional USGS hydrologic data, including river discharge and groundwater levels, will be increasingly collected using more advanced and novel collection methods to improve modeling and prediction capabilities. Additionally, other aspects of the hydrologic cycle, primarily evapotranspiration, snowpack, and soil moisture, will be included to support both IWAA and IWP programs, as well as to provide real-time data to national and regional modeling efforts and the NCSMMN. Instrumentation testing and deployment began in 2018 in the Delaware River Basin as part of a pilot effort and will be enhanced in the Upper Colorado and Illinois River Basins starting in 2021. Similarly, the U.S. Forest Service has begun planning for a Forest Service Soil Moisture Monitoring Network in coordination with the NCSMMN. All the above activities, being conducted in coordination with or under the auspices of the NCSMMN, will serve to extend and improve soil moisture monitoring across the US and support nationally-relevant product development.

Future uses of the NCSMMN would include inclusion in the decision making for the National Drought Monitor in the U.S. to help improve the accuracy of drought estimates. Improved satellite calibration and validation of model and satellite products would also be possible. Numerous decision support systems related to agriculture, forestry, and hydrology will benefit with an improved network of real time in situ measurements to quantify one of the most critical parameters at the land surface atmosphere interface.

In conclusion, there must be a strategic and coordinated effort to utilize and expand in situ soil moisture monitoring across the United States. The NCSMMN will coordinate this process. The collection of high-quality soil moisture data can be a complicated and challenging process, but it is ultimately necessary to coordinate disparate networks, if the value of soil moisture data is to be fully realized and connections between broader agencies and applications to can demonstrate the value of soil moisture resources.

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10 Supplemental Material

Supplemental materials include references noted in **Table 1** and **Table 2**.

11 References

Babaeian, E., M. Sadeghi, S. B. Jones, C. Montzka, H. Vereecken, and M. Tuller (2019), Ground, Proximal, and Satellite Remote Sensing of Soil Moisture, *Reviews of Geophysics*, *57*, 530-616, doi: 10.1029/2018rg000618.

Brotzge, J. A., J. Wang, C. D. Thorncroft, et al. (2020), A Technical Overview of the New York State Mesonet Standard Network, *Journal Of Atmospheric And Oceanic Technology*, *37*, 1827-1845, doi: 10.1175/jtech-d-19-0220.1.

Caldwell, T. G., T. Bongiovanni, M. H. Cosh, et al. (2019), The Texas Soil Observation Network: A comprehensive soil moisture dataset for remote sensing and land surface model validation, *Vadose Zone Journal*, *18:100034*, doi:10.2136/vzj2019.04.0034.

Clayton, J., S. Quiring, T. Ochsner, M. Cosh, C. Baker, T. Ford, J. Bolten, and M. Woloszyn (2019), Building a one-stop shop for soil moisture information, *EOS*, *100*, doi: 10.1029/2019eo123631.

Coopersmith, E. J., M. H. Cosh, W. A. Petersen, J. Prueger, and J. J. Niemeier (2015), Soil moisture model calibration and validation: An ARS watershed on the South Fork Iowa River, *Journal of Hydrometeorology*, *16*, 1087-1101.

Cosh, M. H., T. E. Ochsner, L. McKee, et al. (2016), The Soil Moisture Active Passive Marena, Oklahoma, In Situ Sensor Testbed (SMAP-MOISST): Testbed design and evaluation of in situ sensors, *Vadose Zone Journal*, *15*, doi: 10.2136/vzj2015.09.0122.

Fatichi, S., D. Or, R. Walko, et al. (2020), Soil structure is an important omission in Earth System Models, *Nature Communications*, *11*, 522, doi: 10.1038/s41467-020-14411-z.

Gruber, A., G. De Lannoy, C. Albergel, et al. (2020), Validation practices for satellite soil moisture retrievals: What are (the) errors?, *Remote Sensing of Environment*, *244*, 111806, 10.1016/j.rse.2020.111806.

Hollinger, S. E., and S. A. Isard (1994), A soil moisture climatology of Illinois, *Journal of Climate*, *7*, 822-833.

Hoogenboom, G. (1993), The Georgia automated environmental monitoring network, in *Proceedings of the 1993 Georgia Water Resources Conference*, edited by K. J. Hatcher, pp. 398-402, University of Georgia, Athens, GA.

IAEA (2008), Field Estimation of Soil Water Content, International Atomic Energy Agency, *TCS No. 30*, 131 pp, Vienna.

Johnson, A. I. (1962), Methods of measuring soil moisture in the field, U.S. Geological Survey, *Water-Supply Paper 1619-U*, 25 pp, Denver, CO, doi: 10.3133/wsp1619U.

Lawrence, G. B., I. J. Fernandez, P. W. Hazlett, et al. (2016), Methods of soil resampling to monitor changes in the chemical concentrations of forest soils, *Journal of Visualized Experiments*, doi: 10.3791/54815, e54815, doi: 10.3791/54815.

Mahmood, R., M. Schargorodski, S. Foster, and A. Quilligan (2019), A technical overview of the Kentucky Mesonet, *Journal Of Atmospheric And Oceanic Technology*, *36*, 1753-1771, doi: 10.1175/Jtech-D-18-0198.1.

McNutt, C., J. Verdin, and L. Darby (2013), Developing a Coordinated National Soil Moisture Network, NOAA/NIDIS, *Findings from a meeting in Kansas City, Missouri, Nov. 13-14, 2013*, 4 pp, Kansas City, MO.

McNutt, C., M. Strobel, J. Lucido, and S. Quiring 2016, National Soil Moisture Network Workshop 2016, Progress made, future directions, NOAA/NIDIS, Boulder, CO, May 24-26, 2016.

Mohanty, B. P., M. H. Cosh, V. Lakshmi, and C. Montzka (2017), Soil Moisture Remote Sensing: State-of-the-Science, *Vadose Zone Journal*, *16*, 1-9, doi: 10.2136/vzj2016.10.0105.

Montzka, C., M. Cosh, B. Bayat, et al. (2020), Soil Moisture Product Validation Good Practices, Protocol Version 1.0., Committee on Earth Observation Satellites, Working Group on Calibration and Validation, Land Product Validation Subgroup, 123 pp, doi:10.5067/doc/ceoswgcv/lpv/sm.001.

Or, D. (2020), The tyranny of small scales—On representing soil processes in global land surface models, *Water Resources Research*, *56*, doi: 10.1029/2019wr024846.

Palecki, M. A., and J. E. Bell (2013), U.S. Climate Reference Network soil moisture observations with triple redundancy: Measurement variability, *Vadose Zone Journal*, *12*, doi: 10.2136/vzj2012.0158.

Pan, W., R. P. Boyles, J. G. White, and J. L. Heitman (2012), Characterizing soil physical properties for soil moisture monitoring with the North Carolina Environment and Climate Observing Network, *Journal Of Atmospheric And Oceanic Technology*, *29*, 933-943, doi: 10.1175/jtech-d-11-00104.1.

Ralph, F. M., R. J. Zamora, E. Clark, and T. Schneider (2011), The NOAA Hydrometeorology Testbed Soil Moisture Observing Networks: Design, instrumentation, and preliminary Results, *Journal Of Atmospheric And Oceanic Technology*, *28*, 1129-1140, doi: 10.1175/2010jtecha1465.1.

Roberti, J. A., E. Ayres, H. W. Loescher, et al. (2018), A robust calibration method for continental-scale soil water content measurements, *Vadose Zone Journal*, *17:170177*, 19, doi: 10.2136/vzj2017.10.0177.

Schaefer, G. L., and F. Paetzold (2001), SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network), in *Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives*, edited by K. Hubbard and M. V. K. Sivakumar, p. 7, Lincoln, NE.

Schaefer, G. L., M. H. Cosh, and T. J. Jackson (2007), The USDA Natural Resources Conservation Service Soil Climate Analysis Network (SCAN), *Journal Of Atmospheric And Oceanic Technology*, *24*, 2073-2077, doi: 10.1175/2007jtecha930.1.

Scott, B. L., T. E. Ochsner, B. G. Illston, C. A. Fiebrich, J. B. Basara, and A. J. Sutherland (2013), New soil property database improves Oklahoma Mesonet soil moisture estimates, *Journal Of Atmospheric And Oceanic Technology*, *30*, 2585-2595, Doi 10.1175/Jtech-D-13-00084.1.

Shulski, M., S. Cooper, G. Roebke, and A. Dutcher (2018), The Nebraska Mesonet: Technical overview of an automated state weather network, *Journal Of Atmospheric And Oceanic Technology*, *35*, 2189-2200, doi: 10.1175/Jtech-D-17-0181.1.

SOGW (2013), A National Framework for Ground-Water Monitoring in the United States, Subcommittee on Ground Water, U.S. Geological Survey, *available at* https://cida.usgs.gov/ngwmn/, 168 pp, Reston, VA.

Sonmez, I., K. B. Haynie, W. S. Burgett, J. L. Schroeder, G. D. Skwira, A. L. Doggett, and J. W. Lipe (2005), The West Texas Mesonet: A technical overview, *Journal Of Atmospheric And Oceanic Technology*, *22*, 211-222, doi: 10.1175/jtech-1690.1.

USACE (2021), Upper Missouri River Basin – Plains Snow and Soil Moisture Monitoring Network, U.S. Army Corps of Engineers, Northwestern Division, *Fact Sheet*, 5 pp, Omaha, NE.

Van Metre, P. C., S. Qi, J. Deacon, et al. (2020), Prioritizing river basins for intensive monitoring and assessment by the US Geological Survey, *Environmental Monitoring and Assessment*, *192*, 458, doi: 10.1007/s10661-020-08403-1.

Vaz, C. M. P., S. Jones, M. Meding, and M. Tuller (2013), Evaluation of standard calibration functions for eight electromagnetic soil moisture sensors, *Vadose Zone Journal*, *12*, doi: 10.2136/vzj2012.0160.

Vereecken, H., J. A. Huisman, H. Bogena, J. Vanderborght, J. A. Vrugt, and J. W. Hopmans (2008), On the value of soil moisture measurements in vadose zone hydrology: A review, *Water Resources Research*, *44*, W00D06, doi:10.1029/2008wr006829.

Xia, Y. L., Z. C. Hao, C. X. Shi, Y. H. Li, J. S. Meng, T. R. Xu, X. Y. Wu, and B. Q. Zhang (2019), Regional and global land data assimilation systems: Innovations, challenges, and prospects, *Journal of Meteorological Research*, *33*, 159-189, doi: 10.1007/s13351-019-8172-4.

Zhang, Y., T. E. Ochsner, C. A. Fiebrich, and B. G. Illston (2019), Recalibration of sensors in one of the world's longest running automated soil moisture monitoring networks, *Soil Science Society of America Journal*, *83*, 1003-1011, doi: 10.2136/sssaj2018.12.0481.

12 Tables

Table 1. A summary of common (but not all-inclusive) in situ and profile sensor errors, as root mean squared error (RMSE), stated from the manufacturer and determined by researchers using the factory standard coefficients and soil-specific calibrations. References are available in supplemental information.

In situ Sensor	Company	Type[1]	Freq. (MHz)	Output[2]	RMSE (m^3/m^3)			Reference
					Stated	Standard calibration	Soil specific	
10HS	Meter	Cap.	70	V	0.03	0.073, 0.053	0.013, 0.012	[1], [2]
5TE[d]	Decagon	Cap.	70	Ka, EC, T	0.03	0.040, 0.039	0.026, 0.013	[1], [3]
CS616	CSI	TLO	175	period	0.025	0.057,0.129, 0.073	-, 0.025, 0.063	[4], [1], [5]
						0.140, 0.157	0.027, 0.016	[6], [3]
CS650/655	CSI	TLO	175	Ka, EC, T	0.03	0.073, 0.078	0.025, 0.022	[7], [3]
Digital TDT	Acclima	TDT	1230	Ka, EC, T	0.02	0.049, 0.080	-, 0.025	[4], [5]
EC-5[d]	Decagon	Cap.	70	V	0.03	-, 0.054	0.013, 0.025	[8], [3]
Field Connect	J. Deere	Cap.				0.083	0.026	[3]
Hydra Probe	Stevens	Imp.	50	Ka, EC, T	0.01	0.073, 0.033, 0.048	0.056, 0.022, 0.028	[9], [10], [1]
						0.040, 0.102, 0.010	0.029, 0.013, -	[5], [3], [11]
SM150/300	Delta-T	Imp.	100	V, T	0.03	0.037	0.014	[1]
TDR100[d]/ TDR200	Campbell	TDR	1450	Ka, EC	-	0.042, 0.023	-, 0.022	[4], [1]
TDR315	Acclima	TDR			-	0.050, 0.020	0.016, -	[3], [11]
Theta Probe	Delta-T	Imp.	100	V	0.01	0.066, 0.029, 0.030	-, 0.015, 0.028	[4], [1], [5]
Trime-PICO	IMKO	TDR	1000	V	-	0.042, -	0.023, 0.044	[5], [12]
Wet	Delta-T	Cap.	20	Ka, EC, T	0.03	0.041, 0.034	0.029, 0.025	[13], [1]
Profile Sensors								
AquaCheck	–	Cap.			-	0.163	0.013	[3]
Diviner 2000	Sentek	Cap.	250	counts	-	0.030–0.053, -	0.025, 0.018-0.044	[14], [15]
EasyAg	Sentek	Cap.		–	0.06	-	-	
EnviroSCAN	Sentek	Cap.	75	count		0.018 – 0.073, -	0.020, 0.021-0.051	[14], [15]
Gro-Point	ESI	TDT		current				
PR2/6	Delta-T	Cap.	100	V	0.04	0.091–1.30, -	0.027, 0.024–0.063	[14], [15]
SoilVUE-10	Campbell	TDR	1450	Ka, EC, T	0.02			
Trime-T3	IMKO	TDR		time (ps)	0.03	0.051- 070	0.020	[14]

[d]Discontinued sensor, - indicates no value stated in reference.

[1]Sensor type: Cap., capacitance; Imp., impedance; TLO, transmission line oscillator; TDR, time domain reflectometry.

[2]Sensor output includes Ka, dielectric permittivity; EC, electrical conductivity; T, temperature; V, analog voltage; time in picoseconds; and periods or pulse counts.

Table 2. The soil moisture products derived from space-borne platforms and operational[1] land surface models. References are available in supplemental information.

Satellite Soil Moisture Missions

Mission	Duration	Coverage	Revisit time	Band	Spatial Resolution	Reference
AMSR-E (JAXA)	2002-2011	Global	1 day	X/C	10-50 km	[16]
Aquarius	2011-2015	Global	8 days	L	100 km	[17]
ASCAT	2009-pres.	Global	2-3 days	C	25 km	[18]
CYGNSS	2017-pres.	Mid-latitudes	Week-Month	L	1-3 km	[19, 20]
GCOM-W (AMSR2)	2012-pres.	Global	2-3 days	X/S	25 km	[21]
Grace/Grace-FO	2002-pres.	Global	30 days	K-band Ranging	200 km	[22]
NISAR	202?-?	Global	12 days	L/S	200 m	[23]
Sentinel-1 (ESA)	2015-pres,	Europe	3-8 days	C	1 km	[24]
	2015-pres,	Global index	1 day	C	0.1 degree	
SMAP (NASA)	2015-pres.	Global	2-3 days	L	3 km/9 km/36 km	[25, 26]
SMOS (ESA)	2009-pres.	Global	2-3 days	L	25 km	[27, 28]
WindSat (DoD)	2003-2020?	Global	8 days	X	25 km	[29]

Operational Land Surface Models

Product	Models	Coverage	Time	Agency	Spatial Resolution	Reference
NLDAS-2	Noah, Mosaic, SAC, VIC	CONUS	1979 - pres.	NASA	0.125 degree (~15 km)	[30]
WLDAS	Noah-MP	Western US	1979 - pres.	NASA	0.01 degree (~1 km)	[31]
National Water Model	WRF-Hydro	CONUS	Short, med, long forecasts	NOAA	1 km and 250 m	[32]
National Hydrologic Model	PRMS	CONUS	1980 - pres.	USGS	1 km	[33]

[1]Operational implies continuous simulations in near-real time for use operationally by a number of federal services like flood forecasting, drought mitigation, and weather forecasting.

Table 3. Current major soil moisture monitoring networks in the United States including the network operator type (federal, state, university), number of active (real-time) stations, network start date, type of sensor, and measurement depths.

Network	Op[1]	N[2]	Start Year	Sensor[3]	Depth (cm)	Citation/URL
AmeriFlux	F/U	60	1997	Various	Variable	https://ameriflux.lbl.gov
Atmospheric Radiation Measurement (ARM)	F	16	1996	CS229, Hydra	5, 15, 25, 35, 60, 85, 125, 175	https://www.arm.gov/capabilities/observatories/sgp
Delaware Environmental Observing System	S	47	2005	CS616	5	http://www.deos.udel.edu
Georgia Automated Environmental Monitoring Network	U	87	1992	CS616	5, 10, 20	*Hoogenboom* [1993] http://georgiaweather.net/
Illinois Climate Network	S/U	20	1999	Hydra	5, 10, 20, 50, 100, 150	*Hollinger and Isard* [1994] https://www.isws.illinois.edu/warm/soil
Indiana Water Balance Network	S/U	13	2011	CS655, Enviro-SCAN	Variable ~10-180	https://igws.indiana.edu/cgda/waterBalanceNetwork
Iowa Environmental Mesonet	U	27	1986	CS655	30, 60, 125	https://mesonet.agron.iastate.edu/agclimate/
Kansas Mesonet	U	51	2010	CS655	5, 10, 20, 50	http://mesonet.k-state.edu/

Kentucky Mesonet	U	56	2008	Hydra	5, 10, 20, 50, 100	*Mahmood et al.* [2019] https://www.kymesonet.org/soil.html
Michigan State Enviro-Weather (formerly MAWN)	U	106	2000	CS616	5, 10	https://enviroweather.msu.edu/
Montana Mesonet	U	75	2016	GS3, Teros12	10, 21, 51, 91	http://climate.umt.edu/mesonet/
National Ecological Observatory Network (NEON)	F	46	2016	Enviro-SCAN	Variable ~6-200	*Roberti et al.* [2018] https://www.neonscience.org/data-collection/soil-sensors
Nebraska Mesonet (formerly NAWDN)	S/U	68	2006	Hydra, TP	10, 25, 50, 100	*Shulski et al.* [2018] https://mesonet.unl.edu/
New York State Mesonet	U	126	2015	Hydra	5, 25, 50	*Brotzge et al.* [2020] http://www.nysmesonet.org/
NOAA Hydrometeorology Testbed Observing Network (NOAA HMT)	F	14	2004	CS616, Hydra	5, 15	*Ralph et al.* [2011] https://hmt.noaa.gov/data/
North Carolina Environment and Climate Observing Network (ECONet)	U	43	1999	TP	20	*Pan et al.* [2012] https://climate.ncsu.edu/econet
North Dakota Agricultural Weather Network	U	48	2016	CS655	5, 10, 20, 30, 50, 75, 100	https://ndawn.ndsu.nodak.edu/soil-moisture.html

Oklahoma Mesonet	S	120	1996	CS229	5, 10, 25, 60	*Zhang et al.* [2019] http://mesonet.org/
Snow Telemetry Network (SNOTEL)	F	352	2005	Hydra	5, 10, 20, 50, 100	*Schaefer and Paetzold* [2001] https://www.wcc.nrcs.usda.gov/snow
Soil Climate Analysis Network (SCAN)	F	223	1999	Hydra	5, 10, 20, 50, 100	*Schaefer et al.* [2007] https://www.wcc.nrcs.usda.gov/scan/
South Dakota Mesonet	U	32	2002	Hydra	5, 10, 20, 50, 100	https://climate.sdstate.edu/
Texas Mesonet (TexMesonet)	S	23	2017	CS655, GS-3	5, 10, 20, 50	https://www.texmesonet.org/
Texas Soil Observation Network (TxSON)	U	80	2015	CS655	5, 10, 20, 50	*Caldwell et al.* [2019] https://www.beg.utexas.edu/research/programs/txson
Texas Water Observatory (TWO)	U	9	2017	CS655, MPS6	5, 15, 30, 75, 100	https://two.tamu.edu/
U.S. Climate Reference Network (USCRN)	F	114	2009	Hydra, TDR-315	5, 10, 20, 50, 100	*Palecki and Bell* [2013] https://www.ncdc.noaa.gov/crn/
West Texas Mesonet	U	67	2002	CS615	5, 20, 60, 75	*Sonmez et al.* [2005] http://www.mesonet.ttu.edu/

[1]Network operator is federal (F), state (S), and/or university (U)

[2]The number (N) includes active stations with soil moisture sensors within the network.

[3]Sensor types include a heat dissipation (CS229, Campbell scientific, US), impedance sensors (Hydra, Hydraprobe, Stevens Water, US; TP, Theta Probe, Delta-T, Inc., UK), transmission line oscillators (CS615, CS616, CS655, Campbell Scientific, US), capacitance sensors (GS3, EC-5, EnviroSCAN, Sentek, Australia), time-domain reflectometers (TDR-315, Acclima, US), and matric potential sensors (MPS6, Water Potential Sensor, Meter Group, US).

Table 4. Nine recommendations from NCSMMN strategy document.

#	Strategy Recommendations
1	Codify organizational structure and lead agency for the NCSMMN
2	Formalize communications and establish a web presence
3	Codify partnerships with state Mesonets and the National Mesonet Program
4	Develop criteria for Tier 1 data providers
5	Support research into methodologies to create and improve NCSMMN products
6	Expand in situ soil moisture monitoring efforts nationwide
7	Explore opportunities and development with the private sector
8	Engage with the citizen science community and build public support
9	Develop, release, and promote NCSMMN products

13 Figures

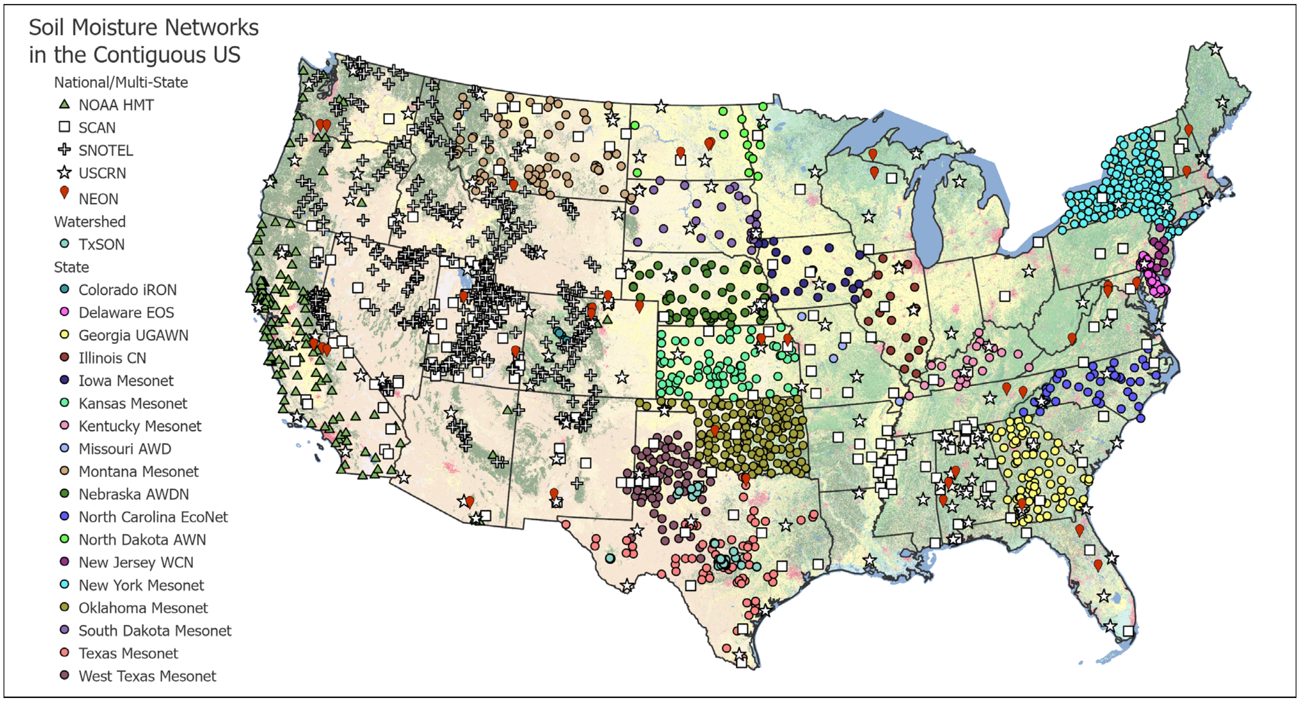

Figure 1. Current distribution of in situ soil moisture sensor networks across the contiguous United States from federal, state, and research networks.

1. Data Quality Assessment

What criteria should be used to assess data quality from a network?

- Metadata
- Soil characterization and properties
- Quality Assurance/Quality Control
- Data availability
- Ancillary data collection

2. Impediments to high-quality data

What are the obstacles to generating high-quality data? What assistance could be provided?

- Financial support
- Technical support
- Coordination/standardization of installation
- Data management and dissemination
- Data ownership and network identity

What are the most important data attributes or products needed to meet user needs?

- Data accessibility and latency
- Data availability/completeness and latency
- Data standardization and quality control
- Maps, gridded data, and visualizations
- Education and outreach

3. Research Priorities and Products

What are three priorities in the near-term?

- Long-term data management planning
- Shared repository for data processing
- National network assessment
- High-quality observations from more complex landcovers
- Establishing a NCSMMN steering committee

And over the long-term?

- Network expansion
- Augment mesonets to include soil moisture sensors
- Standardization of sensors, installation, and data collection
- Develop data use metrics and quantify users' needs
- Merge in situ and remotely sensed data
- Spatial interpolation methods and uncertainty approaches
- Develop application-driven tools
- Develop data use metrics and quantifying users' needs
- Better implementation of soil moisture in land surface models
- Integration of soil moisture with other novel processes
- Standardization of sensors, installation, and data collection

Figure 2. Summary of breakout questions and results from the 2020 National Soil Moisture Network Workshop discussion groups.

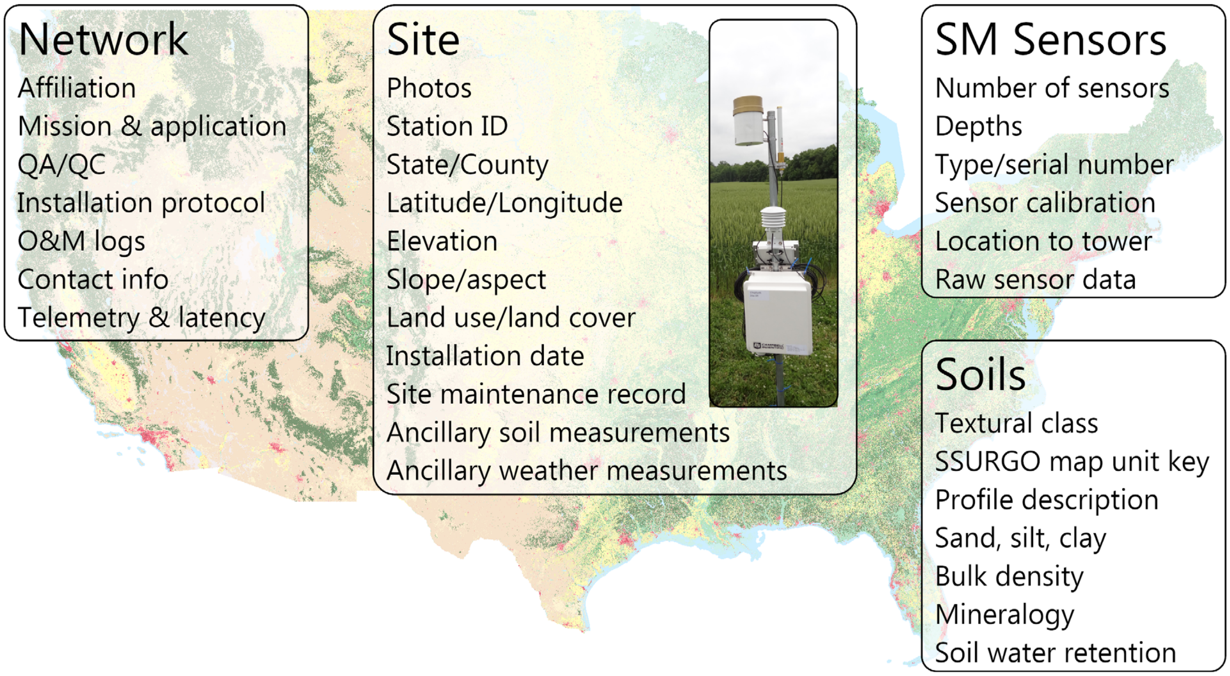

Figure 3. Proposed metadata requirements for soil moisture data included in the NCSMMN network.