BAMS Article

Working toward a National Coordinated Soil Moisture Monitoring Network

Vision, Progress, and Future Directions

C. Bruce Baker, Michael Cosh, John Bolten, Mark Brusberg, Todd Caldwell, Stephanie Connolly, Iliyana Dobreva, Nathan Edwards, Peter E. Goble, Tyson E. Ochsner, Steven M. Quiring, Michael Robotham, Marina Skumanich, Mark Svoboda, W. Alex White, and Molly Woloszyn

ABSTRACT: Soil moisture is a critical land surface variable, impacting the water, energy, and carbon cycles. While in situ soil moisture monitoring networks are still developing, there is no cohesive strategy or framework to coordinate, integrate, or disseminate these diverse data sources in a synergistic way that can improve our ability to understand climate variability at the national, state, and local levels. Thus, a national strategy is needed to guide network deployment, sustainable network operation, data integration and dissemination, and user-focused product development. The National Coordinated Soil Moisture Monitoring Network (NCSMMN) is a federally led, multi-institution effort that aims to address these needs by capitalizing on existing wide-ranging soil moisture monitoring activities, increasing the utility of observational data, and supporting their strategic application to the full range of decision-making needs. The goals of the NCSMMN are to 1) establish a national "network of networks" that effectively demonstrates data integration and operational coordination of diverse in situ networks; 2) build a community of practice around soil moisture measurement, interpretation, and application—a "network of people" that links data providers, researchers, and the public; and 3) support research and development (R&D) on techniques to merge in situ soil moisture data with remotely sensed and modeled hydrologic data to create user-friendly soil moisture maps and associated tools. The overarching mission of the NCSMMN is to provide *coordinated high-quality, nationwide soil moisture information for the public good* by supporting applications like drought and flood monitoring, water resource management, agricultural and forestry planning, and fire danger ratings.

KEYWORDS: Atmosphere; Drought; Hydrologic cycle; Soil moisture

https://doi.org/10.1175/BAMS-D-21-0178.1
Corresponding author: Michael Cosh, michael.cosh@usda.gov
In final form 4 August 2022

AFFILIATIONS: Baker*—National Oceanic and Atmospheric Administration, Durham, North Carolina; **Cosh and White**—Hydrology and Remote Sensing Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland; **Bolten**—National Aeronautics and Space Administration, Beltsville, Maryland; **Brusberg**—U.S. Department of Agriculture, Washington, D.C.; **Caldwell**—Nevada Water Science Center, U.S. Geological Survey, Carson City, Nevada; **Connolly**—Northern Research Station, Forest Service, U.S. Department of Agriculture, Madison, Wisconsin; **Dobreva and Quiring**—The Ohio State University, Columbus, Ohio; **Edwards**—South Dakota State University, Aberdeen, South Dakota; **Goble**—Colorado State University, Fort Collins, Colorado; **Ochsner**—Oklahoma State University, Stillwater, Oklahoma; **Robotham**—Natural Resource Conservation Service, U.S. Department of Agriculture, Washington, D.C.; **Skumanich**—National Integrated Drought Information System, National Oceanic and Atmospheric Administration, and University Corporation for Atmospheric Research, Boulder, Colorado; **Svoboda**—National Drought Mitigation Center, University of Nebraska–Lincoln, Lincoln, Nebraska; **Woloszyn**—National Integrated Drought Information System, National Oceanic and Atmospheric Administration, and Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado
* Retired.

Soil moisture is one of the smallest components of the hydrologic cycle, yet it plays an important role as a critical land surface parameter influencing Earth's water, energy, and carbon cycles (Fig. 1). As a result, natural resources and the economic activities that depend on them are directly impacted by soil moisture levels in unique ways that may not be fully captured by more traditional meteorological and hydrologic indicators such as precipitation, temperature, evapotranspiration, and streamflow. Soil moisture can be estimated by several methods, including in situ monitoring, remote sensing, and numerical modeling. While each is valuable, no one method for obtaining soil moisture information is perfect, as each has unique limitations relative to attributes such as accuracy, historical record, data availability, spatial distribution, and latency. Yet, when used in complementary ways, these three methods of estimation have the potential to provide a comprehensive picture of soil moisture levels to support a wide range of applications.

The demand for a timely, accurate, and well-coordinated soil moisture information system is seen across an array of weather-driven societal needs. Such needs include drought and flood monitoring (e.g., Chifflard et al. 2018; Otkin et al. 2016), water resource management in both snow-dominated and rainfall-dominated watersheds (e.g., Harpold et al. 2017; Wyatt et al. 2020), agricultural and forestry planning (e.g., Krueger et al. 2021, 2019), and fire danger ratings (e.g., Krueger et al. 2015; Sharma et al. 2020). Additionally, soil moisture patterns are expected to be significantly altered by anthropogenic climate change (USGCRP 2018). Expected soil moisture pattern changes will alter future seasonal runoff predictability and expectations (e.g., Koster et al. 2010), flooding risk (e.g., Wasko and Nathan 2019), and flash drought probabilities (e.g., Yuan et al. 2019; Christian et al. 2021). Tracking these changes would aid future disaster mitigation and planning efforts. The National Coordinated Soil Moisture Monitoring Network (NCSMMN), is a federally led, multi-institution effort that aims to address these varied needs.

Overview of the NCSMMN

Over the past two decades, there has been growing interest within both the research and practitioner/end user communities to develop a national initiative to harness and improve

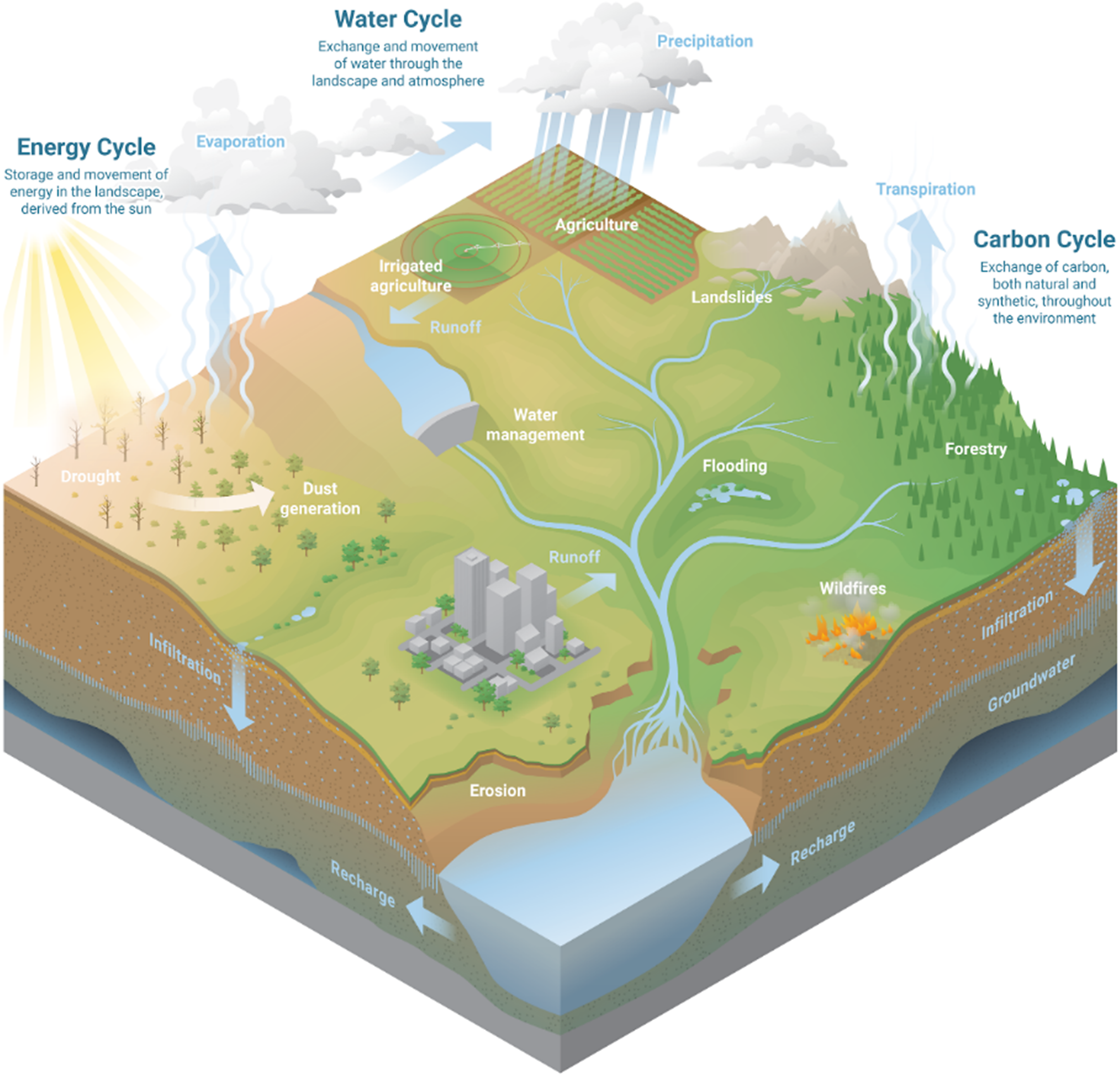

Fig. 1. The importance of soil moisture is illustrated in relation to the energy, water, and carbon cycles. Soil moisture plays a role in surface energy exchange, partitioning of surface runoff and infiltration, and influences land–atmosphere soil water dynamics, affecting many surface processes such as water management and agricultural productivity. Credit: Fiona Martin, Visualizing Science.

soil moisture information for natural resource assessment and hazards management. In 2013, the National Oceanographic and Atmospheric Administration's (NOAA) National Integrated Drought Information System (NIDIS), working in collaboration with the U.S. Department of Agriculture (USDA) and other federal, state, and academic partners, began hosting a series of regular meetings to explore the formation of such a national initiative. Between 2013 and 2018, a combination of national scoping meetings and pilot research activities were conducted, leading to a better understanding of what such a national initiative should entail.

In 2018, Congress provided formal direction to this effort in the NIDIS Reauthorization Act of 2018 (Pub. L. 115-423), by calling for NIDIS to develop a "strategy for a national coordinated soil moisture monitoring network." This was reinforced in the Agriculture Improvement Act of 2018 (Pub. L. 115-334; i.e., the "Farm Bill"), which called for the USDA to coordinate with NOAA and the National Drought Mitigation Center (NDMC) to enhance the collection of soil moisture data to improve the accuracy of the U.S. Drought Monitor. While these directives were focused on the application of soil moisture for drought early warning, there was wide recognition that any such initiative would support applications across the entire spectrum from drought to flooding/pluvial conditions. For example, based on postevent assessments of the 2011 floods in the upper Missouri River basin, in the Water Resources Development Act of 2014, Congress recognized the importance of soil moisture monitoring as part of flood early warning.

To organize the development of a strategy for the NCSMMN, an Executive Committee was formed in 2018 that included soil moisture subject matter experts and program managers from key federal agencies, state-affiliated academic institutions, and other interested parties, including NOAA, USDA, NDMC, the U.S. Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), South Dakota State University, The Ohio State University, Oklahoma State University, and the citizen science group CoCoRaHS (Community Collaborative Rain, Hail and Snow Network). This committee worked collaboratively over a 2-yr period with a wide set of stakeholders to develop the strategy, culminating in the formal release of "A Strategy for the National Coordinated Soil Moisture Monitoring Network" in May 2021 (Executive Committee of the NCSMMN 2021).

As detailed in the Strategy, the overarching mission of the NCSMMN is to provide *coordinated high-quality, nationwide soil moisture information for the public good*. In concrete terms, this will entail the integration of soil moisture data from the wide range of existing in situ monitoring networks throughout the United States into a consistent set of data products, and the merging of these in situ data as appropriate with remotely sensed and modeled hydrologic data for the generation of real-time, meaningful, easy-to-understand soil moisture maps, tools, and related services. These near-real-time products and services are expected to reduce societal risks from hazards such as drought, flood and fire; contribute to better hazard early warning systems; improve characterization of national water budgets and climate models; inform crop production decisions, forest management, and natural system resilience; and benefit many additional natural resource applications.

The NCSMMN Strategy identifies a series of nine recommendations (see appendix) to advance this mission, all focused on supporting three essential components of the effort: 1) building a functional and flexible *network of (monitoring) networks*, including the technical and organizational infrastructure to allow aggregation of disparate and differently scoped data streams (e.g., with different depths, periods of record, etc.), along with their application to new products and tools; 2) building a coordinated *network of people*, i.e., a community of practice, that ensures ongoing and multidirectional information exchange between data providers, researchers, product developers, and practitioners and end users; and 3) *supporting research and development* on techniques to merge in situ soil moisture data with remotely sensed and modeled hydrologic data to capitalize on the strengths of each to create user-friendly soil moisture maps and associated tools.

In situ networks which form the basis of the national network of networks include federal networks such as the USDA Natural Resources Conservation Service (NRCS) Soil Climate Analysis Network (SCAN) and Snowpack Telemetry network (SNOTEL), NOAA's U.S. Climate Reference Network (USCRN), the National Ecological Observatory Network (NEON), as well as a number of state mesonets such as the Oklahoma Mesonet, the South Dakota State University Mesonet, West Texas Mesonet, and the Montana Mesonet. Figure 2 shows the distribution of currently actively monitoring networks. Over time, the NCSMMN hopes to expand partnerships to include additional academic and research networks

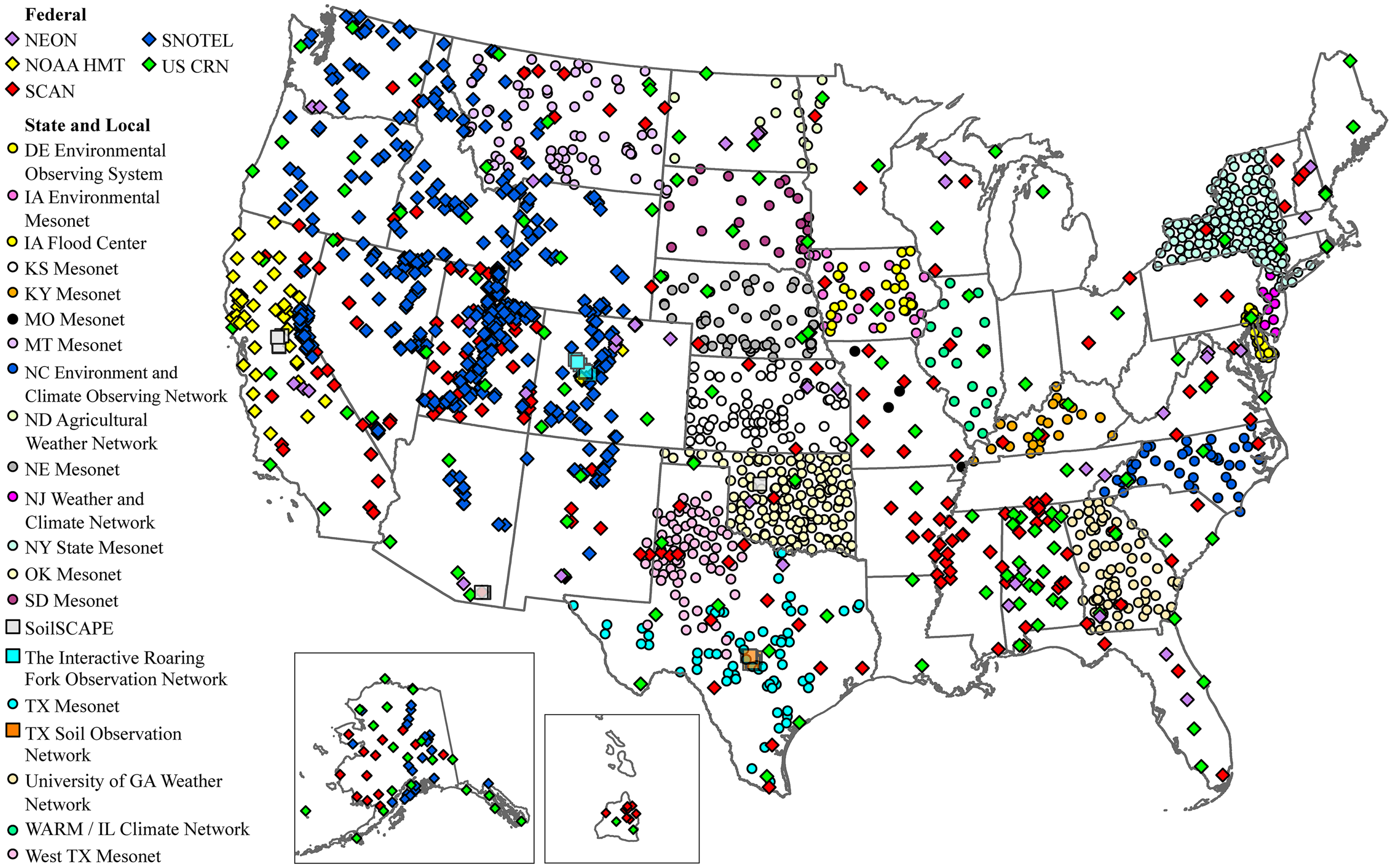

Fig. 2. Federal, state, and regional networks that actively monitor soil moisture. Once integrated, these networks could provide a consistent national-scale source of soil moisture information for planning and forecasting.

[e.g., AmeriFlux, the U.S. Forest Service's (USFS) Remote Automatic Weather Stations (RAWS), citizen science networks (e.g., CoCoRaHS), and private networks, as available].

Soil moisture estimates from in situ resources can be combined with, as well as used to calibrate and validate, satellite-based remote sensing products such as NASA's Soil Moisture Active/Passive (SMAP) satellite, the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) satellite, and others. Models are also available that can provide independent, physically based estimates of soil moisture, and/or can be used to assimilate real-time observations into merged products. Modeled soil moisture products are produced operationally by various modeling systems, including the North American Land Data Assimilation System (NLDAS-2), the National Water Model, and others. Here, too, in situ monitoring data are often used as the basis for accuracy assessments of modeling products (Montzka et al. 2020).

One goal of NCSMMN is to generate products designed to support a variety of applications such as improved drought and flood monitoring or water resource management; however, there are challenges to be addressed relative to meeting the needs of multiple applications. For example, near-surface in situ soil moisture data may be most suited for integration with remotely sensed data, but deeper (root-zone) measurements may be most useful for drought monitoring. NCSMMN also aims to develop resources to identify and facilitate the use of best practices for the collection and provision of in situ soil moisture data. The approach is to effectively leverage data from the existing observational networks and to promote adoption of unified approaches for new stations and networks. Toward that end, the NCSMMN initiative includes projects to develop expert guidance for future sensor installations and soil moisture network development.

Once fully established, the NCSMMN will require substantial resources for database management, quality control of current and historic soil moisture data, support of the data interface for end users, data storage, and NCSMMN group coordination. A coordinated NCSMMN requires resolution of data ownership and resources, including funding; therefore, one of the NCSMMN strategy recommendations is to develop and maintain formal agreements with respective partners—both federal and nonfederal—with several already in place between the USDA, NASA, and NOAA.

Ultimately, the backbone of a national monitoring strategy will be working with state and regional mesonets to maintain and operate their networks in a coordinated manner. Therefore, an important consideration for robust participation in the NCSMMN by nonfederal networks is financial support to operate and maintain these networks. At any given time, a network is usually operating with ~80% of stations reporting, as in situ stations require regular maintenance, sensor replacements, communications upgrades, and licensing and rental agreements. This maintenance requires personnel who are experts in field equipment and troubleshooting and who able to work at stations often far removed from local services. To realize a fully integrated network of networks will require addressing the cost recovery issues faced by nonfederal networks.

Finally, the ultimate NCSMMN objective is to develop user-friendly products and services. Some agencies have funded projects specifically in response to NCSMMN priorities (e.g., NIDIS has funded the development of the USCRN monitoring network and its associated data products specifically to support national-scale product development). However, fully developing the range of products and services envisioned will require a broader set of funding vehicles and a more established institutional home.

Implementation of the NCSMMN: The path forward

Over the past two years, implementation of the NCSMMN Strategy has begun in a series of key focus areas: Community Building and Outreach, Protocols Development, Network Expansion, and Product Development. Each of these will be reviewed in turn, with an emphasis on activities currently being undertaken. A subsequent section will review priority activities starting in 2022, and the NCSMMN Executive Committee will conclude with some brief observations about future direction.

Community building and outreach. A cornerstone of the NCSMMN Strategy is to build a community of experts trained in the different aspects of soil moisture monitoring, on both the research and operations sides. Since 2010, annual self-organized soil moisture workshops have brought together experts from across the United Stated to discuss the latest science research and technical innovations regarding soil moisture monitoring and applications. These workshops have provided the initial formation of a community of practice. Under the NCSMMN Strategy, these community-led annual National Soil Moisture Workshops have evolved to a nationwide audience of over 100 attendees annually. The workshop is hosted by different universities and agencies, though recently it has been virtual. Site visits are planned part of these workshops to explore local scientific testbeds and study sites, including the Oklahoma Mesonet, Konza Prairie in Kansas, and the Kellogg Soil Survey Laboratory in Lincoln, Nebraska.

In addition to these annual National Soil Moisture Workshops, in 2021 the NCSMMN sponsored a series of other workshops and webinars to provide focused sectoral engagement, from network operators to researchers to end users.

Network Operators Workshop, March 2021. To provide a forum for peer-to-peer sharing of best practices among soil moisture data providers, the NCSMMN hosted this first-in-kind workshop specifically focused on the practical considerations in installing and maintaining soil moisture monitoring stations, including station siting, soil characterization, sensor selection and calibration, site maintenance, data management and communications. One major issue network operators identified is a lack of standardized methods for collecting in situ data and of quality assurance and quality control (QA/QC) guidance for verifying data records.

Soil Moisture and Wildfire Symposium, May 2021. This online research symposium highlighted the emerging application of soil moisture information to better understand and predict wildfire danger. Recent discoveries are revealing the potential for soil moisture estimates to improve fire danger predictions and to advance our understanding of fire behavior. The symposium provided an interactive forum to build connections between researchers and practitioners, to share relevant research in this area, and to identify ways to move forward with new research and applications. A comprehensive review paper from this symposium is currently under review.

End Users Listening Sessions, July 2021. Recognizing the importance of co-development of soil moisture products aimed at decision-makers, the NCSMMN hosted two listening sessions as an opportunity for end users to share their thoughts, wish lists, and out-of-the-box ideas about what types of soil moisture products would best serve their needs. Participants included federal, regional, and state program staff; state climatologists; water resource managers; extension agents; and others interested in products derived from soil moisture data. Findings from the listening sessions are being used to direct NCSMMN research and outreach activities.

Soil Moisture Webinar Series, February–March 2022. As a broad educational outreach activity, the NCSMMN, in conjunction with NIDIS and the National Weather Service (NWS), recently hosted a two-part national webinar series on soil moisture for NWS operational forecasters, other weather and climate service providers, and the general public. The first webinar, Soil Moisture 101, provided an overview of soil moisture monitoring and interpretation, including a review of the three main techniques for estimating soil moisture conditions—in situ, satellite, and land surface models—and was attended by over 750 people. The second webinar, Practical Applications of Soil Moisture Information, featured presentations from climate service professionals on how soil moisture informs their decision-making. Materials from each webinar were recorded and are available on the U.S. Drought Portal (drought.gov), the current home for the NCSMMN web presence.

Protocols development. The NCSMMN Strategy explicitly recognizes the need for best practices documentation and standardization protocols, including 1) standards and specifications for sensor performance, validation, and data output; 2) quality-control procedures for evaluation of current and period-of-record data; 3) database management and storage protocols, including prototype metadata system architecture to capture and provide access to ancillary information such as soil type and land cover that will be an integral part of fully interpreting the soil moisture data; and 4) general technical assistance materials covering site and sensor selection, installation, maintenance, data transmission, and so forth. There is recognition that existing observational networks may perform at a range of levels relative to NCSMMN standards; the long-term strategy is to provide technical and logistical support to networks so they can engage in a way that best fits their mission and resources, while supporting the collection of high-quality data for monitoring and prediction on a national scale.

Several entities have developed their own internal documentation for soil moisture data collection and record processing. This includes the American Association of State Climatologists (AASC), SCAN, and USCRN. In addition, in 2021 the USGS began developing a comprehensive Techniques and Methods (T&M) protocol for collecting and evaluating soil moisture data, following methods similar to those utilized for more traditional in-stream sensors (e.g., Rasmussen et al. 2009), and other soil moisture guidance documents (IAEA 2008; AASC 2019; Caldwell et al. 2019; Montzka et al. 2020). In 2022, the USGS will be completing an NCSMMN project to synthesize these independent resources into an interagency installation and maintenance guide and video training.

Network expansion. In addition to efforts to standardize and integrate soil moisture data from existing monitoring networks, the NCSMMN has also identified the need for a strategic and coordinated increase of in situ soil moisture monitoring stations nationally. Currently, the spatial distribution of monitoring stations across the United States is uneven, with large areas having either no soil moisture monitoring stations or an inadequate density and/or distribution of stations (Fig. 2). The estimated 2,106 (as of March 2022) active soil moisture monitoring stations in the United States today will need to be increased by 50% to reach the National Research Council's target of approximately 3,000 stations (National Research Council 2009). Furthermore, the unequal distribution of existing stations implies that the actual number of stations needed may be substantially higher than that target.

Three major NCSMMN-affiliated network expansions that address this deficit are currently underway.

USACE Upper Missouri River Basin Project. In the upper Missouri River basin, the U.S. Army Corps of Engineers (USACE) is sponsoring a major soil moisture and snowpack monitoring project to support improved monitoring of flood and drought conditions in the region, along with other related applications. Over the next several years, the USACE will be funding a major build-out of 500+ monitoring stations by partnering with state mesonets in Montana, North Dakota, South Dakota, Wyoming, and Nebraska. These stations will be configured to collect a full set of atmospheric and ground-based conditions, including year-round precipitation (rainfall and liquid equivalent of snowfall), snow depth, soil moisture, and temperature at five depths (5, 10, 20, 50, 100 cm), frost–thaw depth, along with atmospheric variables to support the determination of total water cycles (air temperature, humidity, solar radiation, wind). In addition, the stations have cameras that will inform quality control efforts and provide land status characterization. Once implemented, this network will provide a proof-of-concept for total water monitoring.

Southeast region. The University of Alabama in Huntsville, the University of Florida, and The University of Georgia are collaborating on a NOAA-funded NCSMMN project to enhance the soil moisture monitoring network in the southeastern United States and to improve the application of soil moisture data to decision-making in the region. The project involves a series of interrelated activities, including testbed calibration and evaluation of low-cost soil moisture sensors, subsequent expansion of the regional network using viable low-cost sensors identified, development of a series of crop-support tools from the soil moisture data stream, and research on validation of remote sensing–derived root-zone soil moisture. Results from the project will not only enhance regional hydro-hazard monitoring, but also will inform national objectives such as better standardization of sensor performance and improved validation of national models.

USDA Forest Service Soil Moisture Monitoring Network. Expansion of soil moisture monitoring is also needed to address various major land-cover types across the United States that are currently underserved, particularly forests and rangelands. Few, if any, of the stations in existing long-term monitoring networks are located under forest canopies, outside of the

National Ecological Observatory Network (NEON). Furthermore, it is much more difficult to obtain accurate remotely sensed retrievals over forests due to forest canopy cover, thick layers of duff, and widely varying slope aspects.

In coordination with the NCSMMN, the USFS is leading an agency-wide effort to develop a national forest soil moisture monitoring network to meet the needs of forest managers for timely, location-based soil moisture. This effort is intended to equip forest managers to better plan and manage forest operations, anticipate fire risks, and address other challenges for forest management. The effort involves four core elements: 1) expanding existing monitoring networks such as the RAWS network (which currently includes 17 stations equipped for soil moisture monitoring), 2) building the knowledge base within the USFS and across other forest management agencies, 3) developing forest observation systems and protocols to help link shifts in soil moisture to broader changes in forest conditions, and 4) creating a centralized data repository for easy national access. As a key first step in this effort, the USFS is partnering with NIDIS on a series of pilot studies in Kentucky, Montana, New York, and North Carolina to address the complexities of forest/rangeland soil moisture monitoring, such as the often-complex forest topography.

But even with all the above efforts, it is clear that distribution of in situ stations will continue to lag optimal levels needed for reliable national conditions monitoring. A preliminary analysis by the USACE of an adequate station density within the Upper Missouri River Basin Project was estimated at one station per 500 mi^2 (USACE 2021). If this were extended across the contiguous United States (CONUS), it would be approximately equivalent to one station per the remote sensing Equal Area Scalable Earth 2 (EASE2) 36-km grid (Brodzik et al. 2012).

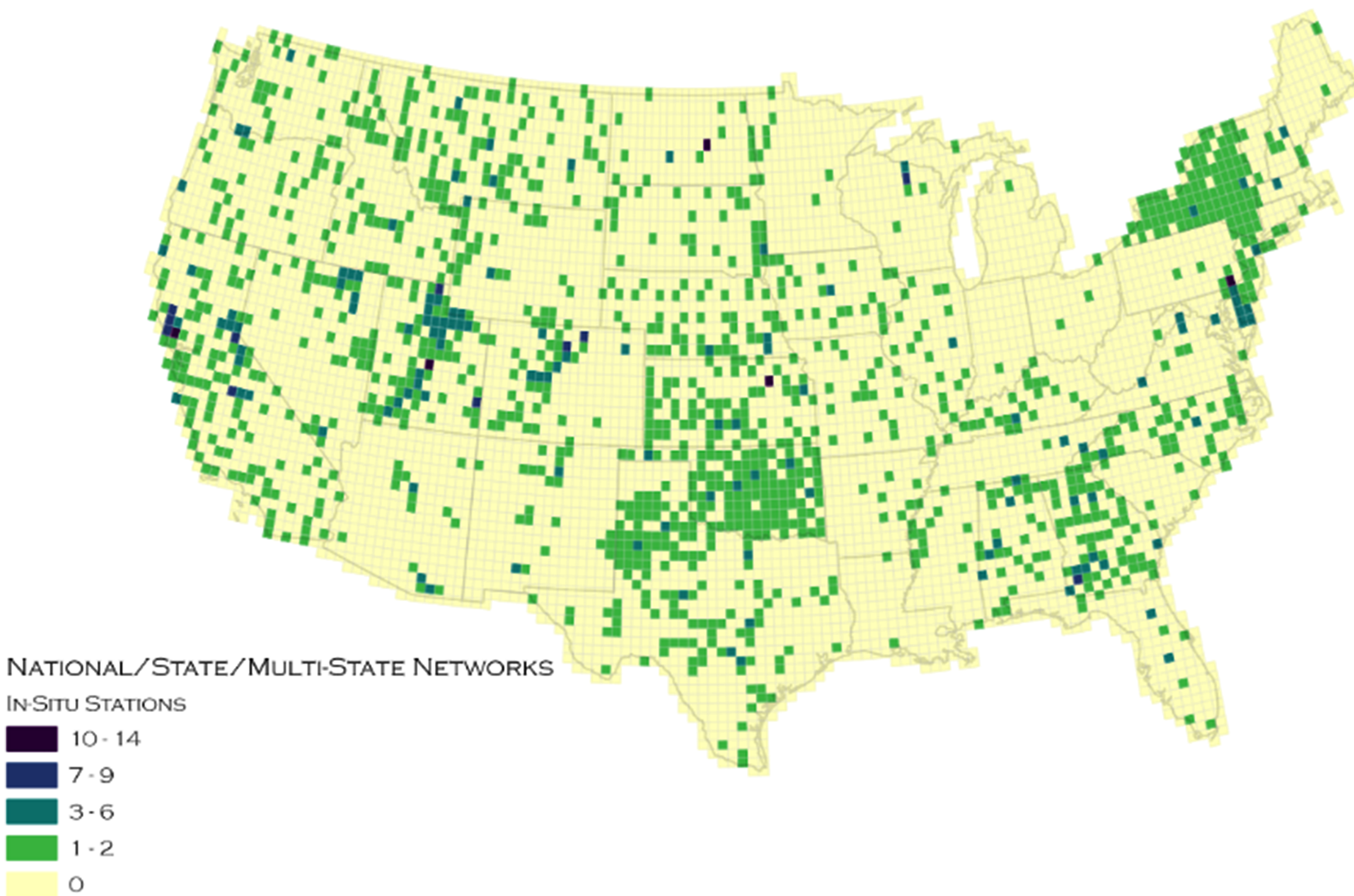

Fig. 3. The number of soil moisture stations available per 36-km EASE2 grid cell. Analysis suggests a minimum of at least 1 station per 36-km EASE2 grid cell to provide adequate density. Credit: Alex White.

Figure 3 shows this grid distribution along with the current number of stations found within each grid. For the national networks, only 5% of the grid cells have a soil moisture station. When including both national and state mesonets, only 20% of the grid cells have at least one soil moisture station. It is clear that while near-term expansions of several regional networks will improve this situation, there will continue to be a need to extend the coverage (both in CONUS and beyond), along with efforts to refine the use of remote sensing and modeled outputs to complement in situ data collection.

Product development. There are a number of potential NCSMMN products envisioned, including 1) national maps generated from high-resolution, gridded data showing variables such as volumetric water content (VWC), VWC percentiles relative to climactic records, VWC anomalies, and VWC anomaly percentiles designed to correspond with U.S. Drought Monitor categories (which indicate drought status); 2) linked downloadable data for a range of spatial and temporal scales, including time series graphs of soil moisture for different regions; 3) plain-language summaries of current conditions; 4) contextual information for current soil moisture levels, such as soil physical and hydraulic properties, and data related to other soil moisture variables (percent normal, percent saturation, soil water deficit, plant available water, and fraction of available water capacity); and 5) interactive visualization tools and other resources to support decision-making.

Many of these products depend on resolving issues related to how best to blend, assimilate, synchronize, and standardize disparate, heterogeneous, and variable-period data sources, and how best to represent information for different user groups. A number of research efforts are underway to provide proof-of-concept solutions for these issues. At the same time, researchers are continuing to refine and improve existing soil moisture products. The following provide a sample of these efforts.

NationalSoilMoisture.com. This research-based website is a signature project of the NCSMMN and provides near-real-time soil moisture products from a first-in-kind blending of in situ data, satellite remote sensing data, and land surface model output. A key initial component of the research was to assess the fidelity of various satellite remote sensing and model-based soil moisture products for drought monitoring (Ford and Quiring 2019), to perform a systematic review of the quality of available federal and state in situ data measurements (Ford et al. 2020). Through these quality-control assessments, the researchers determined that NLDAS-2 models and SMAP L3 remote sensing products outperformed the other model and satellite soil moisture products tested. They also demonstrated that the vast majority of in situ stations (~90%) provided usable data that were consistent with satellite remote sensing and land surface model soil moisture datasets. From the in situ datasets, the research team developed the first U.S.-wide gridded dataset of in situ soil moisture values (Zhao et al. 2020), as well as a series of blended soil moisture products that combined the in situ data with satellite and model-derived soil moisture (Zhang et al. 2021). All of the gridded soil moisture products display soil moisture in percentiles so that they can be readily compared to the U.S. Drought Monitor maps. These data are served through a map interface, with maps available from 2018 to present, as well as through a historical database (2000 to present) to support retrospective analysis by climatologists and modelers.

NASA SPoRT-LIS. The Short-Term Prediction and Transition Center–Land Information System (SPoRT-LIS) is a NASA product that provides real-time high-resolution gridded soil moisture data to support regional and local modeling and improve situational awareness. The SPoRT-LIS is a long-term run of the Unified Noah land surface model (Ek et al. 2003) over CONUS that is updated every 6 h. SPoRT-LIS provides soil moisture estimates at 3-km grid resolution over a 2-m-deep soil column. The basis of SPoRT-LIS is a 33-yr soil moisture climatology simulation spanning 1981–2013 and extended to the present time, forced by atmospheric analyses from NLDAS-2. Another unique feature of SPoRT-LIS is the incorporation since 2012 of daily, real-time satellite retrievals of vegetative "greenness," derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite instrument (Vargas et al. 2015). This enables a more complete depiction of subcounty conditions in space and time, including accounting for vegetation/crop health. SPoRT-LIS has been used both for drought (e.g., Case and Zavodsky 2018) and for pluvial conditions (e.g., Case et al. 2021).

Crop-CASMA. An important soil moisture user group is the USDA National Agricultural Statistics Service (NASS), which conducts weekly national top and root-zone soil moisture surveys and publishes weekly cropland soil moisture statistics at the state level in the Crop Progress and Condition Report and the Crop Weather Report. Currently, the assessment is conducted manually by visual observation and tactile sensing without instrumentation, and the assessments are qualitatively classified into four categories of very short, short, adequate, and surplus for both top and root-zone soil moisture.

To improve this assessment process, USDA NASS and NASA, working in collaboration with George Mason University, recently released Crop-CASMA (Crop Condition and Soil Moisture Analytics). Crop-CASMA is a web-based geospatial application that provides access to high-resolution data from NASA SMAP and MODIS missions to map surface soil moisture and crop vegetation conditions across the United States. The tool is designed to help farmers, researchers, and others with spring planting, track damage after natural disasters, and monitor crop health.

NOAA USCRN Soil Water Analysis Model Product (SWAMP). This unique experimental 4-km gridded soil moisture product utilizes soil moisture measurements from the U.S. Climate Reference Network to create the initial conditions from which future soil moisture levels are estimated using daily analyses of precipitation and evapotranspiration (ET). The 4-km-resolution Parameter-Elevation Regressions on Independent Slopes Model (PRISM) is used as the precipitation field, and the Atmosphere–Land Exchange Inverse (ALEXI) model is used as the ET field (Buban et al. 2020). These precipitation and ET fields are used along with the statistical relationships from the USCRN soil moisture measurements, soil type, and vegetation to produce a daily 4-km gridded soil moisture analysis for each grid cell for the upper 25 cm of soil. This depth was chosen to help inform drought analysis, as it represents a soil zone that reacts on the daily to weekly time scale.

SWAMP is currently in development but is planned for dissemination in near–real time via Climate Engine, an innovative cloud computing platform where users can quickly and easily process satellite and climate data and create custom maps and time series graphs viewable in a web browser.

Upcoming priorities for the NCSMMN

The NCSMMN Executive Committee recently conducted a program review of activities and experience from the past few years and identified a revised set of near-term priorities to guide NCSMMN efforts. These priorities can be grouped into three main areas: Data Generation, Data Delivery and Application, and Community Building and Engagement.

Data Generation. In Data Generation, a priority will be on continuing to *deliver technical assistance to data providers*, including completion of the "Installation Protocol for In Situ Soil Moisture Data Collection" previously mentioned, along with new activities, including 1) coordination and documentation of soil moisture testbed activities to facilitate community-based information sharing on sensor performance and 2) developing a Soil Moisture School, intended as an opportunity for students of all types (potentially including potentially citizen science observers) to have a "hands in the dirt" experience with in situ soil moisture monitoring.

There will be continuing efforts to *increase monitoring in underserved areas*, particularly in forests/rangelands and on tribal lands. As mentioned previously, the USFS has an active effort to increase forest monitoring, which will continue to be a priority for the NCSMMN. In addition, soil moisture (and other weather and climate) monitoring on tribal lands is sparse, despite the significant land area these lands represent. Therefore, the NCSMMN will focus on identifying opportunities to build capacity for monitoring on tribal lands. This will include both supporting expansion of federal monitoring programs as well as providing information and technical assistance to interested tribal and/or state entities. From 2017 to 2021, USDA NRCS, in partnership with the Bureau of Indian Affairs and others, operated a soil moisture and climate information network on Tribal lands. The Tribal Soil Climate Analysis Network, also known as Tribal SCAN (TSCAN), supported natural resource assessments and conservation activities through a network of over 20 automated climate monitoring and data collection sites primarily in Tribal agricultural areas. These stations monitor soil moisture, soil temperature, and climatic conditions in support of agricultural operations and STEM (science, technology, engineering, and math) education for Tribal communities. This successful program provides for a starting point for developing a longer-term plan to engage tribal communities and support their agricultural and conservation needs.

Data Delivery and Application. The NCSMMN will focus on three key priorities in the area of Data Delivery and Application. The first priority is *addressing the soil moisture and wildfire nexus*, that is, exploiting the emerging opportunity to use soil moisture information to help natural resource managers anticipate and manage wildfire risks. Among other components, the NCSMMN executive committee will be supporting efforts to include soil moisture information in USFS National Fire Danger Ratings. Beyond that, we will be supporting and promoting research that explores how best to apply soil moisture information to land management decisions related to wildfire, on both forested and other ecosystems.

Second, the NCSMMN will be working to develop a *curated "kiosk" for soil moisture products*. There are multiple soil moisture products currently available and in development. Through the NCSMMN listening sessions, we have heard from the user community that a better way to navigate through these products is needed; for example, a central location where details on latency, coverage, methodology, and other metadata information are documented and user-friendly software interface tutorials are provided. Ultimately, the aim is to also include peer-reviewed product validation and comparison studies.

A third key priority in the Data Applications area is working to *address the needs of U.S Drought Monitor (USDM) authors*. The USDM is a highly referenced national drought alert system that provides maps of drought location and severity on a weekly basis, and there is widespread recognition that the use soil moisture information could provide a higher level of confidence in determining drought status. This will entail both the development of specific soil moisture products tuned to USDM author requirements as well as increasing the use of in situ data to help ground truth and better train land surface models and to calibrate/validate remotely sensed soil moisture products.

Community Building and Engagement. Finally, the NCSMMN will continue to prioritize robust Community Building and Engagement, including continued support for the annual National Soil Moisture Workshop as well as sector-based and regional workshops, research seminars, national educational webinars, and other such outreach opportunities. The development of an active network of people ensures that NCSMMN efforts in data generation, delivery, and application will best meet the needs of the entire community.

Conclusions

The NCSMMN is intended to be both a network of networks and a network of people who can advance the science of soil moisture estimation, monitoring, and forecasting. Developing near-real-time and easy-to-understand soil moisture products that support decision-making is the ultimate goal of the NCSMMN initiative. With an improved understanding of soil moisture, we can reduce societal risks from hazards such as drought, flood, and fire. In addition to enhanced hazards early warning, these products can help to improve the characterization of water, energy, and carbon cycles; improve weather and climate models; validate remote sensing–based soil moisture products; boost crop production and ecological resilience; and benefit additional natural resource applications. Building this capacity within the United States will also support the development of new modeled and remote sensing–based soil moisture resources and increase the utility of all soil moisture–related data, tools, and value-added products.

Acknowledgments. We would like to acknowledge the thoughtful collaboration of the many mesonet data providers, research scientists, federal and state agency climate and water resources program staff, and others that have contributed to the vision and progress of the NCSMMN. We would further like to acknowledge the Interagency Council for Advancing Meteorological Services and the National Drought Resilience Partnership for their cross-agency leadership that underlies and endorses the NCSMMN. This research was supported by the U.S. Department of Agriculture, Agricultural Research Service. USDA is an equal opportunity provider and employer.

Data availability statement. No datasets were generated or analyzed during the current study. Site locations are provided at Quiring (2022).

Appendix: Key Recommendations from the NCSMMN Strategy, May 2021

The following nine recommendations were detailed in the National Coordinated Soil Moisture Monitoring Network (NCSMMN) Strategy and are intended to provide actionable guidelines to ensure successful NCSMMN implementation:

1) Determine permanent home agency, i.e., an institutional home for the NCSMMN.
2) Emphasize communication and outreach, including the annual national meeting along with targeted workshops, webinars, and other activities.
3) Formalize partnerships with existing mesonets to secure in situ soil moisture data from existing monitoring networks in a mutually beneficial way.
4) Develop data-quality criteria to support data comparability via a series of tiered categories.
5) Support research on data integration and analysis to address research issues related to integration of disparate datasets, quantifying uncertainty, etc.
6) Increase in situ soil moisture monitoring nationwide, especially for underrepresented areas, such as in forests and tribal lands.
7) Explore increasing partnerships with the private sector to expand monitoring data and to share expertise.
8) Engage with the citizen science community to explore community soil moisture monitoring as well as build public support for such monitoring.
9) Develop, release, and promote NCSMMN products to meet the needs of diverse end-user groups for the full range of natural resource applications.

References

AASC, 2019: Recommendations and best practices for mesonets, version 1. American Association of State Climatologists, 36 pp., https://stateclimate.org/best-practices/.

Brodzik, M. J., B. Billingsley, T. Haran, B. Raup, and M. H. Savoie, 2012: Correction: Brodzik, M.J., *et al. EASE-Grid 2.0*: Incremental but Significant Improvements for Earth-Gridded Data Sets. *ISPRS International Journal of Geo-Information* 2012, *1*, 32–45. *ISPRS Int. J. Geoinf.*, **3**, 1154–1156, https://doi.org/10.3390/ijgi3031154.

Buban, M. S., T. R. Lee, and C. B. Baker, 2020: A comparison of the U.S. Climate Reference Network precipitation data to the Parameter-Elevation Regressions on Independent Slopes Model (PRISM). *J. Hydrometeor.*, **21**, 2391–2400, https://doi.org/10.1175/JHM-D-19-0232.1.

Caldwell, T. G., and Coauthors, 2019: The Texas Soil Observation Network: A comprehensive soil moisture dataset for remote sensing and land surface model validation. *Vadose Zone J.*, **18**, 1–20, https://doi.org/10.2136/vzj2019.04.0034.

Case, J. L., and B. T. Zavodsky, 2018: Evolution of 2016 drought in the southeastern United States from a land surface modeling perspective. *Results Phys.*, **8**, 654–656, https://doi.org/10.1016/j.rinp.2017.12.029.

——, L. T. Wood, J. L. Blaes, K. D. White, C. R. Hain, and C. J. Schultz, 2021: Soil moisture responses associated with significant tropical cyclone flooding events. *J. Oper. Meteor.*, **9**, 1–17, https://doi.org/10.15191/nwajom.2021.0901.

Chifflard, P., J. Kranl, G. zur Strassen, and H. Zepp, 2018: The significance of soil moisture in forecasting characteristics of flood events. A statistical analysis in two nested catchments. *J. Hydrol. Hydromech.*, **66**, 1–11, https://doi.org/10.1515/johh-2017-0037.

Christian, J. I., and Coauthors, 2021: Global distribution, trends, and drivers of flash drought occurrence. *Nat. Commun.*, **12**, 6330, https://doi.org/10.1038/s41467-021-26692-z.

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of the Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *J. Geophys. Res.*, **108**, 8851, https://doi.org/10.1029/2002JD003296.

Executive Committee of the NCSMMN, 2021: A strategy for the National Coordinated Soil Moisture Monitoring Network. National Integrated Drought Information System, 75 pp., www.drought.gov/documents/strategy-national-coordinated-soil-moisture-monitoring-network.

Ford, T. W., and S. M. Quiring, 2019: Comparison of contemporary in situ, model, and satellite remote sensing soil moisture with a focus on drought monitoring. *Water Resour. Res.*, **55**, 1565–1582, https://doi.org/10.1029/2018WR024039.

——, ——, C. Zhao, Z. T. Leasor, and C. Landry, 2020: Statistical evaluation of in situ soil moisture observations from 1,200+ stations as part of the U.S. National Soil Moisture Network. *J. Hydrometeor.*, **21**, 2537–2549, https://doi.org/10.1175/JHM-D-20-0108.1.

Harpold, A. A., K. Sutcliffe, J. Clayton, A. Goodbody, and S. Vazquez, 2017: Does including soil moisture observations improve operational streamflow forecasts in snow-dominated watersheds? *J. Amer. Water Resour. Assoc.*, **53**, 179–196, https://doi.org/10.1111/1752-1688.12490.

IAEA, 2008: Field estimation of soil water content. IAEA TCS-30, International Atomic Energy Agency, 131 pp., www-pub.iaea.org/MTCD/publications/PDF/TCS-30_web.pdf.

Koster, R., S. Mahanama, B. Livneh, D. P. Lettenmaier, and R. H. Reichle, 2010: Skill in streamflow forecasts derived from large-scale estimates of soil moisture and snow. *Nat. Geosci.*, **3**, 613–616, https://doi.org/10.1038/ngeo944.

Krueger, E. S., T. E. Ochsner, D. M. Engle, J. D. Carlson, D. Twidwell, and S. D. Fuhlendorf, 2015: Soil moisture affects growing-season wildfire size in the southern Great Plains. *Soil. Sci. Soc. Amer. J.*, **79**, 1567–1576, https://doi.org/10.2136/sssaj2015.01.0041.

——, ——, and S. M. Quiring, 2019: Development and evaluation of soil moisture-based indices for agricultural drought monitoring. *Agron. J.*, **111**, 1392–1406, https://doi.org/10.2134/agronj2018.09.0558.

——, ——, M. R. Levi, J. B. Basara, G. J. Snitker, and B. M. Wyatt, 2021: Grassland productivity estimates informed by soil moisture measurements: Statistical and mechanistic approaches. *Agron J.*, **113**, 3498–3517, https://doi.org/10.1002/agj2.20709.

Montzka, C., and Coauthors, 2020: Soil moisture product validation good practices protocol version 1.0. *Good Practices for Satellite-Derived Land Product Validation*, C. Montzka et al., Eds., Committee on Earth Observation Satellites, Working Group on Calibration and Validation, Land Product Validation Subgroup, 123 pp., https://doi.org/10.5067/doc/ceoswgcv/lpv/sm.001.

National Research Council, 2009: *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks.* National Academies Press, 234 pp.

Otkin, J. A., and Coauthors, 2016: Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought. *Agric. For. Meteor.*, **218–219**, 230–242, https://doi.org/10.1016/j.agrformet.2015.12.065.

Quiring, S., 2022: National soil moisture network. Ohio State University, accessed 5 January 2022, www.nationalsoilmoisture.com.

Rasmussen, P. P., J. R. Gray, G. D. Glysson, and A. C. Ziegler, 2009: Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data. USGS Techniques and Methods 3-C4, 54 pp., https://doi.org/10.3133/tm3C4.

Sharma, S., and Coauthors, 2020: Soil moisture as an indicator of growing-season herbaceous fuel moisture and curing rate in grasslands. *Int. J. Wildland Fire*, **30**, 57–69. https://doi.org/10.1071/WF19193.

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

USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* D. R. Reidmiller et al., Eds., U.S. Global Change Research Program, 1515 pp., https://doi.org/10.7930/NCA4.2018.

Vargas, M., Z. Jiang, J. Ju, and I. A. Csiszar, 2015: Real-time daily rolling weekly green vegetation fraction (GVF) derived from the Visible Imaging Radiometer Suite (VIIRS) sensor onboard the SNPP satellite. *20th Conf. on Satellite Meteorology and Oceanography*, Phoenix, AZ, Amer. Meteor. Soc., 210, https://ams.confex.com/ams/95Annual/webprogram/Paper259494.html.

Wasko, C., and R. Nathan, 2019: Influence of changes in rainfall and soil moisture on trends in flooding. *J. Hydrol.*, **575**, 432–441, https://doi.org/10.1016/j.jhydrol.2019.05.054.

Wyatt, B. M., T. E. Ochsner, E. S. Krueger, and E. T. Jones, 2020: In-situ soil moisture data improve seasonal streamflow forecasts accuracy in rainfall-dominated watersheds. *J. Hydrol.*, **590**, 125404, https://doi.org/10.1016/j.jhydrol.2020.125404.

Yuan, X., L. Wang, P. Wu, P. Ji, J. Sheffield, and M. Zhang, 2019: Anthropogenic shift towards higher risk of flash drought over China. *Nat. Commun.*, **10**, 4661, https://doi.org/10.1038/s41467-019-12692-7.

Zhang, N., S. M. Quiring, and T. W. Ford, 2021: Blending SMAP, Noah and in situ soil moisture using multiple error estimation methods. *J. Hydrometeor.*, **22**, 1835–1854, https://doi.org/10.1175/JHM-D-20-0119.1.

Zhao, C., S. M. Quiring, S. Yuan, D. B. McRoberts, N. Zhang, and Z. Leasor, 2020: Developing and evaluating national soil moisture percentile maps. *Soil. Sci. Soc. Amer. J.*, **84**, 443–460, https://doi.org/10.1002/saj2.20045.