Rating Fire Danger from the Ground Up

Soil moisture information could improve assessments of wildfire probabilities and fuel conditions, resulting in better fire danger ratings.

Among other applications, soil moisture data can help determine optimal conditions for conducting controlled burns, like this one in a sagebrush ecosystem in Hart Mountain National Antelope Refuge in southeastern Oregon, as well as for postfire restoration efforts. Credit: Scott Shaff, U.S. Geological Survey

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Wildfires consumed more than 3.5 million hectares in the United States in 2018, and federal fire suppression costs topped US$3 billion (https://www.nifc.gov/fireInfo/fireInfo_statistics.html). These fires destroyed more than 18,000 residences (https://www.predictiveservices.nifc.gov/intelligence/2018_statssumm/2018Stats&Summ.html) and caused the deaths of at least 85 people. Wildfire damages like these are not unique to the United States; they are a threat in many nations. Researchers from across the globe and across multiple scientific disciplines are working to improve fire danger rating systems to help protect natural resources and human health and safety.

Soil moisture is a key link between weather conditions and the characteristics of the live vegetative "fuel bed," which strongly influence wildfire probability.

One new concept emerging as a valuable contribution to this effort is the integration of soil moisture information as a predictor of wildfire probability (http://www.publish.csiro.au/WF/WF15104). Soil moisture, particularly within the zone where plant roots reside, is a key link between weather conditions, such as precipitation and temperature, and the characteristics of the live vegetative "fuel bed," which include fuel moisture and fuel loads (weight of fuel per unit area). These dynamic vegetation characteristics, which strongly influence wildfire probability, can be challenging to model and monitor at relevant spatial and temporal scales using field data. Optical remote sensing of fuel moisture also presents challenges; for example, remote sensing models that predict live-fuel moisture contain relatively large margins of error (https://www.sciencedirect.com/science/article/abs/pii/S0034425713001831)that vary by vegetation type.

Soil moisture monitoring (https://dl.sciencesocieties.org/publications/sssaj/abstracts/77/6/1888) capabilities, in contrast, have been steadily growing because of the development of in situ networks and dedicated satellites. Researchers have intuitively understood the relationships between soil moisture, fuel conditions, and wildfire occurrence for a long time. However, the increasing availability of soil moisture information (https://eos.org/editors-vox/the-paramount-societal-impact-of-soil-moisture) is creating significant opportunities to quantify these relationships and incorporate them into new or existing weather-based fuel moisture models and fire danger rating systems.

Scientists and Practitioners in Dialogue

To explore these opportunities and envision next steps, 34 researchers and fire management practitioners participated in a 1-day workshop held in April in association with the 6th International Fire Behavior and Fuels Conference, hosted by the International Association of Wildland Fire (https://www.iawfonline.org/). The workshop's aims were to identify the needs and interests of the fire management community and to explore how soil moisture information could be used in wildfire modeling, risk assessment, planning, and decision support tools.

Invited speakers discussed the current trends and status of wildfire occurrence, impacts, and response; fire modeling and fire danger ratings; soil moisture monitoring and modeling; and linkages between soil moisture, fuel bed characteristics, and wildfires. Small group discussions identified practitioners' needs related to fire management decision-making at local, regional, and national scales.

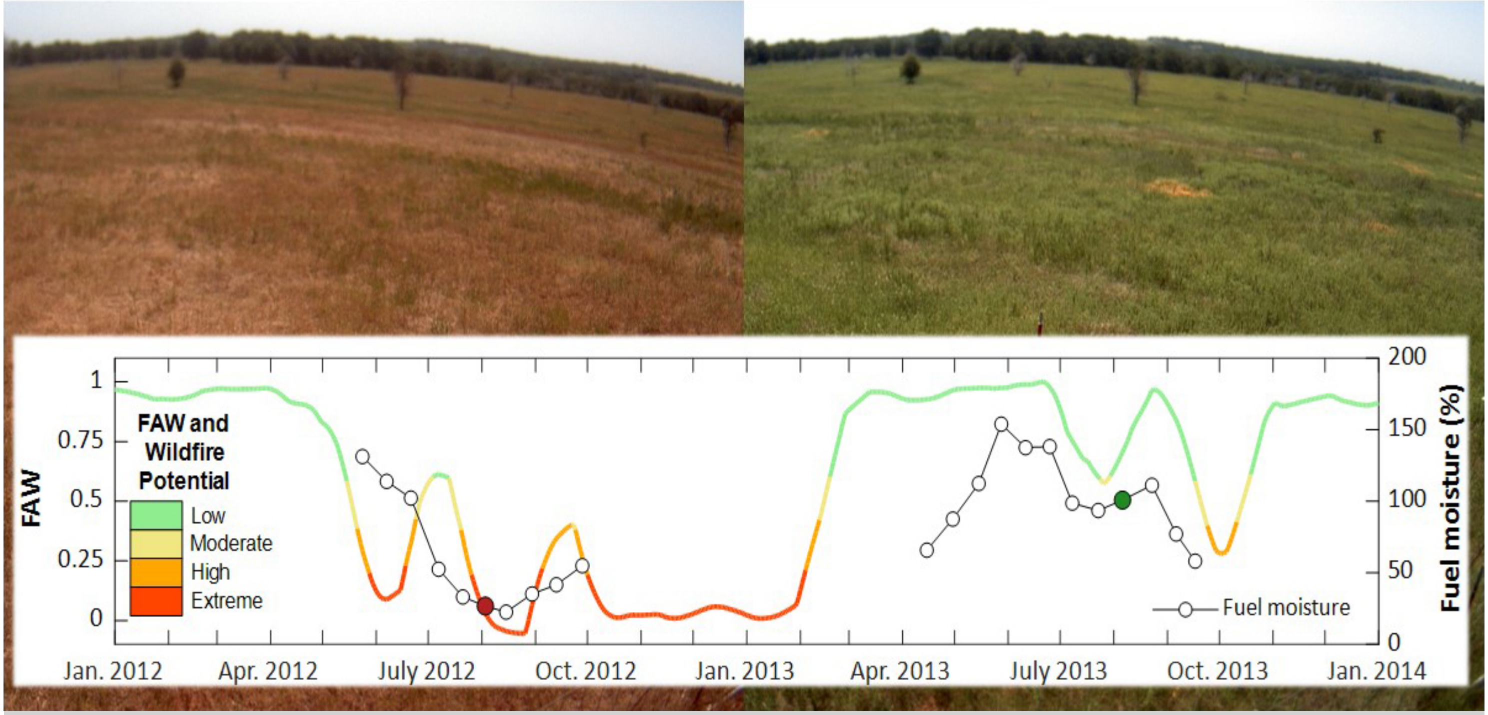
Raising Soil Moisture Awareness

Fire management decision-makers often are unaware of recent research indicating the utility of soil moisture information in fire danger prediction.

These discussions revealed that fire management decision-makers (approximately one third of the attendees) are not generally seeking soil moisture information. They often are unaware of recent research indicating the utility of such information in fire danger prediction. Instead, these decision-makers often consult decades-old drought indices (e.g., the Keetch-Byram drought index (https://www.drought.gov/drought/data-gallery/keetch-byram-drought-index)). These indices were designed to roughly mimic soil moisture dynamics, even though research has shown that direct soil moisture observations are more effective (https://dl.sciencesocieties.org/publications/sssaj/abstracts/81/3/490) in fire danger assessment.

Research has also shown, and stakeholders intuitively understand, that soil moisture represents the land's integrated "memory" of recent weather conditions and could therefore provide valuable early warnings of rising fire danger. To facilitate greater use of soil moisture information in fire management, workshop participants identified a need to increase the quantity and quality of available soil moisture information at relevant spatiotemporal scales (https://eos.org/editors-vox/seeing-soil-moisture-from-the-sky) and to determine how soil moisture can be integrated effectively into existing fire danger rating systems. Furthermore, stakeholders expressed a need to consider both statistical and mechanistic modeling approaches to develop a better understanding of the relationships between soil moisture and fuel moisture conditions.

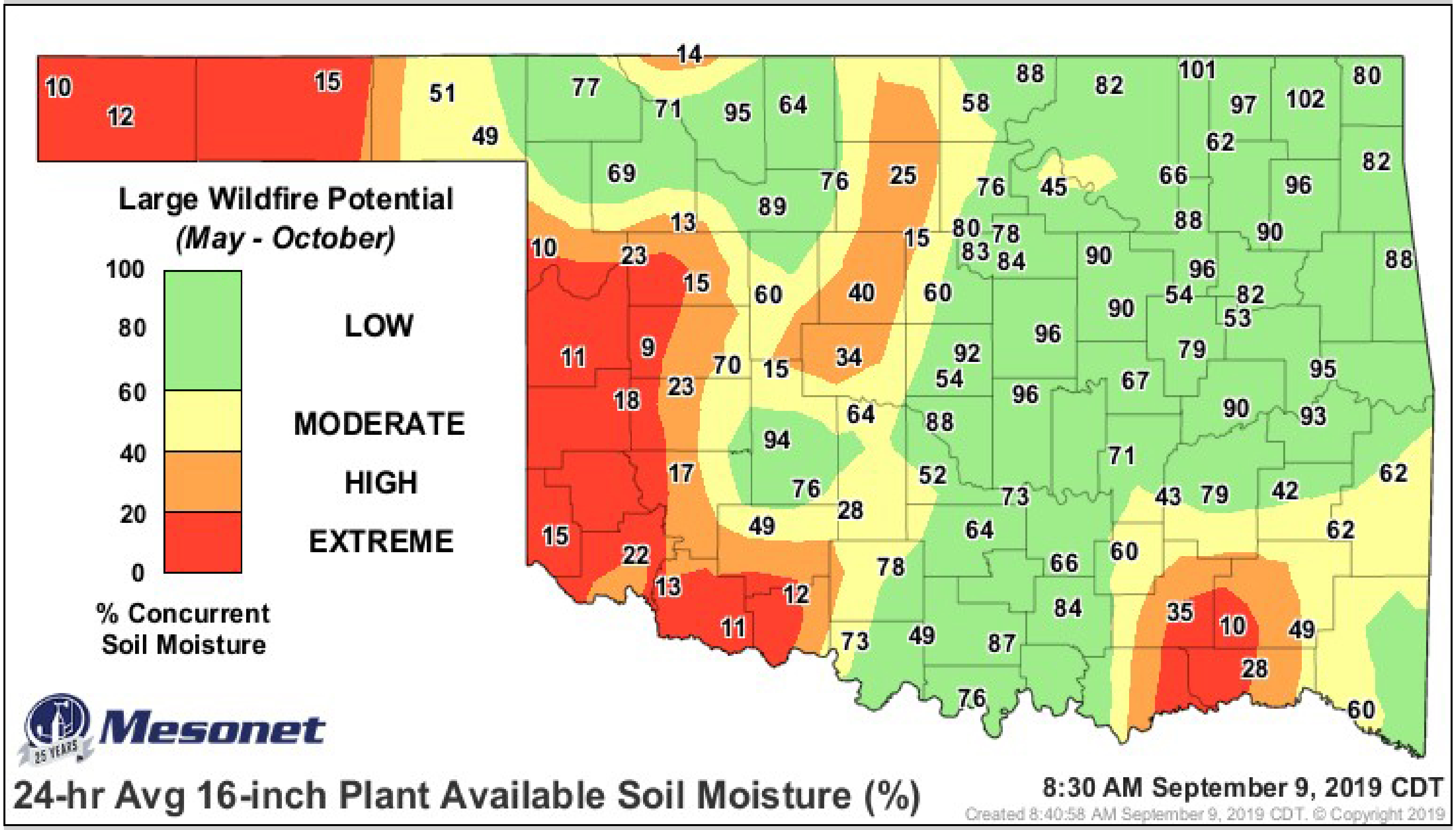
A Case Study in Oklahoma



(https://eos.org/wp-content/uploads/2019/12/phenocam-image-stillwater-oklahoma-2012-2013.jpg)

Fig. 1. PhenoCam images collected over rangeland on 2 August 2012 (https://phenocam.sr.unh.edu/data/archive/marena/2012/08/marena_2012_08_02_133001.jpg) (left) and 6 August 2013 (https://phenocam.sr.unh.edu/data/archive/marena/2013/08/marena_2013_08_06_133001.jpg) (right) near Stillwater, Okla., show the influence of rainfall on vegetation (and by extension, fire hazard). The graph shows the measured fraction of available water capacity (FAW) at the image location, with colors indicating relative wildfire danger and solid circles representing fuel moisture on days the images were collected. Conditions in the latter half of 2012 were ripe for wildfires; the devastating Freedom Hills fire ignited the day after the image was collected. The fire burned nearly 24,000 hectares, destroyed more than 300 homes, and resulted in Federal Emergency Management Agency assistance claims totaling more than $7 million. Credit: Erik Krueger; data from Oklahoma Mesonet (http://mesonet.org/); photos from the Marena Oklahoma PhenoCam site (https://phenocam.sr.unh.edu/webcam/sites/marena/), CC BY 3.0 US (https://creativecommons.org/licenses/by/3.0/us/legalcode)

Oklahoma is among the top 10 U.S. states in wildfire risk (https://www.iii.org/fact-statistic/facts-statistics-wildfires) and has one of the world's oldest soil moisture monitoring networks (http://www.mesonet.org/). It therefore provides a natural laboratory for exploring relationships between soil moisture and fuel moisture. PhenoCam images (a series of time-lapse digital images from a fixed location) from a tallgrass prairie site in north central Oklahoma (Figure 1) show the stark contrast in vegetation conditions occurring during 2012, a drought year (Figure 1, left), and 2013, a year of near-average precipitation (Figure 1, right). The year 2012 was characterized by low soil moisture, shown in the graph in Figure 1 as the fraction of available water capacity (FAW). This condition led to fuel having a low moisture content, which created conditions of extreme fire danger. Several large wildfires ignited near the PhenoCam site in the days after the image on the left was captured, one of which—the Freedom Hills Fire (https://oklahoman.com/article/5560790/freedom-hill-blaze-lingers-in-residents-lives-five-years-later)—burned 24,000 hectares and destroyed more than 300 homes.



(https://eos.org/wp-content/uploads/2019/12/oklahoma-wildfire-potential-map-soil-mosture.jpg)

Fig. 2. Map showing the estimated large wildfire potential across Oklahoma based on in situ soil moisture observations from the Oklahoma Mesonet on 4 September 2019. Numbers indicate the FAW, expressed as a percentage, for the soil layer from 0 to 16 inches (0–41 centimeters) depth. Extreme growing season wildfire potential occurs when FAW drops below 20%. Credit: Oklahoma Mesonet (http://www.mesonet.org/index.php/weather/category/soil_moisture)

To improve advance warning of these types of wildfires and predict safe conditions for prescribed burning, Oklahoma's fire danger information system, OK-FIRE (https://www.mesonet.org/index.php/okfire/home), now includes soil moisture data as a metric available to the state's fire management personnel (e.g., Figure 2).

Workshop participants noted that although this encouraging progress in Oklahoma illustrates the feasibility of using soil moisture information in fire danger ratings, key challenges remain. One of the foremost challenges is to overcome the limited number of existing in situ monitoring systems and improve the spatiotemporal resolution of satellite-based soil moisture monitoring systems.

Current Limitations and Promising Solutions

In situ measurements continue to be the "gold standard" for quantifying soil moisture for many applications, but monitoring stations are costly to install and maintain. As a result, many regions still lack in situ measurements, so estimates of soil moisture conditions must be interpolated (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018WR024535), simulated, or derived from remote sensing (https://iopscience.iop.org/article/10.1088/1748-9326/aa9853/meta) estimates for unsampled areas, many of which are fire-prone landscapes. Operational simulation systems such as NASA's North American Land Data Assimilation System (NLDAS (https://ldas.gsfc.nasa.gov/nldas)) provide soil moisture estimates for central North America, but the 4-day lag between when the data are recorded and when estimates are made available and the spatial resolution of the data (one eighth degree) are not optimal for fire danger monitoring.

Advances in satellite remote sensing for soil moisture, such as the Soil Moisture Active Passive (SMAP (https://smap.jpl.nasa.gov/)) mission, suggest a bright future for global soil moisture monitoring; however, there are some important limitations to using SMAP data for wildfire danger prediction. For example, the record of soil moisture is too short for use in statistical modeling of wildfire probability. Also, remote sensing observes only the surface soil, not the root zone, and the spatial resolution is too coarse for localized analysis.

Researchers are actively pursuing ways to overcome the deficiencies in current sources of soil moisture information.

Researchers are actively pursuing ways to overcome the deficiencies in these current sources of soil moisture information. The coordinated National Soil Moisture Network (https://eos.org/science-updates/building-a-one-stop-shop-for-soil-moisture-information), for example, is an ongoing initiative to combine data from a diverse collection of state and federal in situ networks in the United States to create a standardized national soil moisture data product. Likewise, organizers of this year's workshop are part of an interdisciplinary team working to develop a near-real-time, high-resolution soil moisture simulation model that is based on measured soil moisture and suitable for fire danger monitoring at regional or national scales.

In addition, a new data product called SoilMERGE (SMERGE (https://www.tamiu.edu/cees/smerge/overview.shtml)) provides retrospective root zone soil moisture estimates across the continental United States. This record stretches back to 1979, a period that is adequate for statistical modeling of wildfire probability and size. SMERGE is produced (https://ieeexplore.ieee.org/abstract/document/8804227) by merging root zone soil moisture simulations from Noah (https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2010JD015140) land surface model version 3.2 within

NLDAS phase 2 (https://ldas.gsfc.nasa.gov/nldas/v2/models) with remotely sensed surface soil moisture (https://www.esa-soilmoisture-cci.org/node/237) retrievals from the multisensor European Space Agency Climate Change Initiative. This merging of two different methods harnesses and combines their complementary strengths to create a unified set of root zone soil moisture (0- to 41-centimeter depth) estimates, available on a daily time step, across multiple decades (1979–2018), for the continental United States at a one-eighth-degree scale. In situ soil moisture measurements are then used to validate SMERGE (https://ieeexplore.ieee.org/abstract/document/8804227) estimates. SMERGE has not been applied to wildfire probability mapping yet, but such improvements in the availability of long-term soil moisture data are key steps forward for analyzing the relationships with wildfire.

The Many Applications of Soil Moisture Data

Momentum is building for enhanced spatial and temporal root zone soil moisture information and for inclusion of that information in regional and national fire danger ratings systems.

The workshop participants identified specific areas in need of further research efforts, some of which are currently under way. Field research is being conducted in diverse environments to better understand the relationships between soil moisture and fuel moisture conditions. Researchers are exploring both statistical and mechanistic modeling approaches to overcome data scarcity in measured soil moisture, with the goal of integrating these data into existing fire danger rating systems. As researchers and fire management professionals continue to learn about soil moisture–wildfire relationships, momentum is building for enhanced spatial and temporal root zone soil moisture information and for inclusion of that information in regional and national fire danger ratings systems.

In addition to improving wildfire danger forecasting, soil moisture data can potentially support other important aspects of wildfire management and decision-making. Applications for this data can include use in planning and implementing prescribed fires under optimal soil and fuel moisture conditions to ensure maximum success, as well as in predicting fire behavior during resource benefit (managed) wildfires. Soil moisture data could also be used to identify postfire windows for restoration seeding. Similarly, soil moisture could help predict the spread of invasive plants that readily exploit early-season soil moisture (e.g., cheatgrass, red brome, and buffelgrass in the western United States) and increase fire hazard at the wildland-urban interface by altering fire regimes (https://academic.oup.com/bioscience/article/54/7/677/223532).

Soil moisture information is vital for numerous other applications that intertwine social well-being and natural resource management. Often, scientific advancements emerge by solving problems that were not the original target of investigation. Improved soil moisture information could generate a wide range of societal benefits through such applications as drought monitoring (https://dl.sciencesocieties.org/publications/aj/abstracts/111/3/1392) for agricultural (https://journals.ametsoc.org/doi/10.1175/JHM-D-13-0125.1?mobileUi=0) applications, groundwater recharge estimation (https://dl.sciencesocieties.org/publications/vzj/abstracts/16/6/vzj2017.01.0016), ground saturation flooding, and seasonal streamflow forecasting. Root zone soil moisture products can also link with satellite remote sensing products to provide valuable interpretations of ecological phenomena related to fire (e.g., tree die-offs, beetle outbreaks).

More details of the soil moisture and wildfire workshop are available, (https://wildfire.swclimatehub.info/)including expanded takeaways, speaker presentations, and a video summarizing the workshop. A similar workshop will be organized in 2021 in Stillwater, Okla., to continue conversations about integrating soil moisture and wildfire information.

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