Monitoring soil parameters affecting the forest fuel dryness

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Research Article

Keywords: soil moisture, litter dryness, forest fires, soil temperature and moisture measurement device, SMAT-meter

Posted Date: March 9th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1375667/v1

Abstract

Background: Soil moisture affects the moisture content of forest fuels and therefore flammability. However, due to the lack of a previously long series of soil moisture data based on observations, previous studies have taken into account fuel and soil moisture by calculating special indices based on meteorological indicators. The growing availability of soil moisture data is now making their inclusion in forest fire risk assessments more feasible. Sources of soil moisture information generally fall into one of three broad categories: *in situ* measurements, satellite remote sensing, and models. There are no open data on soil moisture measurements, and the soil temperature data series ends in 2013 in Russia.

Results: In our work, we present a tool for monitoring soil parameters SMAT-meter. The device is designed for autonomous automatic measurement of soil moisture and temperature, and data transmission to the Recorder Control Center via cellular communication. Power is supplied by a solar panel. SMAT-meter measurements will provide *in situ* soil moisture and temperature data for forest fire hazard modeling.

Conclusions: SMART-meter allows you to organize monitoring of the hydrothermal regime of soils. Weather station data covers the need for atmospheric meteorological data. Copies of the SMAT-meter on various types of soils, organized in a network, in conjunction with weather stations, can provide comprehensive monitoring of the onset of forest fire danger.

Background

The weather has a direct and indirect effect on the behavior of a fire (Rapp et al. 2021). While fires can be ignited by humans or lightning, climate influences the possible fire spread and size (O, Hou, and Orth 2020). The weather has a dominant influence on fuel moisture (Johnson and Balice 2006). The moisture content present in the fuel is a key factor influencing the ignition potential and ignition behavior (Sharples et al. 2009; Nyman et al. 2015). The fuel moisture content (FMC) determines its combustibility and, along with wind speed, is the main factor determining the behavior (speed and intensity) of forest fires (Sullivan and Matthews 2013). Higher moisture content fuels require higher temperatures or longer periods of heat exposure to ignite because heat is required to vaporize and there is less energy left to initiate combustion. In addition, fire propagates slower in wet fuels than in dry fuels as the evaporated fuel moisture inhibits combustion by diluting the flammable gases in the reaction zone and cooling the flames (Jurdao, Chuvieco, and Arevalillo 2012). The most fire-prone situation coincides with very low FMC when large quantities of fuel across landscapes are dry enough to ignite and sustain burning (Cawson et al. 2020). Early detection of the dryness of forest fuels to identify potential hot spots is extremely useful for predicting the occurrence of forest fires (Ambadan et al. 2020).

Obtaining moisture measurements with traditional destructive sampling techniques can be prohibitively time-consuming and extremely limited in spatial resolution (Barber et al. 2021). FMC is usually given by

$$FMC = \left(\frac{W_w - W_d}{W_d}\right) \times 100$$

where W_w and W_d are the wet and dry weights of a sample unit. The dry weight is usually obtained after oven drying the sample at 60°C for either 24 h or 48 h (Pollet and Brown 2007; Hill, Bakker, and Dunwiddie 2017; Jurdao, Chuvieco, and Arevalillo 2012) or 105°C (C. Schunk et al. 2016; Rakhmatulina, Stephens, and Thompson 2021). These methods include manual sampling in the field, weighing, bringing the samples to the oven, drying (24 or 48 hours), and re-weighing the dried samples, which adds a time delay before fuel moisture measurements become available, rendering them useless for any immediate fire prevention or decision-making. To overcome these problems, so-called fuel moisture sticks with a dry mass of exactly 100 g from Pinus ponderosa pine are used, the moisture content of which is automatically measured, for example, using capacitive sensing (Christian Schunk, Leuchner, and Menzel 2014). These sticks are mounted horizontally at a height of 10–12 inches, or 30 cm, from the ground (Lee et al. 2020).

Such automated fuel moisture sensors are part of many remote automated weather stations (RAWS) designed to monitor potential wildfire conditions in the United States (Rakhmatulina, Stephens, and Thompson 2021). In general, this system is a satisfactory option when a direct measurement of the moisture content of a similar fuel is required, giving values that can be considered at least acceptable for this difficult parameter. Automated operation as well as the possibility of immediate data transfer and availability are the great advantages of this system. However, even the annual replacement of fuel moisture sticks is expensive when using original sticks. In addition, the accuracy, reliability, and long-term performance of these systems remain somewhat questionable (Christian Schunk, Leuchner, and Menzel 2014). Raised fuel sticks tend to underestimate FMC values compared to FMC measured at the surface (Cawson et al. 2020). These results indicate that RAWS fuel moisture sensors alone may not be sufficient to predict FMC and that there may be important ground surface processes that change FMC. One possible explanation for FMC errors is that soil moisture is not taken into account. Because surface fuels are often in direct contact with the soil, a heterogeneous soil moisture environment can lead to FMC variations (Rakhmatulina, Stephens, and Thompson 2021). Also (Rakhmatulina, Stephens, and Thompson 2021) note that FMC datasets are highly limited in time and place, and none of the US datasets have appropriate measurements with the suitable temporal and spatial resolution to accurately predict surface fuel FMC.

Soil moisture (SM) not only influences the growth conditions of vegetation and therefore the accumulation of fuel for forest fire, but also determines the moisture content of forest fuel and hence flammability. However, due to the lack of previously long series of SM data based on observations (O, Hou, and Orth 2020), previous studies took into account fuel and soil moisture by calculating special indices, for example, Keetch–Byram Drought Index (KBDI) (Keetch and Byram 1968) or Nesterov index (Nesterov 1961) based on meteorological indicators (temperature, humidity, precipitation, evapotranspiration, dew point, etc.). The growing availability of SM data is now making it more feasible to include them in wildfire risk assessments (Krueger et al. 2016). SM information sources generally fall into one of three broad categories: *in situ* measurements, satellite remote sensing estimates, and models (Holgate et al. 2016).

Works using ground-based *in situ* measurements usually investigate the effect of SM on FMC. Researchers usually study FMC in two separate components: live (LFMC) and dead (DFMC) vegetation. Dead vegetation, such as twigs, leaf litter, and weeds, reacts more quickly to atmospheric changes, while living fuel reacts more to SM, plant physiology, and long-term weather trends (Barber et al. 2021). The effect of soil moisture and temperature on fuel moisture was significant in-ground measurements (Masinda et al. 2021). The topsoil where the litter meets the soil is more affected by SM than the surface layer of the litter, which is more strongly bound to the atmosphere. The value of SM in the definition of DFMC litter is closely related to soil conditions. Relatively dry soil has a limited effect on litter FMC and only through soil vapor flow (Zhao et al. 2021). However, wet soil has a more significant effect on litter FMC through both vapor transport and capillary flow (Zhao et al. 2022). In general, litter moisture models linked to SM perform better in wet soil conditions than models not linked to SM (Rakhmatulina, Stephens, and Thompson 2021). The LFMC varies seasonally and is highly dependent on summer SM, which is influenced by temperature and precipitation (McCaw et al. 2018), as well as evapotranspiration and plant physiology (Qi et al. 2012). Fire prediction considering the relationship between the forest litter and surface SM conditions is discussed in (Vinodkumar and Dharssi 2019).

Works using remote sensing of the earth from space compare SM with fire indicators (Hiraga and Kavvas 2021; Ju Hyoung 2021; Schaefer and Magi 2019) since satellite extraction of SM data is not possible for areas with dense vegetation (for example, tropical or boreal forests) or at sub-zero soil temperatures (Schaefer and Magi 2019). It is noted that increased soil moisture in dry regions in the months before the fire season contributes to sufficient biomass growth necessary to start large fires. In humid regions, fires are usually preceded by dry soil moisture anomalies that create suitable ignition conditions (Jensen et al. 2018; Waring and Coops 2016). In both types of regions, in the months preceding the onset of fires, SM decreases anomalously. These signals are most pronounced in sparsely populated areas with low human impact and larger fires (O, Hou, and Orth 2020).

In Russia, the Nesterov index is used as an indicator of fire danger. This index is based on meteorological data such as temperature, dew point, and precipitation (Nesterov 1961; Vonskii and Zhdanko 1976). In 1979, the Nesterov index was improved by introducing the above-ground moisture index (PV-1) with differentiated corrections for precipitation and the forest litter moisture index (PV-2). These indicators are tabular data developed based on experimental studies of changes in the layer-by-layer moisture content of forest combustible materials depending on the meteorological factors that cause these changes (air temperature and dew point deficit, measured in the daytime) (Vonskii et al. 1979). It must be said that there are no open data on soil moisture for Russia, and the data series on soil temperature end in 2013. In our paper, we present a tool for measuring *in situ* soil temperature and moisture under the forest canopy and for verifying satellite data. The device is called “Soil Moisture and Temperature meter” or “SMAT-meter for short. The SMAT-meter is designed for long-term automatic monitoring of soil moisture and temperature profiles up to 50 cm deep and for verification of satellite data.

Methods

The device is a system for autonomous long-term monitoring of soil temperature and moisture profiles. The system is designed for automatic measurements of temperature and soil moisture at a depth of 50 cm. The autonomy of the device is provided by power from the solar battery and the presence of a cellular modem for data transmission to the user. The scheme is shown in Fig. 1; the main technical characteristics of the equipment are given in the Table 1.

1 - electronic unit with a solar battery and a cellular modem, 2 - sensors for soil volumetric moisture, 3 - temperature probe, 4 - ruler (for demonstration)

The protective case for the electronic unit is made of plastic pipes. Autonomy of work is provided by a power supply from the lithium accumulator charged from the solar battery. Data transfer is performed by a cellular modem. Therefore, a small ground part is needed as a holder for the solar panel and modem antenna. The main sensors are located directly in the ground. The temperature probe is made as a three-wire printed circuit board with high-precision digital thermometers DS18B20 soldered to it, protected by a heat shrink tube. Therefore, the location of the sensors provided during the manufacture of the probe cannot be changed. Moisture meters are connected to the electronic unit via flexible cables, so the levels of their placement in the ground can be selected during installation.

Table 1
Technical characteristics of the SMAT-meter

Characteristic	Range
Logger unit operating temperature range	−60…+55°C
Soil moisture measurement range	0…100%
Soil moisture calibration error	± 3% (0…40%), ± 5% (40…70%)
Soil moisture sensor operating temperature range	1…+50°C
Temperature sensor levels on the soil temperature profile probe	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, 35, 40, 45, 50 cm
Temperature measurement range	-55…+50°C
Temperature sensor calibration error	≤ ±0.1°C
Settable measurement period	from 1 to 720 minutes
The amount of non-volatile memory	4 MB (20000 measurements)
Data transmission interface	GSM

Soil moisture sensors measure the ratio of the volumetric content of water to the volume of a substance in terms of permittivity. The soil temperature profile probe must be placed at a distance of 1 m from other sensors according to (Shein et al. 2001). The logger queries the sensors via a digital interface and sends the data to the server via a GSM modem to the database, from where they can be exported in *.csv format. The equipment is controlled and fine-tuned via a GSM or USB interface.

The reliability of temperature probe measurements was estimated in (Kiselev et al. 2018), the correlation coefficient with reference measurements at a certified meteorological station of Roshydromet was 90% or more at all depths. To measure the volumetric soil moisture, MEC10-CBCBC005 sensors manufactured in China are used.

These sensors provide the required measurement accuracy and are much cheaper than the more accurate TRIME-PICO32 ("TRIME-PICO 32: Sensor with Integrated TDR Electronics" 2020; *Moisture Sensors for Agricultural Engineering, Hydrology and Irrigation* 2020), which have an error of ± 1…±2% at 0...40% moisture and ± 2…±3% at 40...70% moisture (*TRIME-PICO 64/32. Manual* 2015). The TRIME-PICO32 was used to validate the measurement accuracy of the MEC10-CBCBC005 sensors as a benchmark infield and bench comparison test. To check the measurement accuracy of soil moisture sensors, a reference mixture of water and glass (plastic) balls was used according to (*TRIME-PICO 64/32. Manual* 2015). Readings in air, water, and blends were also used.

In this paper, we propose equipment for long-term automatic monitoring of soil temperature and moisture profiles without air measurements. This approach involves the use of data from weather stations as a source of atmospheric meteorological parameters. The use of weather stations data significantly reduces the cost of construction. Thus, the need for expensive ground equipment is eliminated. Time series of weather data for air temperature and precipitation at meteorological stations of Roshydromet of Russia is available on the Internet portal of the Federal Service for Hydrometeorology and Environmental Monitoring ("Specialized Datasets," n.d.). Also, data from meteorological stations are available on weather portals ("Weather and Climate" 2021) and ("Weather Schedule" 2021). The data of Roshydromet stations include the following indications:

- Air temperature;

- Air humidity;

- Atmospheric pressure;

- Amount of precipitation;

- Snow depth;

- Dew point temperature;

- Speed and

- wind direction;

- etc.

The measurement results are posted with a time step of three hours. Thus, the set of weather station data, in our opinion, is quite sufficient.

SMART-meter allows you to fine-tune the measurement and data transmission step from two minutes to several hours. It is reasonable to adjust the operation of the instrument synchronously with the readings of weather stations. The data is transmitted to the server and displayed by the special software "Logger Control Center (LCC)" to the Institute for Monitoring Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences via cellular communication. If necessary, it is possible to replicate instruments and create a monitoring network for observations of soil moisture and temperature parameters.

Results

The device is installed at the Verkhnyaya Berezovka (Upper Birch) scientific station of the Institute of Physical Materials Science of the Siberian Branch of the Russian Academy of Sciences near the city of Ulan-Ude and has been measuring the temperature and humidity of the soil since July 11, 2021. The monitoring results are presented in Figs. 2 (C) and (D). For representativeness, average readings for 10 days are given. For comparison and analysis, Figs. 2 (a) and (b) show synchronously processed data from the Ulan-Ude weather station.

Data on air temperature (A) and precipitation (B) according to the Ulan-Ude weather station; display of the soil temperature and moisture regime at the Verkhnyaya Berezovka scientific station: (C) thermal isopleths, (D) soil moisture isopleths. For representativeness, average readings for 10 days are given.

The data obtained from the SMAT-meter for the soil temperature profile are presented in the form of thermoisopleths, for soil moisture - in the moisture isolines. The cooling of the soil is visible with a decrease in air temperature during the autumn period of 2021. An interesting break in the soil temperature graph is synchronous with a short-term increase in the average air temperature in the period from November 21 to December 10. The temperature at ground level coincides with the air temperature before the onset of frost. The slightly higher soil temperature compared to the atmospheric values after the zero barrier is due to the warming effect of the snow cover that first fell on November 4. Precipitation readings during this time interval characterize the amount of snowfall. Before frost, the moisture-holding capacity of the layer at the level of 5–30 cm in the suburban area of Verkhnyaya Berezovka is visible on the soil moisture graph. With the onset of negative temperatures, the soil moisture readings level off and decrease along with the entire measured profile.

The results shown in the graphs show the correspondence of the readings of the SMAT-meter to the ongoing natural processes. Thus, the representativeness of the measurements of this equipment is shown. Significant positive characteristics include its low cost. Inexpensive sensors are much easier and cheaper to replace. Thus, the duration of the gaps due to failed individual sensors in the time series of measurements is reduced. In addition, low cost allows you to install a larger number of devices to control soil meteorological parameters. (Wilson et al. 2014).

Discussion

Initially, we created equipment with a ground part. The atmospheric-soil measuring complex (ASMC) is an automatic weather station with an additional set of soil sensors (A. V. Bazarov et al. 2016; 2018). ASMC stations can only be installed at year-round protected stations because they need protection from animals and non-law-abiding people. ASMC were equipped with a temperature profile probe up to 3.2 m according to (Ivanova 1990) and only one TRIME-PICO moisture sensor. The cost of the TRIME-PICO32 is very high for us and has prevented us from purchasing multiple sensors to measure the soil moisture profile. Annual air temperature fluctuations in our region of Eastern Siberia can be 80°C from − 40°C to + 40°C, and daily averages are 10°C, often reaching up to 20°C. The temperature of the soil surface can exceed 80°C in open areas due to solar insolation, in winter it drops to − 20°C. The soil temperature in winter is higher than the air temperature due to the influence of the snow cover. TRIME-PICO32 moisture probes withstood in our climatic conditions from one to 3 years, after which we thought about developing cheaper analogs. The temperature profile probes lasted up to five years, but it is very difficult to retrieve them from 3.2 m. Even harder to set them back to this depth. Therefore, we decided to limit the maximum installation depth of the sensors to 50 cm.

The temperature probes in the SMAT-meter are the same as those on the ASMC, only shorter. The results of soil temperature measurements were used to study the processes of thawing-freezing of soils on the southern border of permafrost (N. Badmaev and Bazarov 2019). Also, ASMC measurements have been used in some work related to forest fires (N. V. Baranovskiy and Bazarov 2021; Nimazhap Badmaev and Bazarov 2021; N. Baranovskiy et al. 2018). In these works, we have already used ASMC devices without a ground part, completely abandoning it. We left the ability to control and read data only via USB. Cases with electronics were completely buried in the place of measurements. Subsequently, it was difficult to find them even with the use of a GPS navigator, since in the forest it shows the location with a greater error. In addition, sealed cases with electronics over several years still gained moisture. They sucked in moisture from the environment during the expansion and contraction of the cases due to temperature changes, but underground they did not have the opportunity for its evaporation. Therefore, we abandoned this option. The ground part of the SMAT-meter is very small and can be hidden in the bush (Fig. 3).

SMAT-meter at the installation site (A) and next to the person (B) to represent the size of the device. We did not try to disguise the SMAT-meter, as this is a protected area. However, it is still poorly visible.

Under the snow cover, the voltage on the battery drops a little but is not critical. After the snow melts, the solar panel should fully charge the battery. In case of loss of the SMAT-meter in unprotected areas in the field, a GPS sensor can be installed inside the device. The GPS sensor will transmit its location data every communication session. The location information will also be used to locate the device for repair if necessary.

The zero level sensor of the temperature profile probe is installed at the horizon level and covered with sod from above. The SM zero level sensor is inserted into the soil as high as possible just below the litter layer. Soil probes that are in full contact with the soil tend to make poor contact with the litter because the litter is looser (Wilson et al. 2014). Automatic measurement of the moisture content of fuels is difficult due to several fuel properties: finely dispersed fuels such as litter layers are often very inhomogeneous and discontinuous, typically shallow in-depth, and low in density and compactness. In addition, changes throughout the year in litter density and structure require relatively frequent recalibration (at least every 2 or 3 months) of the sensors (C. Schunk et al. 2016).

The article (Shvetsov, Ruzicka, and Mironov 2013) shows that satellite data moisture estimates give a significant error for forested areas. Also, the disadvantage of using remote sensing data is the low spatial resolution (radiometers suitable for calculating soil moisture have a spatial resolution of about 40 km/pixel) and the fact that it is impossible to directly measure soil moisture - it is determined within the framework of some physical model as a calculated value ("Study of Soil Moisture Content Using Satellite Data," n.d.). Spot continuous measurement of drought status *in situ* can provide better predictive power for LFMS estimation. Remote sensing measures provide greater spatial coverage. Thus, the joint use of point and satellite measurements of SM can improve the relationship with more accuracy for the operational management of indirect indicators of remote sensing for estimating LFMS (Qi et al. 2012).

In situ, soil moisture measurements can improve wildfire risk assessments, which often rely on KBDI as a proxy for soil moisture (McCaw et al. 2018; Krueger et al. 2017) described the relationship between measured soil moisture as a fraction of available water capacity (FAW) and the occurrence of large wildfires. Comparison of this relationship with the relationship between KBDI and wildfire probability showed better use of FAW than KBDI. (Krueger et al. 2017) recommended replacing KBDI with FAW when assessing growing season wildfire risk in temperate regions. (Krueger et al. 2016) used data from Oklahoma's Mesonet weather monitoring network in their research (McPherson et al. 2007). Oklahoma Mesonet stations measure soil temperature and moisture *in situ* with soil sensors. Soil moisture measurements cover 184,900 km^2, making Oklahoma's Mesonet one of the largest soil moisture networks in the world (Ochsner et al. 2013). Large-scale observations of soil moisture are organized in Australia. The measurement results of OzNet, OzFlux, and CosmOz networks are widely used in the JASMIN monitoring system to predict forest fire danger (Vinodkumar and Dharssi 2019).

Replication of the SMAT-meter and installation of its copies in the field involves the deployment of a network of soil measurements based on it. In addition to hidden installations camouflaged in the forest or the bush, it can be used as part of measuring platforms. The SMAT-meter will naturally complement automatic fire hazard forecast monitoring systems in conjunction with weather stations, fuel moisture sticks (Rakhmatulina, Stephens, and Thompson 2021), satellite monitoring of soil moisture, LFMC (Qi et al. 2012), vapor pressure deficit (VPD) (Rigden et al. 2020), and other data sources.

Conclusions

Automatic soil moisture monitoring is easier to organize than forest litter moisture monitoring. The medium to be probed must fit snugly around the rods of the moisture meters to ensure close contact. It is important to avoid air pockets around the rods as the highest measurement sensitivity is directly around them. Air pockets around the probe rods can reduce the measured moisture value. In highly moistured litter, water-filled air pockets will result in high readings. Forest litter always contains such air pockets. Sealing the litter to remove air will destroy the litter structure and result in measurement errors. The introduction of the probe rods of the SMAT-meter into the soil does not cause disturbance of the soil structure. The proposed SMAT-meter tool allows you to organize long-term automatic monitoring of soil moisture and temperature profiles up to 50 cm deep. The low cost of the SMAT-meter facilitates the replication of devices and the creation of an automatic monitoring network for continuous remote measurements. Weather station data cover the need for atmospheric meteorological data. Copies of the SMAT-meter on various types of soils, organized in a network, in conjunction with weather stations, can provide comprehensive monitoring of the onset of forest fire danger.

Abbreviations

DFMC
Dead Fuel Moisture Content
FMC
Fuel Moisture Content
LFMC
Live Fuel Moisture Content
RAWS
Remote Automated Weather Stations
SMAT-meter
Soil Moisture And Temperature meter
FAW
Fraction of Available Water

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The weather datasets used or analyzed during the current study are available at http://www.pogodaiklimat.ru/ and https://rp5.ru/. The soil datasets used and analyzed during the current study are available from the author on reasonable request.

Competing interests

The authors declare that they have no competing interests".

Funding:

The reported study was funded by RFBR, Sirius University of Science and Technology, JSC Russian Railways and Educational Fund “Talent and success”, project number 20-31-51001.

Authors' contributions

AVB wrote Background, part of the Methods section, Results, and Discussions. SAK made the equipment, provided soil data, and wrote part of the Methods section. ASB processed the weather and soil data, made plots, and performed preliminary analysis. YBB provided general supervision and provided a science station for equipment installation. All authors read and approved the final manuscript.

Acknowledgements

We would like to thank N. V. Baranovskiy for valuable comments on forest fires. We also thank B. V. Basanov for his help in installing the SMAT-meter and for providing photos.

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References

1. Ambadan, Jaison, Matilda Thomas, Ze’ev Oja, Gedalof, and Aaron A. Berg. 2020. Satellite-Observed Soil Moisture As an Indicator of Wildfire Risk. *Remote Sensing* 12 (10): 8–12. https://doi.org/10.3390/rs12101543.

2. Badmaev, N., and A. Bazarov. 2019. “Monitoring Network for Atmospheric and Soil Parameters Measurements in Permafrost Area of Buryatia, Russian Federation.” Geosciences 9 (1). https://doi.org/10.3390/geosciences9010006.
3. Badmaev, Nimazhap, and Aleksandr Bazarov. 2021. “Correlation Analysis of Terrestrial and Satellite Meteodata in the Territory of the Republic of Buryatia (Eastern Siberia, Russian Federation) with Forest Fire Statistics.” *Agricultural and Forest Meteorology* 297 (February 2020): 108245. https://doi.org/10.1016/j.agrformet.2020.108245.
4. Baranovskiy, N., A. Razva, V. Maksimov, and A. Bazarov. 2018. “Experimental Equipment to Simulate Fire Impact on Surface Soil Layer in Forests.” In *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*. Vol. 18. https://doi.org/10.5593/sgem2018/3.2/S13.025.
5. Baranovskiy, Nikolay Viktorovich, and Aleksandr Vladimirovich Bazarov. 2021. Assessment, Monitoring and Prediction of Forest Fire Danger Using Atmospheric Soil Measuring Complex. *International Journal on Engineering Applications* 9 (2): 71–85. https://doi.org/10.15866/irea.v9i2.20270.
6. Barber, Nastassia, Ernesto Alvarado, Van R. Kane, William E. Mell, and L. Monika Moskal. 2021. Estimating Fuel Moisture in Grasslands Using UAV-Mounted Infrared and Visible Light Sensors. *Sensors (Basel, Switzerland)* 21 (19): 6350. https://doi.org/10.3390/s21196350.
7. Bazarov, A. V., N. B. Badmaev, S. A. Kurakov, and B.-M. N. Gonchikov. 2018. Mobile Measurement System for the Coupled Monitoring of Atmospheric and Soil Parameters. *Russian Meteorology and Hydrology* 43 (4): 271–275. https://doi.org/10.3103/S106837391804009X.
8. Bazarov, A. V., N. B. Badmaev, S. A. Kurakov, B.-M.N. Gonchikov, Yu.B. Tsybenov, and A. I. Kulikov. 2016. The Measuring System for Automatic Long-Term Monitoring of Atmospheric and Soil Climatic Parameters. *Instruments and Experimental Techniques* no. 4: 158–159.
9. Cawson, Jane G., Petter Nyman, Christian Schunk, Gary J. Sheridan, Thomas J. Duff, Kelsy Gibos, William D. Bovill, Marco Conedera, and Gianni B. Pezzatti, and Annette Menzel. 2020. Estimation of Surface Dead Fine Fuel Moisture Using Automated Fuel Moisture Sticks across a Range of Forests Worldwide. *International Journal of Wildland Fire* 29 (6): 548–559. https://doi.org/10.1071/WF19061.
10. Hill, Kathryn C., D. Jonathan, Bakker, and W. Dunwiddie Peter. 2017. Prescribed Fire in Grassland Butterfly Habitat: Targeting Weather and Fuel Conditions to Reduce Soil Temperatures and Burn Severity. *Fire Ecology* 13 (3): 24–41. https://doi.org/10.4996/fireecology.130302441.
11. Hiraga, Yusuke, and M. Levent Kavvas. 2021. “Hydrological and Meteorological Controls on Large Wildfire Ignition and Burned Area in Northern California during 2017–2020.” Fire 4 (4). https://doi.org/10.3390/fire4040090.
12. Holgate, C. M., R. A. M. De Jeu, .M. A. I.J, Y. Y. van Dijk, L. J. Liu, I. Renzullo, Vinodkumar, and Dharssi, et al. 2016. Comparison of Remotely Sensed and Modelled Soil Moisture Data Sets across Australia. *Remote Sensing of Environment* 186: 479–500. https://doi.org/10.1016/j.rse.2016.09.015.

13. Ivanova, A. B., ed. 1990. *Instructions for Hydrometeorological Stations and Posts. Release 8*. Leningrad: Hydrometeoizdat. Third edit.
14. Jensen, Daniel, John T. Reager, Brittany Zajic, Nick Rousseau, and Matthew Rodell, and Everett Hinkley. 2018. “The Sensitivity of US Wildfire Occurrence to Pre-Season Soil Moisture Conditions across Ecosystems.” Environmental Research Letters 13 (1). https://doi.org/10.1088/1748-9326/aa9853.
15. Johnson, Scot D., and Randy G. Balice. 2006. Seasons within the Wildfire Season: Marking Weather-Related Fire Occurrence Regimes. *Fire Ecology* 2 (2): 60–78. https://doi.org/10.4996/fireecology.0202060.
16. Ju Hyoung, Lee. 2021. Prediction of Large-Scale Wildfires with the Canopy Stress Index Derived from Soil Moisture Active Passive. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 14: 2096–2102. https://doi.org/10.1109/JSTARS.2020.3048067.
17. Jurdao, Sara, and Emilio Chuvieco, and Jorge M. Arevalillo. 2012. Modelling Fire Ignition Probability Fromsatellite Estimates of Live Fuel Moisture Content. *Fire Ecology* 8 (1): 77–97. https://doi.org/10.4996/fireecology.0801077.
18. Keetch, John James, and George Marsden Byram. 1968. *A Drought Index for Forest Fire Control*. vol. 38. Asheville: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.
19. Kiselev, M. V., N. N. Voropay, E. A. Dyukarev, S. A. Kurakov, P. S. Kurakova, and E. A. Makeev. 2018. “Automatic Meteorological Measuring Systems for Microclimate Monitoring.” *IOP Conference Series: Earth and Environmental Science* 190 (1). https://doi.org/10.1088/1755-1315/190/1/012031.
20. Krueger, Erik S., E. Tyson, J. D. Ochsner, David M. Carlson, Dirac Engle, Twidwell, and Samuel D. Fuhlendorf. 2016. Concurrent and Antecedent Soil Moisture Relate Positively or Negatively to Probability of Large Wildfires Depending on Season. *International Journal of Wildland Fire* 25 (6): 657–668. https://doi.org/10.1071/WF15104.
21. Krueger, Erik S., E. Tyson, Steven M. Ochsner, David M. Quiring, J. D. Engle, Dirac Twidwell Carlson, and Samuel D. Fuhlendorf. 2017. Measured Soil Moisture Is a Better Predictor of Large Growing-Season Wildfires than the Keetch-Byram Drought Index. *Soil Science Society of America Journal* 81 (3): 490–502. https://doi.org/10.2136/sssaj2017.01.0003.
22. Lee, Hoon, Myoungsoo Taek, Sukhee Won, Yoon, and Keunchang Jang. 2020. “Estimation of 10-Hour Fuel Moisture Content Using Meteorological Data: A Model Inter-Comparison Study.” Forests 11 (9): 1–19. https://doi.org/10.3390/f11090982.
23. Masinda, Maombi, Fei Mbusa, Qi Li, Long Liu, and Sun, and Tongxin Hu. 2021. Prediction Model of Moisture Content of Dead Fine Fuel in Forest Plantations on Maoer Mountain, Northeast China. *Journal of Forestry Research* 32 (5): 2023–2035. https://doi.org/10.1007/s11676-020-01280-x.
24. McCaw, W., Devin M. Matt, S. Bruce Grobert, Sam Brown, Guy A. Strickland, Glen Thompson, Lucien M. Gillman, Ball, and Christopher D. Robinson. 2018. Seasonal Patterns and Drivers of Ashe Juniper

Foliar Live Fuel Moisture and Relevance to Fire Planning. *Fire Ecology* 14 (1): 50–64. https://doi.org/10.4996/fireecology.140150064.

25. McPherson, Renee A., Christopher A. Fiebrich, Kenneth C. Crawford, Ronald L. Elliott, James R. Kilby, David L. Grimsley, and Janet E. Martinez, et al. 2007. Statewide Monitoring of the Mesoscale Environment: A Technical Update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology* 24 (3): 301–321. https://doi.org/10.1175/JTECH1976.1.
26. *Moisture Sensors for Agricultural Engineering, Hydrology and Irrigation*. 2020. IMKO Micromodultechnik GmbH.
27. Nesterov, V. G. 1961. *Issues of Modern Forestry*. Moscow: Sel'khozgiz.
28. Nyman, Petter, Daniel Metzen, Philip J. Noske, N. J. Patrick, and Lane, and Gary J. Sheridan. 2015. Quantifying the Effects of Topographic Aspect on Water Content and Temperature in Fine Surface Fuel. *International Journal of Wildland Fire* 24 (8): 1129–1142. https://doi.org/10.1071/WF14195.
29. Sungmin, O., and Xinyuan Hou, and Rene Orth. 2020. Observational Evidence of Wildfire-Promoting Soil Moisture Anomalies. *Scientific Reports* 10 (1): 1–8. https://doi.org/10.1038/s41598-020-67530-4.
30. Ochsner, Tyson E., Michael H. Cosh, Richard H. Cuenca, A. Wouter, Clara S. Dorigo, Yutaka Draper, H. Hagimoto, Yann, and Kerr, et al. 2013. State of the Art in Large-Scale Soil Moisture Monitoring. *Soil Science Society of America Journal* 77 (6): 1888–1919. https://doi.org/10.2136/sssaj2013.03.0093.
31. Pollet, Jolie, and Annie Brown. 2007. *Fuel Moisture Sampling Guide*. Salt Lake City: Bureau of Land Management.
32. Qi, Yi, Philip E. Dennison, Jessica Spencer, and David Riaño. 2012. Monitoring Live Fuel Moisture Using Soil Moisture and Remote Sensing Proxies. *Fire Ecology* 8 (3): 71–87. https://doi.org/10.4996/fireecology.0803071.
33. Rakhmatulina, Ekaterina, and Scott Stephens, and Sally Thompson. 2021. “Soil Moisture Influences on Sierra Nevada Dead Fuel Moisture Content and Fire Risks.” Forest Ecology and Management 496 (March). https://doi.org/10.1016/j.foreco.2021.119379.
34. Rapp, Claire E., S. Robyn, Eric L. Wilson, Toman, and W. Matt Jolly. 2021. “Assessing the Role of Short-Term Weather Forecasts in Fire Manager Tactical Decision-Making: A Choice Experiment.” Fire Ecology 17 (1). https://doi.org/10.1186/s42408-021-00119-y.
35. Rigden, Angela J., S. Robert, Aleyda Powell, Kaighin A. Trevino, and McColl, and Peter Huybers. 2020. “Microwave Retrievals of Soil Moisture Improve Grassland Wildfire Predictions.” Geophysical Research Letters 47 (23). https://doi.org/10.1029/2020GL091410.
36. Schaefer, Alexander J., and I. Magi. Brian. 2019. Land-Cover Dependent Relationships between Fire and Soil Moisture. *Fire* 2 (4): 1–15. https://doi.org/10.3390/fire2040055.
37. Schunk, C., B. Ruth, M. Leuchner, C. Wastl, and A. Menzel. 2016. Comparison of Different Methods for the in Situ Measurement of Forest Litter Moisture Content. *Natural Hazards and Earth System Sciences* 16 (2): 403–415. https://doi.org/10.5194/nhess-16-403-2016.

38. Schunk, Christian, and Michael Leuchner, and Annette Menzel. 2014. “Evaluation of a System for Automatic Dead Fine Fuel Moisture Measurements.” In *Advances in Forest Fire Research*, 1115–23. Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-0884-6_121.
39. Sharples, J. J., R. H. D. McRae, R. O. Weber, and A. M. Gill. 2009. A Simple Index for Assessing Fuel Moisture Content. *Environmental Modelling and Software* 24 (5): 637–646. https://doi.org/10.1016/j.envsoft.2008.10.012.
40. Shein, E. V., T. A. Arkhangelskaya, V. M. Goncharov, A. K. Guber, T. N. Pochatkova, M. A. Sidorova, A. V. Smagin, and A. B. Umarova. 2001. *Field and Laboratory Methods for Studying Physical Properties and Regimes of Soils. Methodological Manual*. Edited by E. V. Shein. Moscow: MSU Publishing House.
41. Shvetsov, E. G., Z. Ruzicka, and V. L. Mironov. 2013. Investigation of Possibilities of Using SMOS Data for Fire Danger Assessment at the Territory of Krasnoyarsk Region. *Bulletin of the Siberian State Aerospace University* 48 (2): 110–115.
42. “Specialized Datasets.” n.d. All-Russia Research Institute of Hydrometeorological Information - World Data Centre (RIHMI-WDC).
43. “Study of Soil Moisture Content Using Satellite Data.” n.d. Institute of Computational Modeling SB RAS.
44. Sullivan, A. L., and S. Matthews. 2013. Determining Landscape Fine Fuel Moisture Content of the Kilmore East ‘Black Saturday’ Wildfire Using Spatially-Extended Point-Based Models. *Environmental Modelling and Software* 40: 98–108. https://doi.org/10.1016/j.envsoft.2012.08.008.
45. “TRIME-PICO 32. 2020. *Sensor with Integrated TDR Electronics.” 2020*. IMKO Micromodultechnik GmbH.
46. *TRIME-PICO 64/32. Manual*. 2015. Ettlingen: IMKO Micromodultechnik GmbH.
47. Vinodkumar, and Imtiaz Dharssi. 2019. “Evaluation and Calibration of a High-Resolution Soil Moisture Product for Wildfire Prediction and Management.” *Agricultural and Forest Meteorology* 264 (September 2018): 27–39. https://doi.org/10.1016/j.agrformet.2018.09.012.
48. Vonskii, S. M., and V. A. Zhdanko. 1976. *Principles for the Development of Meteorological Indicators of Fire Hazard in the Forest. Guidelines*. Leningrad: LenNIILKh.
49. Vonskii, S. M., V. A. Zhdanko, V. I. Korbut, M. M. Semenov, L. V. Tetyusheva, and L. S. Zavgorodnyaya. 1979. *Determination of Natural Fire Hazard in the Forest (Guidelines)*. Leningrad: USSR State Committee on Forestry.
50. Waring, Richard H., and Nicholas C. Coops. 2016. Predicting Large Wildfires across Western North America by Modeling Seasonal Variation in Soil Water Balance. *Climatic Change* 135 (2): 325–339. https://doi.org/10.1007/s10584-015-1569-x.
51. “Weather and Climate.” 2021. 2021.
52. “Weather Schedule.”. 2021. 2021.

53. Wilson, T. B., J. Kochendorfer, T. P. Meyers, M. Heuer, K. Sloop, and J. Miller. 2014. Leaf Litter Water Content and Soil Surface CO2 Fluxes in a Deciduous Forest. *Agricultural and Forest Meteorology* 192–193: 42–50. https://doi.org/10.1016/j.agrformet.2014.02.005.
54. Zhao, Li, Marta, I. J. M. Yebra, Albert, Geoffrey J. van Dijk, and Cary, and Dale Hughes. 2022. “Controlled Field Experiment Clarifies the Influence of Soil Moisture on Litter Moisture Content.” *Agricultural and Forest Meteorology* 314 (December 2021): 108782. https://doi.org/10.1016/j.agrformet.2021.108782.
55. Zhao, Li, Marta, I. J. M. Yebra, Albert, Geoffrey J. van Dijk, Stuart Cary, and Matthews, and Gary Sheridan. 2021. “The Influence of Soil Moisture on Surface and Sub-Surface Litter Fuel Moisture Simulation at Five Australian Sites.” *Agricultural and Forest Meteorology* 298–299 (August 2020): 108282. https://doi.org/10.1016/j.agrformet.2020.108282.

Figures

Figure 1

Scheme of the SMAT-meter

Figure 2

Data on air temperature (A) and precipitation (B) according to the Ulan-Ude weather station; display of the soil temperature and moisture regime at the Verkhnyaya Berezovka scientific station: (C) thermal isopleths, (D) soil moisture isopleths. For representativeness, average readings for 10 days are given.

Figure 3

SMAT-meter at the installation site (A) and next to the person (B) to represent the size of the device. We did not try to disguise the SMAT-meter, as this is a protected area. However, it is still poorly visible.