Drought monitoring: a system for tracking plant available soil moisture based on the Oklahoma Mesonet

Authors' Names and Affiliations:
Tyson Ochsner
Asst. Professor, Soil Physics
Plant and Soil Sciences
Oklahoma State University
368 Agricultural Hall
Stillwater, OK 74078
tyson.ochsner@okstate.edu
405-744-3627

Jeff Basara
Director of Research
Oklahoma Climatological Survey
120 David L. Boren Blvd., Suite 2900
Norman, OK 73072
jbasara@ou.edu
405-325-2541

Albert Sutherland
OSU Mesonet Agricultural Coordinator
Biosystems and Agricultural Engineering
Oklahoma State University
120 David L. Boren Blvd., Suite 2900
Norman, OK 73072
albert.sutherland@okstate.edu
405-325-3463

Chris Fiebrich
Associate Director for Mesonet
Oklahoma Climatological Survey
120 David L. Boren Blvd., Suite 2900
Norman, OK 73072
chris@mesonet.org
405-325-6877

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Principal Investigators:

Tyson Ochsner
Asst. Professor, Soil Physics
Plant and Soil Sciences
Oklahoma State University

Jeff Basara
Director of Research
Oklahoma Climatological Survey

Albert Sutherland
OSU Mesonet Agricultural Coordinator
Biosystems and Agricultural Engineering
Oklahoma State University

Chris Fiebrich
Associate Director for Mesonet
Oklahoma Climatological Survey

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Problem and Research Objectives:

Real-time drought monitoring is essential for early detection and adaptive management to mitigate the negative impacts of drought on the people, economy, and ecosystems of Oklahoma, and improved drought monitoring is a key need identified in the 1995 Update of the Oklahoma Comprehensive Water Plan. Drought impacts can be severe in Oklahoma. For example, the 2006 drought cost the state's economy over $500 million from lost crop production alone. While drought monitoring is critical to Oklahoma's resource managers, it is hampered by a lack of data on a crucial drought indicator: plant available water. Crop yield losses and, by extension, the economic impacts of drought, are strongly linked to plant available water (i.e. the amount of soil moisture which is available for plant uptake). Real-time monitoring of plant available water requires two components: (1) sensors which monitor soil moisture and (2) knowledge of the site-specific soil properties controlling the plant availability of soil moisture. In Oklahoma, the first of these requirements is already met via the Oklahoma Mesonet (Brock et al., 1996; McPherson et al., 2007), an automated network of 120 stations that collect real-time observations of soil and atmospheric variables across the state. However, the component needed to monitor plant available water and dramatically improve drought monitoring across Oklahoma is increased knowledge of the soil properties at the Mesonet sites.

The *long term goal* of the team of collaborators representing Oklahoma State University, the Oklahoma Mesonet, the Oklahoma Climatological Survey, and the University of Oklahoma is to develop and implement a system for accurately monitoring soil moisture and plant available water at each Mesonet station and to predict those values in near real-time for all other locations across Oklahoma. The *objective of this project* is to complete a critical first stage of the research and improve drought monitoring in Oklahoma through the development of a Mesonet-based system for tracking plant available water. The project has the following specific aims:

Specific aim #1: Determine the soil properties controlling the plant availability of soil moisture at each Mesonet site.

Specific aim #2: Develop a routine to calculate plant available water by integrating the sensor output and the site-specific soil properties.

Methodology:

Specific aim #1: Determine the soil properties controlling the plant availability of soil moisture at each Mesonet site. Plant available water is the difference between the current amount of soil moisture and the amount of soil moisture retained at a matric potential of -1500 kPa. This matric potential approximates the threshold at which plants wilt irreversibly, and the soil moisture at this matric potential is called the permanent wilting point. This threshold soil moisture value varies between locations and with depth at a given location. Therefore, we will collect soil samples at every operational Mesonet site for laboratory measurements of soil moisture retained at -1500 kPa.

The soil samples will be taken on the west side of each Mesonet station within 2-3 m of the soil moisture sensors. Soil samples will be collected using a hydraulic sampler (Giddings Machine Co., Windsor, CO) with a 3.5 inch outer diameter steel sampling tube (no liner). The diameter of the resulting soil core will be 7.47 cm. This relatively large diameter helps to minimize the potential for compaction during sampling. The soil core will be extruded onto a cutting tray, and the core length will be measured. The depth of the hole resulting from removal of the core will also be measured. If the core length differs from the depth of the hole by more than 10%, the core will be discarded and a new core will be collected.

Soil segments will be cut from the core for the 3-10, 20-30, 40-50, 55-65, and 70-80 cm depth intervals. Preliminary work has shown that the 0-3 cm layer at most sites contains a thick mat of grass roots which preclude accurate measurement of soil properties (Mohanty et al., 2002). The 40-50 cm sample does not correspond to an existing sensor depth, but is being considered as a target depth for future sensor deployment. The 70-80 cm sample corresponds to sensors installed at 75 cm at some sites, but these sensors are being decommissioned. Still the soil properties can be used to re-analyze archived data. Impenetrable layers may prevent the deeper segments from being sampled at some sites. Each core segment will be sealed in a plastic bag to prevent moisture loss. Two cores will be collected per site (Mohanty et al., 2002) and care will be taken to keep the soil samples intact. The samples will be stored in plastic boxes. The boxes will be placed inside a foil-lined insulated bag, kept shaded, and transported to the laboratory within 24 hours.

In the laboratory, each sample will be weighed. The intact portion of each sample will be trimmed to a length of ~4 cm and placed inside an 8.9 cm o.d. brass ring. The gap between the ring and the soil will be sealed with paraffin wax (Ahuja et al., 1985). These intact samples will be used in Tempe cells to determine the soil moisture retained at -33 kPa (Dane and Hopmans, 2002). A sub-sample of the remaining soil will be dried at 105°C for 24 hr. The data from this sub-sample will permit calculation of bulk density and soil moisture at the time of sampling. Next, the sub-sample which was dried at 105°C will be ground to pass a 2 mm sieve. The pressure plate method will be used to determine the soil moisture retained at -1500 kPa (Dane and Hopmans, 2002).

Specific aim #2: Develop a routine to calculate plant available water by integrating the sensor output and the site-specific soil properties. Plant available water (mm or inches) will be calculated as

$$\mathrm{PAW} = \sum_{i=1}^{n}\left(\theta_i - \theta_{\mathrm{wp}i}\right) dz_i \qquad [1]$$

where q_i is the current volumetric water content of layer *i*, q_{wpi} is the permanent wilting point for layer *i*, dz_i is the thickness of layer *i*, and *n* is the number of layers considered. For 81 Mesonet sites with sensors at 5, 25, and 60 cm, n = 3, and PAW would summarize water available in the top 80 cm of soil. For 25 additional sites, n = 2, and PAW would summarize water available in the top 40 cm. Sites which lack sensors at 60 cm typically have impenetrable layers above depth. The thickness of the soil layers represented are 10, 30, and 40 cm for the sensors at 5, 25, and 60 cm, respectively.

Accurate plant available water measurements are contingent upon knowing the soil water retention curve (soil moisture versus matric potential) for each site and depth. The retention curve is required because the 229 sensors measure matric potential, not soil moisture directly (Starks, 1999). The water retention curve is used to convert the sensor readings to soil moisture estimates. Water retention curves for each Mesonet site have been previously estimated (Illston et al., 2008) using the modeling approach of Arya and Paris (1981). This was one of the earliest approaches developed to estimate water retention curves from basic soil data like the particle size distribution and bulk density. The Arya and Paris (1981) method does not account for the effects of soil structure, thus large errors can result when applying it to medium and fine-textured soils (Basile and D'Urso, 1997). This fact helps to explain why errors in the soil moisture data often exceed 0.05 $m^3\ m^{-3}$ with the existing calculation routines.

A sub-objective of the project is, therefore, to improve the accuracy of the Mesonet soil moisture estimates on which plant available water monitoring will depend. These improvements will be gained by more accurate estimation of the water retention curve. Up to this time these curves have been estimated based only upon the particle size distribution and measured or estimated soil bulk density, because no better data were available. Now, through the proposed project, direct measurements of bulk density, soil moisture retention at -33 kPa and -1500 kPa, and soil organic matter will be obtained. These data will lead to improved estimation of the water retention curve. Schaap et al. (2001) found a RMSE in soil moisture at a given matric potential of 0.068 $m^3\ m^{-3}$ when only particle size distribution and bulk density are known. Others have shown that, with direct measurements of soil moisture at -33 kPa and -1500 kPa, the RMSE can be cut in half to 0.034 $m^3\ m^{-3}$ (Twarakavi et al., 2009).

Gains in accuracy such as those discussed above arise not only from the use of more complete input data, but also from the use of models more accurate than that of Arya and Paris (1981). This project will employ the widely used ROSETTA pedotransfer functions (Schaap et al., 2001). These models were developed using advanced numerical methods, i.e. artificial neural networks, and an extensive soil property database. The ROSETTA pedotransfer functions have been successfully employed in a number of prior studies. Our preliminary data show that, with direct measurement of key soil properties and use of ROSETTA, the accuracy of the soil moisture data can be improved from RMSE = 0.066 $m^3\ m^{-3}$ to RMSE = 0.032 $m^3\ m^{-3}$. Therefore, significant improvement in the accuracy of Mesonet soil moisture data is likely using the methods described here. In summary, the steps to achieve specific aim #2 are as follows:

(1) Use measured soil properties and the ROSETTA pedotransfer functions to improve the existing estimates of the site- and depth-specific water retention curve.
(2) Convert the 229 sensor measurements of matric potential into soil moisture estimates using the improved water retention curves.
(3) Calculate the plant available water in the soil profile based on the soil moisture estimates and the measured permanent wilting points (Eq. [1]).
(4) Develop prototype plant available water maps.

Principal Findings and Significance:

We have made great progress toward the development of a system for tracking PAW based on mesoscale observations from the Oklahoma Mesonet. The Mesonet is an automated network of 120 stations that collect real-time observations of soil and atmospheric variables across the state (McPherson et al., 2007). Principal findings and their significance are summarized for each specific aim below.

Specific aim #1: Determine the soil properties controlling the plant availability of soil moisture at each Mesonet site. We completed the soil sampling in August 2010 and collected 1,107 discrete soil samples from the Mesonet sites (Fig. 1). Soil samples were stored at 4°C pending analysis.

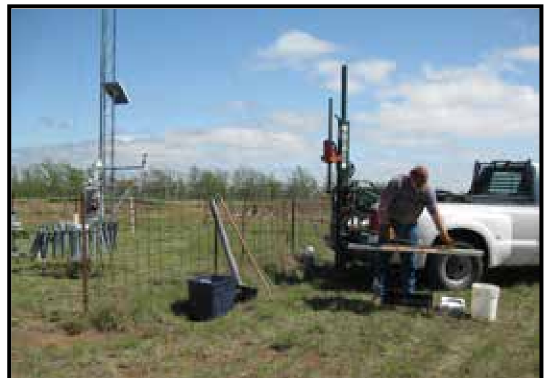

Fig. 1. Soil sampling at the Camargo Mesonet

We are measuring seven soil physical properties for each of these samples in the laboratory (Fig. 2). Currently, we have completed 3,924 of the necessary 7,749 soil property determinations, thus the lab work is 51% complete. We aim to reach 100% completion in July 2011. Once the database of seven measured properties is finished, those data will be used in the pedotransfer function, ROSETTA, resulting in estimates of seven additional soil properties. Thus, the final database will contain 15,498 soil property values for the 120 Mesonet stations. This comprehensive soil property database, connected with the Mesonet environmental sensing capabilities, will create an unprecedented and powerful tool for water resources research and management. The database is likely to have impact for decades to come.

Fig. 2. Measuring soil water retention at -1500 kPa and soil particle size distribution.

Specific aim #2: Develop a routine to calculate plant available water by integrating the sensor output and the site-specific soil properties. We have also developed the numerical routine to integrate the measured soil properties with the sensor data to calculate PAW at each Mesonet site. Example outputs from that routine are shown below in Figs. 3 and 4. These examples are based on pre-existing soil property estimates and are proto-types only. When the lab work is finished, we will incorporate the new soil properties into the calculation routine.

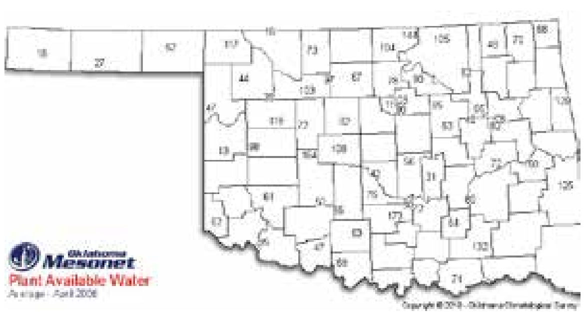

Fig. 3. Average PAW (mm of available water in the top 80 cm of soil) at the Mesonet sites, April 06.

Fig. 4. Time-series of PAW for the El Reno Mesonet site in 2009.

The new calculation routine, supported by the measured soil properties, is significant because it will drive the world's first system for monitoring plant available water at the regional or state level. In the second year of this project, we will be developing procedures to interpolate (estimate) plant available water between the Mesonet sites and to generate daily maps of plant available water for public release. The final plant available water maps will have great value for water resources research and management. They will help farmers and ranchers make more informed management decisions. They will help researchers understand how hydrologic processes are influenced by soil moisture and plant available water. They will also be useful for calibrating and validating new satellite remote-sensing approaches for estimating soil moisture.

A significant outcome of this project is that it contributed to the development and initiation of a major new project on soil moisture sensing. Scientists with the USDA-ARS Hydrology and Remote Sensing Laboratory in Beltsville, MD selected the Marena, OK Mesonet site as the location for a testbed to intercompare existing and emerging technologies for soil moisture sensing. That selection was due, in large part, to the ongoing work under this project. The Marena, OK In Situ Testbed (MOIST) was launched in 2010 and has attracted researchers from eight US states and from Netherlands. The testbed is led by Michael Cosh (USDA-ARS) and Tyson Ochsner (OSU). The process of locating the testbed in Oklahoma was initiated by conversations between Jeff Basara (OCS) and Michael Cosh. The testbed has good potential to attract research funding in the near future and to play a significant role in calibration and validation of NASA's forthcoming SMAP soil moisture satellite mission.

This project has also been significant in that it has provided an excellent training opportunity in water resources research for a M.S. level graduate student and two undergraduate students at Oklahoma State University. The students have benefitted from interaction with PI's at two different institutions and have gained familiarity with the Oklahoma Mesonet, with the geography and soils of Oklahoma, and with the topic of drought monitoring.

Student Status	**Number**	**Disciplines**
Undergraduate	2	Environmental Sci., Biosystems and Ag. Engineering
M.S.	1	Plant and Soil Sciences
Total	3	