THE POTENTIAL OF THE COSMOS NETWORK TO BE A SOURCE OF NEW SOIL MOISTURE INFORMATION FOR SMOS AND SMAP

Brian Hornbuckle, Samantha Irvin *

Department of Agronomy
Iowa State University
Ames, IA USA

Trenton Franz, Rafael Rosolem, Chris Zweck †

Department of Hydrology and Water Resources
University of Arizona
Tucson, AZ USA

ABSTRACT

The COSMOS network will eventually consist of several hundred sensors throughout the United States that report kilometer–scale soil water content via measurement of the intensity of neutrons immediately above Earth's surface. We show that COSMOS sensors must be corrected for the effects of growing vegetation. Once this phenomenon is completely understood the COSMOS network could be a useful source of information for the validation of both soil moisture and vegetation products obtained from current and future microwave remote sensing satellites.

Index Terms— Soil moisture, vegetation water content.

1. INTRODUCTION

Soil moisture affects the amount and variability of precipitation through its influence on the exchange of water and energy between the land surface and the atmosphere. Soil moisture also is the reservoir of water that supports plants, and it influences the severity of flood events through its control on the amount of rainwater or snow melt that infiltrates into the soil. In 2009 the European Space Agency launched the Soil Moisture and Ocean Salinity (SMOS) mission in order to observe soil moisture on a global scale [1]. NASA has plans to launch a similar satellite, the Soil Moisture Active Passive (SMAP) mission, in late 2014 [2]. Both of these satellites employ microwave remote sensing to provide information on soil moisture at the 40 km scale (and possibly the 10 km scale for SMAP) every two–to–three days for every location on Earth's surface where soil moisture retrieval is possible.

While the soil moisture information from SMOS and SMAP represents a breakthrough for weather and climate applications, a gap still exists in soil moisture information at the *O*(1 km) or field scale. The field scale is the scale at which topography influences runoff from precipitation that leads to flooding, and the scale at which agricultural management occurs. Furthermore, both SMOS and SMAP will only be able to sense the water content of the first few centimeters of the soil. The total amount of water available to plants, often called the root–zone soil moisture, is another valuable piece of information for both weather and climate forecasters and farmers. Finally, the data obtained from SMOS and SMAP must be validated before it will be useful. Additional measurement systems are needed in order to provide soil moisture for validation.

2. THE COSMOS NETWORK

A new type of soil moisture sensor that uses extra–terrestrial cosmic rays has the potential to provide data at the critical field scale of $1\ \mathrm{km}$. The COSMOS (COsmic–ray Soil Moisture Observing System) project has begun to deploy relatively inexpensive neutron detectors as soil moisture sensors. Cosmic rays incident on Earth's surface produce neutrons in the atmosphere which are scattered and absorbed by hydrogen in Earth's subsurface. The intensity of neutrons immediately above the ground is inversely related to the hydrogen content of the subsurface, which is dominated by the water stored in the soil. COSMOS sensors have a horizontal spatial resolution of approximately 700 m (350 m radius); a time resolution of minutes to hours; a vertical spatial resolution of typically 10 to 20 cm (depending on the overall soil water content); and a precision of less than $0.01\ \mathrm{m}^3\ \mathrm{m}^{-3}$ [3].

The COSMOS project is managed by the University of Arizona and is funded by the U.S. National Science Foundation (NSF). Low power requirements and satellite communications make large networks of these sensors practical [4]. In the first phase of the project 50 sensors have been deployed in order to refine the measurement technique and management process. In the second phase an additional 450 sensors will be installed throughout the United States (executive summary of NSF grant available at http://cosmos.hwr.arizona.edu). As of June 1, 2012, the network consists of approximately 60 sensors. One of the first COSMOS sensors was installed in September, 2010, at the Iowa Validation Site (IVS), a heavily–instrumented agricultural field funded by NASA that

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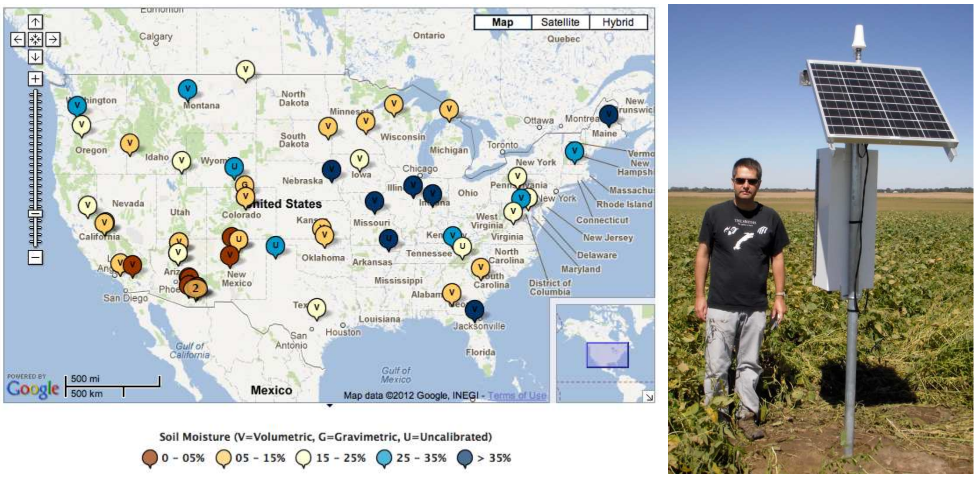

Fig. 1. At left: the current network of COSMOS sensors. At right: the COSMOS sensor installed at the Iowa Validation Site.

lies southwest of the campus of Iowa State University. A map of the current network and the sensor at the IVS is shown in Figure 1.

3. EFFECT OF VEGETATION

Soil water is not the only source of hydrogen at Earth's surface. Water in the vegetation canopy, either within vegetation tissue or residing on plants (dew or intercepted precipitation), may also need to be considered. Are COSMOS sensors influenced by the presence of vegetation? We hypothesized that vegetation will affect soil moisture measurements made by COSMOS sensors. Furthermore, we hypothesized that the effect will increase as the amount of vegetation increases. It is imperative to understand this vegetation effect in order to make accurate measurements of soil moisture with a COSMOS sensor, especially in regions such as the U.S. Midwest where annual crops dominate the landscape.

3.1. Experiment

The COSMOS sensor at the IVS lies at the center of an agricultural field that is approximately 1 km by 1 km. During the summer of 2011, this field was planted with maize. We measured soil moisture at 5 cm intervals down to 30 cm using the thermogravimetric method. These measurements were made at 18 points surrounding the COSMOS sensor throughout the 2011 growing season, from May until October. The 18 points were uniformly distributed at 60° angles on 25, 75, and 225 m diameter rings surrounding the sensor in order to account for the spatial weighting within the sensor's footprint.

In order to characterize the vegetation we developed a measurement method based upon allometry, the relationships that describe the relative size of different components of a single organism. This method allowed us to practically obtain a larger number of measurements of the maize canopy within the footprint of the COSMOS sensor, which we believed would lead to a better overall characterization of the vegetation. We hypothesized there would be a strong relationship between the product of the square of the stem diameter and the height of a maize plant (a rough estimation of the total volume occupied by a single plant) and plant mass. To find this relationship, we harvested 30 plants each day that measurements of vegetation were made. We measured the stem diameter, height, and mass of each plant and later used the data to find a linear empirical model. An example of this relationship for June 24, 2011, is shown in Figure 2. This empirical relationship, along with the plant density of the field, was used to convert measurements of stem diameter and plant height for 5 plants at each of the 18 points sampling points into a total vegetation canopy column density.

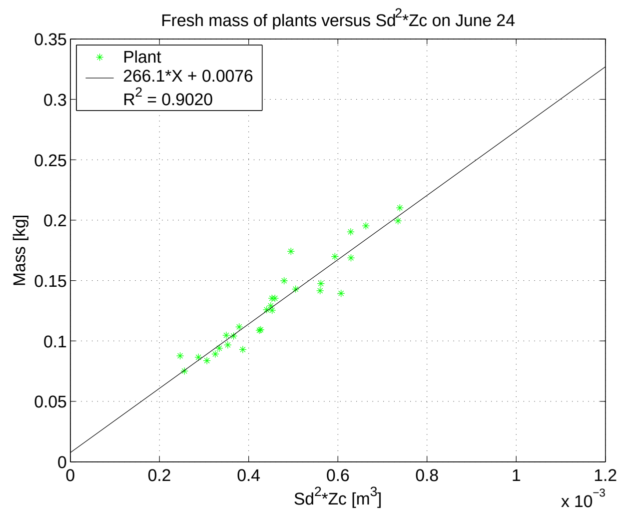

Fig. 2. Example of the relationship between stem diameter (S_d) and height (Z_c) of a maize plant and its fresh mass.

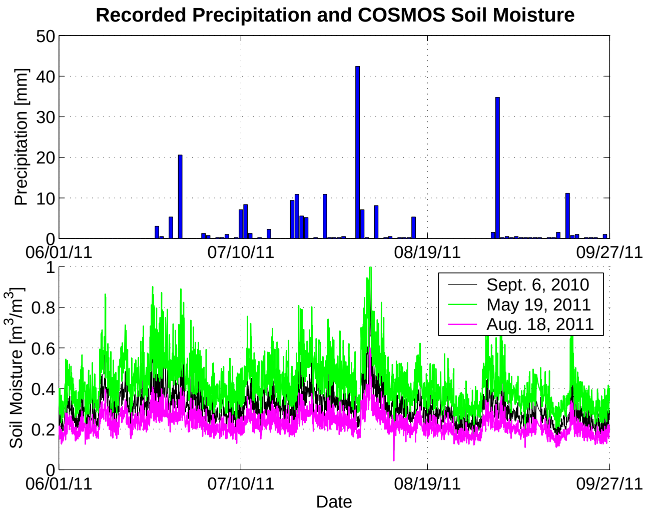

Fig. 3. Above: precipitation recorded during the 2011 growing season at the Iowa Validation Site. Below: soil moisture as sensed by the COSMOS probe according to three different calibrations.

3.2. Analysis and Initial Results

A COSMOS sensor detects the rate of incident neutrons, N. This quantity has been found to be indirectly proportional to soil water content:

$$\theta_v\left(N\right)=\frac{a_0}{\frac{N}{N_0}-a_1}-a_2 \qquad (1)$$

where: θ_v is the volumetric soil moisture; a_0, a_1, and a_2 are constants that are insensitive to soil type; and N_0 is the maximum counting rate over dry soil (i.e. the rate that would be detected if the soil was perfectly dry). As the water content of the soil increases, the number of neutrons scattered by the soil towards the COSMOS sensor decreases.

Theoretically only one parameter, N_0, must be found to calibrate a COSMOS sensor for a particular site. We determined this calibration for the sensor at the IVS using the soil moisture measurements described in Section 3.1. Three of these calibrations are shown in Figure 3. The original calibration when the sensor was installed in September, 2010, is shown in black. At that time the IVS was covered with a crop of soybean. The two other calibrations were made during the 2011 growing season when the IVS was planted with maize. Note the difference in the three calibrations and especially the unreasonably–high soil moisture values for the May 19, 2011 calibration. The original September calibration is too dry in May and too wet in August.

At the same time that we took soil moisture samples we also sampled the amount of vegetation. The variation of N_0 as a function of the amount of vegetation, quantified by both the vegetation column density (mass of fresh vegetation per area) and the water column density (mass of water contained

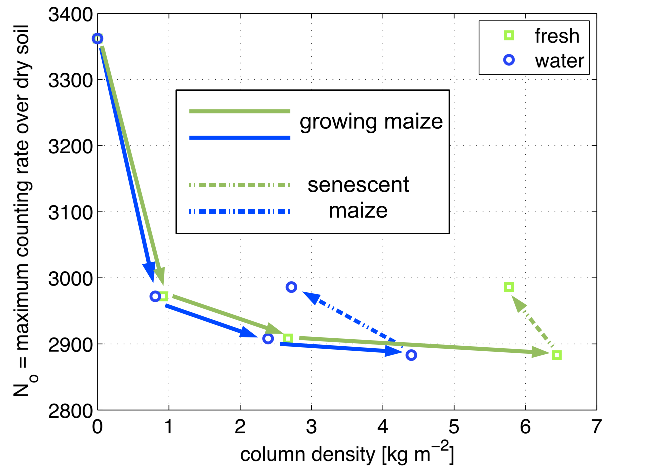

Fig. 4. Variation of the calibration parameter N_0 as a function of vegetation development as quantified by the vegetation column density and water column density.

within vegetation tissue per area) is shown in Figure 4. Note the following. First, N_0 decreases as the amount of vegetation increases. From the COSMOS sensor's point of view, the counting rate for perfectly dry soil must be decreased in order to account for the additional water that is held in the vegetation. Second, the effect of vegetation on N_0 is nonlinear. Third, there appears to be some hysteresis: the change in N_0 as the maize crop grew and accumulated mass is different than the change in N_0 during the period when the maize crop began to senesce and dry out. Perhaps the distribution of water within the canopy (among leaves, stems, and fruit) is important. Fourth, it appears that the effect of vegetation can be modeled, at least empirically.

4. CONTRIBUTION TO SATELLITE VALIDATION

As stated in Section 1, there is a need for additional soil moisture measurements to validate satellite products. COSMOS sensors have the potential to provide this soil moisture information. The following points should be considered.

1. Due to the sheer number of planned COSMOS sensors, it will be possible to organize dense sub–networks in specific regions of the U.S. where SMAP validation activities will occur.

2. Once installed, COSMOS sensors require little maintenance but may have to be regularly calibrated for growing vegetation.

3. COSMOS network data is provided free–of–charge with little latency (<1 day).

4. The large footprint (support) of COSMOS measurements as compared to traditional in–situ soil moisture

sensors is much closer to the footprint of satellite measurements which will likely result in simpler upscaling strategies [5].

5. COSMOS sensors are sensitive to growing vegetation. There is a need to validate the SMOS vegetation product (optical thickness, which is directly proportional to vegetation water content). Unlike SMOS, SMAP *requires* ancillary information on vegetation water content in order to retrieve soil moisture.

6. The sensing depth of a COSMOS sensor (10 to 20 cm) does not match the depth of SMOS and SMAP Level 2 products (≈ 5 cm) nor the SMAP Level 4 product (root zone, ≈ 1 m).

5. FUTURE WORK

In order for the COSMOS network to be a valuable source of information for SMOS/SMAP validation, the following work must be completed.

First, the effective measurement depth of a COSMOS sensor, which can vary from 10 to as much as 70 cm depending on mean moisture content, must be determined. Work in this area is currently in peer review. Once the effective depth is understood, relationships between the soil moisture sensed by SMOS/SMAP and the soil moisture detected by COSMOS sensors must be related to each other. This can be done simply with empirical regressions of in–situ measurements and is not too different than what must be done to relate SMOS/SMAP soil moisture to the soil moisture measured by networks currently in place. Furthermore, COSMOS could provide a link between SMOS/SMAP products and hydrologic models that predict deeper soil moisture, and to the proposed SMAP Level 4 root zone product. Hence COSMOS data may be critical in actually applying SMOS and SMAP information to real–world agricultural and hydrological problems.

Second, models for the effect of other pools of hydrogen, such as those in growing vegetation, must be developed. The approach that we are taking is to quantify the total amount of hydrogen present within the COSMOS footprint from these various pools. These pools include: water stored in the soil (soil moisture); water within in vegetation tissue; water stored on vegetation (dew or intercepted precipitation); water vapor in the air (humidity); hydrogen compounds in the vegetation tissue; and organic matter in the soil. We will then use a full neutron transport model [6] to isolate the response of neutrons to these different hydrogen pools. It is also possible that discriminating between fast and slow neutrons may allow COSMOS sensors to self–calibrate themselves for the effect of growing vegetation [7]. Since SMOS and SMAP measurements of soil moisture are greatly affected by the amount of vegetation present, the independent source of information on vegetation provided by COSMOS could potentially be an even greater benefit to these two satellite missions.

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