A REVIEW STUDY ON NOVEL & EMERGING PROXIMAL SOIL MOISTURE SENSORS

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ABSTRACT

The measuring of soil moisture in agriculture is presently dominated by a few number of sensors, the usage of which is severely restricted by their small sample volume, high cost, requirement for tight soil–sensor contact, and lack of performance in salty, vertic and rocky soils. This study was conducted to investigate the variety of new and developing soil moisture sensors, and assess their potential application in agriculture. The study showed that advances to current methods over the past two decades are modest, and mainly confined to frequency domain reflectometry approaches. However, a wide range of new, novel and arising method of assessing soil moisture were identified including, actively heated fiber optics (AHFO), high capacity tensiometers, paired acoustic / radio / seismic transceiver approaches, thermo approaches, radio frequency identification (RFID), hydrogels and seismoelectric approaches. Excitement about this variety of possible new technologies is nevertheless tempered by the fact that many of these techniques are at initial phases of development, and that few of these methods have been properly tested in situ agricultural soils.

KEYWORDS: *Capacitance, Moisture, Soil Moisture, Sensor, Soil Humidity.*

1. INTRODUCTION

Knowledge of soil moisture is essential for supporting agricultural output, watershed hydrology, flood forecasting, landslide prediction and other ecosystem services. Globally, agriculture is the biggest water consumer accounting for about 70 percent of total water use. Global demand for decreasing water resources has prompted increased interest in the development of proximal soil moisture sensors for better control of irrigation and soil moisture in agriculture. Proximal soil sensors are described as being in touch with, or within proximity to the soil (<2 m). Proximal sensors are generally categorized as being I in-situ, stationary or point scale, including both intrusive or buried sensors, or (ii) noninvasive sensors which may function on or near the ground surface including being connected to a vehicle to produce 'maps' of soil moisture variations[1].

Soil moisture monitoring in agriculture is currently dominated by a small number of 'trusted' technologies namely, frequency domain reflectometry (FDR) or capacitance, gypsum block sensors, time domain reflectometry (TDR), and in some industries the neutron moisture meter (NMM) and amplitude domain reflectometry (ADR. Examination of the soil moisture sensor industry and 'Agri-Tech' boom shows that most of the allegedly 'new' soil moisture sensors that have been commercially accessible in the past 5–10 years are based on pre-existing dielectric methods (mainly FDR) (mostly FDR). Techniques which have been truly improved in recent years include multi-depth down entire TDR, low cost TDR sensors, and pseudo TDR techniques (ADR etc). (ADR etc.). Very few truly innovative techniques for monitoring soil moisture have been marketed or accepted for use in agriculture in the past 2 decades. Inadequate adoption of new methods seems to arise in part poor awareness by technologists of the potential that some of the emerging sensor technology offers for overcoming current limitations to the use of existing soil moisture sensors. Equally low uptake comes from the inadequate knowledge and comprehension of these new methods.

1.1.Advances in In Situ Invasive Matric Potential Sensors:

Matric potential sensors and tensiometers detect the soil matric potential or the amount of suction needed to extract water from the soil rather than soil moisture content. As such matric potential sensors are regarded a better indicator of plant moisture stress than soil moisture content. Matric potential is measured by either tensiometers, gypsum blocks or granular matrix (i.e., watermark) sensors. However, usage of tensiometers is severely limited by water cavitation at 80–100 kPa, their tiny felt area, requirement for hydraulic connection between the sensor and the soil, and problems rewetting after cavitation[2].

The usage of matric potential sensors like tensiometers, gypsum blocks and granular matrix sensors are restricted to non-vertic (non-swelling) soils since these sensors need hydraulic connection between the porous sensor and soil pores. In vertic soils, matric potential sensors frequently fail since drying causes the soil to lose hydraulic connection with the soil. Gypsum block and granular matrix sensors detect the matric potential of the porous material by resistance which is extremely sensitive to soil water salinity (i.e., conductivity) including fertilizer application.

1.2.Time Domain Reflectometry (TDR):

TDR sensors are regarded a highly dependable and precise technique for measuring soil moisture. However, their application in agriculture has been restricted owing to their high cost and requirement for sophisticated wave form analysis to determine soil moisture. In recent years, Acclima, Inc. (Meridian, ID, USA) have decreased the size and cost of TDR sensors via the use of cheaper mass-produced electronics incorporating cellular phone components, so that TDR sensors are now comparably priced with high-end FDR sensors. Campbell Scientific (Logan, UT, USA) have also attempted to reduce the cost of TDR sensors by utilizing transmission line oscillators to construct 'pseudo' TDR sensors in which the number of reflected voltage pulses are detected rather than performing complex waveform analysis of individual reflections[3]–[5].

1.3.Frequency Domain Reflectometry (FDR) and Capacitance:

The expensive expense of TDR sensors has led to the development of alternative lower cost, lower frequency 10–150 MHz, and frequency domain reflectometry (FDR) sensors that do not depend on complex waveform processing. FDR methods assess the soil moisture content indirectly by calculating the bulk dielectric constant from frequency changes of an electromagnetic pulse transmitted into the soil. Due to the lower working frequencies of FDR, the imaginary component of the dielectric constant may be significant, so that FDR sensors are more prone to error from soil texture, electrical conductivity, and temperature than TDR sensors.

1.4.Radio Frequency Identification (RFID):

Ultra-high-frequency radio-frequency identification (UHF RFID) systems work across a broad range of frequencies from 120 kHz into the microwave bands up to 10 GHz to automatically identify and measure tagged objects. RFID offers a very low-cost potential for soil moisture monitoring since individual tags (sensors) cost < USD 1 to USD 50; they may be passive (nonpowered) and they can communicate across distances of several meters. Passive RFID tags operate by utilizing some of the energy produced by the reader to give a unique identifier, and an analogue voltage output that may be used to power external devices such as low-power microcontrollers or sensors[6]–[9].

1.5.Invasive Open Ended Antenna (Radar) Microwave:

Microwaves (300 MHz to 300 GHz) are excellent for distant and proximal sensing of soil moisture, since microwave radiation causes dipole molecules such as water to spin generating detectable changes in resulting electromagnetic waves. Microwave-based soil detectors have 3 obvious advantages compared to the existing intrusive sensors (TDR and FDR), such as they seem to include a larger quantification area (but not necessarily volume), they are not susceptible to error small- airgaps between the soil and the detector, and they have various methods of implementation including proximal invasive, proximal noninvasive and remote setups (aircraft and satellite platforms) (aircraft and satellite platforms).

1.6.In Situ Paired Transceiver Approaches:

Experiments employing radio, acoustic and seismic wave propagation through soil and rock have demonstrated that wave velocity and signal attenuation are affected by moisture content. Paired transceiver methods include utilizing the velocity or attenuation of either radio, acoustic or seismic waves transmitted between the paired subsurface transceivers to infer soil moisture content Paired transceiver methods offer a tempting possibility for the creation of soil moisture sensors which have potential to function across distances of many meters. Moreover, unlike with the NMM and cosmic ray approaches in which results usually consist of information from a variety of soil outlooks, paired transceiver approaches should in theory be allowed to navigate at discrete depths using the flight time (ToF) approach which consider the shortest path between transmitter nodes..

1.7.Seismoelectric Approaches:

Seismoelectric, electro kinetic or electro seismic methods are an emerging field of geophysics utilized for noninvasive subsurface research for pore fluids such as water, oil and gas. These methods include producing a seismic wave which results in the creation of an electromagnetic signal (electro kinetic phenomena) arising from pore water moving from compressed to dilated areas of the soil/rock. Because cations preferentially adhere to capillary walls, the resulting fluid flow separates the cations and anions thus producing an electric dipole causing development of a streaming current and electromagnetic co-seismic field which can be measured at the soil surface using an array of dipole antennas and geophones for measuring the mechanical response. Soil moisture influences both mechanical and electrical characteristics of soil/rock including seismic velocity, seismic attenuation, electrical conductivity and also the electro kinetic coupling. Consequently, both the coseismic field and interface response characteristics are affected by soil water content.

1.8.Heat Pulse:

Heat pulse sensors detect either the thermal conductivity, volumetric heat capacity or the soil thermal diffusivity in reaction to application of heat, in which wet soils will heat up and disperse heat slower than dry soils. Heat pulse sensors are not influenced by salinity or soil temperature. Sensors typically take the shape of either a single probe comprising both the heating and sensing components, or dual (multi) probe setups consisting of a single heater needle surrounded by up to six thermostat needles. Despite their accuracy, heat pulse sensors have not been extensively used in agriculture owing to their sluggish reaction time, high power consumption, expense relative to FDR sensors and necessity for a complex controller to detect heat fluxes[10].

1.9. In Situ Fiber Optic Approaches:

Distributed temperature sensing (DTS) systems detect temperature over a fiber optic cable at the cm scale for lengths in the order of kilometers, with a high temporal frequency and excellent precision. Optic fiber-based soil moisture sensors work by sensing deformation of the optic fiber resulting from either hydration of a hydrophilic (Polyimide) coating on the exterior of the optic fiber, or temperature changes in the soil around the actively heated fiber optic (AHFO) (AHFO). The more typical AHFO method includes administration of an electrical current through the outer metal sheath of an optic fiber which causes the sheath and surrounding soil to heat up and bend the optic fiber.

1.10. Hydrogels:

A limited number of studies have attempted to utilize the swelling capacity of hydrogels to assess either soil moisture or matric potential. Hydrogels are extremely absorbent hydrophilic polymer chains which may absorb 10–1000 times of their initial weight or volume in water over a very short period of time. Hydrogel sensors consist of a chemically inert hydrogel polymer, a semiporous membrane/filter/porous plate that inhibits migration of the hydrogel into the soil, and a method (mechanical, optical, capacitance) of detecting gel expansion. Hydrogel sensors work in a similar way to tensiometers in which soil moisture migrates through the semi permeable/porous material causing the hydrogel to expand and contract in harmony with the soil matric potential.

1.11. Emerging Mobile and Noninvasive Soil Moisture Sensors:

Noninvasive soil moisture sensors may be used for both point source and for mobile ‘mapping’ of soil moisture. Mobile, noninvasive methods offer promise to address problems with the limited measured volume of invasive sensors, by being able to be moved and therefore measure greater regions within acceptable durations. Non-invasive sensors are also able to function in stony soils in which installation of invasive sensors is frequently not feasible, and they can operate in vertic soils in which invasive sensors often lose touch with the soil after drying. Difficulties with the use of noninvasive approaches often include issues with limited penetration depth (L band microwave), variable depth of penetration with moisture content (GPR, EMI, Cosmic Ray, L band microwave), difficulty separating response from different soil depths or layers (EMI, Cosmic Ray), the time and hassle involved with conducting surveys (EMI and GPR) and high level of skill required to operate devices and process large volumes of data (GPR).

1.12. Cosmic Ray Sensors:

Cosmic ray sensors are commercially available, non-invasive (typically) stationary sensors that detect naturally occurring neutrons that are created by cosmic rays traveling through the Earth's atmosphere. They consist of a passive neutron detector positioned a few meters above the ground which detects the release (evaporation) of fast neutrons into the air above the soil after neutron interaction with hydrogen atoms in the soil. As cosmic ray sensors are noninvasive, they may be suitable to rocky and vertic soils in which installation of other popular kinds of soil moisture sensors is problematic. Cosmic ray sensors have a relatively wide measuring footprint of approximately 260–600 m radius which maybe suitable to broadscale farming on uniform soils but are incompatible with the increasing trend toward precision agriculture and variable rate irrigation. Additional limitations with cosmic ray sensors include their high cost, very large and imprecise measured soil volume, long measurement durations which can be in excess of 4 h, variable depth of measurement which ranges from around 15 cm in wet soils, to approximately 70 cm in dry soils, and difficulty deriving precise calibrations.

1.13. Electromagnetic Induction (EMI):

Electromagnetic induction (EMI) surveys are regularly used in agriculture to map bulk soil variability or changes in soil type, but in recent years they have been progressively utilized to map variability in soil moisture. EMI surveys are generally fast to perform, are non-invasive, have excellent spatial resolution, and need less specialized expertise and knowledge to analyze and interpret data than other geophysical techniques such as GPR. Unlike dielectric or microwave-based based methods (TDR, FDR, GPR etc.) EMI sensors are not immediately sensitive to water content or hydrogen ion concentration. They react to the amount of ions (salt content) in the soil solution, in which increasing soil moisture content increases the abundance and mobility of ions and therefore raises the apparent electrical conductivity (ECa).

2. DISCUSSION

With the exception of the neutron probe and cosmic ray sensors, use of soil moisture sensors for informing on farm decisions such as when and how much to irrigate, is greatly limited by the relatively small measured soil volume of most commercially available sensors (FDR, capacitance, gypsum block and granular matrix) (FDR, capacitance, gypsum block and granular matrix). Consider a farmer choosing when and how much to water a 50-ha field based on the reading of a sensor which detects as little as 10 cm3 soil, a measured to managed ratio of 1:1010. Use of current soil moisture sensors needs a high degree of trust that the sensor is properly placed (i.e., no air gaps), that it is situated in a representative soil type, that soil types are more or less consistent across an entire block, center pivot circle or management unit. One way to solve the measuring scale problem, is to employ a large number of low-cost sensors. Use of soil moisture sensors in agriculture is presently dominated by three technologies FDR, TDR and granular matrix matric potential sensors. Over the past decade very few enhancements to existing methods or truly novel ways of monitoring soil moisture have been marketed.

3. CONCLUSIONS

Farmers have never had the technology that they wish to be utilizing for monitoring soil moisture. Instead they have taken use of the technology which has been made accessible to them, notably TDR, FDR and granular matrix sensors. Review of the literature shows a multitude of enhanced, innovative and new methods for monitoring soil moisture, in which agriculture is nearly always mentioned as a possible end user of the technology. However, few studies show awareness of how new sensor technology may overcome limitations associated with the use of current soil moisture sensors or recognize in what soil or agricultural systems emerging technology is suitable or restricted.

Continued direction of soil moisture detectors for use by farm owners in agricultural production would greatly benefit from greater cooperation between sensor engineers, soil scientist, and agriculturalists in order to develop, new, useful, usable soil moisture sensors that overcome the restrictions to the use of established soil moisture sensors. New sensor technologies need to pay greater attention to overcoming logistics related constraints imposed by agriculture including frequent tillage, operation in remote locations and restricted practical expertise of users, as well as the need to increase the capacity of sensed soil without losing specific depth information. In addition, new methods need to be developed for usage in stony, vertical and saline soils. This remains a significant problem, in which no one, fresh, innovative or developing technology is an obvious victor.

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