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A near-infrared reflectance sensor for soil surface moisture measurement

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ABSTRACT

Soil moisture is an important soil property that has important functions in various studies and applications, such as agricultural practices, hydrological processes and ecological issues. A near-infrared (NIR) reflectance sensor designed for moisture measurement at the soil surface is based on the reflectance of two light-emitting diodes (LEDs) of different wavelengths, in which one has a wavelength of 1940 nm and a strong water absorption band, whereas the other has a wavelength of 1800 nm and a weak water absorption band, as related to soil moisture reflectance. The algorithm is designed for estimating soil moisture using the relative absorption depth from reflectance data of the 1800 and 1940 nm wavelengths. Laboratory experiments investigate the relationship between soil moisture and surface reflectance by studying four different soils. The results indicate a strong linear correlation between soil moisture and relative absorption depths for the different soils tested, and the reflectance models are dependent on soil type. The soil moistures predicted using the proposed method agree well with measurements obtained by gravimetric method, indicating the feasibility of the proposed method for soil moisture measurement. The NIR LED reflectance sensor developed in this study is potentially useful for soil surface moisture measurement in the laboratory and field.

1. Introduction

Soil moisture is an important component of plant growth that is closely related to irrigation and exchange of mass and energy between the soil and the atmosphere. Soil moisture is also the primary vehicle for chemicals, such as fertilizers and pesticides, to be transported to the soil surface, inside the soil body, and through plant organs (Loan and James, 2008). Therefore, soil moisture measurement is a critical aspect in many scientific studies. Soil moisture is also closely related to hydrological processes, such as rainfall and runoff, soil erosion and ecological issues (Fitzjohn et al., 1998; Wei et al., 2007)

Only a few direct and indirect methods are available for determining soil moisture content, including gravimetric methods (Gardner, 1986), frequency and time domain reflectometry (FDR and TDR) (Clarke Topp and Reynolds, 1998; Gaskin and Miller, 1996), neutron probes (Chanasyk and Naeth, 1996), capacitance probes (Eller and Denoth, 1996) and microwave techniques (Jackson, 1993).

Gravimetric method is currently the gold standard, most commonly accepted, and most reliable method for soil moisture determination and calibration of all indirect measurement methods. Despite its advantages of accuracy and high reliability, the gravimetric method is time and resource consuming, destructive, and unrepeatable.

TDR and FDR can be used to measure volumetric soil moisture after proper calibration, with automatic logging capability. Soil salinity has unpredictable effects on the measured moisture. The spatial resolution depends on soil moisture and probe length. The neutron probe has a wide range of measurement capability with reasonable accuracy. However, the instrument requires a trained operator due to the use of a radioactive source, which is potentially hazardous to health and the environment (Tarantino et al., 2008). In addition, the neutral probe cannot make reliable measurements at the soil surface. The capacitance method has long been studied but has become commercially available only in recent years. Its resolution also depends on the size of the sensor. The gamma ray attenuation method is capable of determining the moisture content at soil surface layers (up to 1–2 cm), but high cost and difficulty of use limit the applicability of this technique (Dobriyal et al., 2012). The radioactive source also poses a big risk to human health and the environment. Remote sensing of soil moisture is dependent on the electromagnetic energy that is either reflected

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or emitted from the soil surface, and is most suitable for determining the average soil water situations over large areas. However, the uncertainty in determining the relationships among brightness, temperature, and soil moisture limits its accuracy (Wang and Qu, 2009).

Most of the above mentioned techniques essentially measure the average water content over a certain depth of soil layer, and are therefore not suitable for measuring moisture at the soil surface. For example, the neutron probe has been characterized as inaccurate at the top 30 cm soil layer because of the loss of neutrons to the atmosphere at this shallow depth (Evett et al., 2003).

Soil moisture near the soil surface is one of the essential variables for understanding water transfer at the soil–atmosphere interface (Brutsaert, 1983). Inoue et al. (2001) made a good attempt to develop a TDR probe for "non-penetration" and "on-the-move" measurement of moisture condition near the soil surface. Their K-type and S-type probes provided reasonable estimates of soil moisture condition near the surface at depths of 0–5 cm of soil layer. This new TDR probe awaits further operational examination under different specific conditions.

The near-infrared (NIR) reflectance technique can measure the reflectance from the surface of objects and has been widely used for detecting soil attributes, such as soil organic matter, minerals, water content, pH and heavy metal content. Different soil constituents have unique absorption features due to the vibrations in molecular bonds (Wang et al., 2012). Most studies have shown that reflectance in certain spectral bands can be correlated with soil properties (Ben-Dor and Banin, 1995; Bowers and Hanks, 1965; Daniel et al., 2004; Viscarra Rossel and McBratney, 1998; Zhu et al., 2010). Soil moisture has absorption bands of 970, 1200, 1450, and 1940 nm in the NIR spectrum. Two strong absorption bands have been reported at 1450 and 1940 nm due to the first overtone of the OH-bending band and the combination of the OH-stretching band and the OH-bending band (Büning-Pfaue, 2003; Baumgardner et al., 1985; Liu et al., 2003). A higher moisture content is correlated with deeper water absorption band, and vice versa.

Meaningful attempts have been made to investigate the relationship between soil reflectance to NIR and soil moisture by full spectrum and light filters that capture narrow bands.

Lobell and Asner (2002) acquired reflectance measurements of soil moisture in a laboratory setting for four different sieved soil samples at various moisture contents using a full-range (350–2500 nm) spectrometer (Analytical Spectral Devices). Soil reflectance was found to be nonlinearly correlated with soil moisture, which was well defined by an exponential model between the 1100 and 2500 nm wavelengths, suggesting that longer wavelengths are more suitable for measuring volumetric moisture contents above 20%. Measurements of reflected radiation (350–2500 nm) were obtained in the field for four Israeli soils, and they showed moderately successful results, with the R^2 value at the calibration stage between 0.9 and 0.96 and the RMSE ranging from 4.9% to 5.4% (Ben-Dor et al., 2008). Zhu et al. (2010) predicted the moisture content for three types of soils using the wavebands 1400, 1940, and 2250 nm, including one artificially constructed sample, one natural soil core, and one natural surface soil sample. A total of 21 water content levels varying from 0.001 $cm^3\ cm^{-3}$ to 0.373 $cm^3\ cm^{-3}$ were used. The results indicate that the most significant correlation between soil moisture and reflectance was identified at 1400 nm for disturbed soil samples ($R^2 = 0.996$, RMSE = 0.010 $cm^3\ cm^{-3}$) and at 1940 nm for both cored ($R^2 = 0.969$, RMSE = 0.019 $cm^3\ cm^{-3}$) and surface soil samples ($R^2 = 0.895$, RMSE = 0.059 $cm^3\ cm^{-3}$).

All of the above studies were conducted using commercial spectrometer or spectral devices to investigate the responses of NIR reflectance to soil moisture.

Various attempts have been made to develop devices that can measure soil moisture in the laboratory with NIR reflectance. Skidmore et al. (1975) developed a reflectometer to measure the reflectance of near-infrared radiation from a soil surface at four bands. The integrating sphere and filter resulted in cumbersome procedure and slow response. Narrow-band pass filters had to be manually positioned before the reflected light could reach the integrating sphere. Kano et al. (1985) designed a near-infrared reflectance moisture meter to obtain soil moisture readings using NIR reflectance at 1800 and 1940 nm. The entire meter was housed in an aluminum tube with diameter of 38.1 mm and length of 381 mm, with a data acquisition circuitry outside the tube. The large size limits its applicability as a sensor. Given the lack of proper LED light sources, two narrow-band interference filters of 10 nm band pass had to be used as interference filters to isolate the measuring band at 1940 nm and the reference band at 1800 nm. The output voltage of the meter showed good linear correlation with gravimetric soil moisture content, from 2.5% to 35%, with a standard error of ±1.9% moisture units for clay and loam soils. The output voltage failed to respond when the moisture content was higher than 35%. The results also indicated that the meter may require a different calibration for sand and sandy loam. Belisle et al. (1996) discussed an optical reflectance technique with a flashlight and a photodiode, which has small volume and low energy consumption. However, an interference filter had to be used in front of the detector, which made the structure more complex.

The present study has the following objectives: (1) to design a near-infrared sensor for measuring soil surface moisture; (2) to develop a mathematical model for soil moisture determination based on soil surface reflectance data; and (3) to compare the moisture contents measured by the NIR approach with measurements obtained using the oven-dry method.

2. Sensor description

Compared with the tungsten lamp and laser LED, infrared LED has certain advantages, such as low energy consumption, instant response and long lifetime. Therefore, infrared LED was selected as the light source in this study.

The NIR reflectance sensor constructed for soil surface moisture measurement consisted of LED light sources for generating NIR light at 1940 and 1800 nm, which were the same wavelengths used by Kano et al. (1985), photodiodes for receiving the reflectance, sensor case, amplifier circuit, and analog-to-digital (A/D) converter (Fig. 1). The sensor case is made of black polyvinylchloride (PVC), with dimensions of 2 cm in diameter at the upper end, 5.5 cm in diameter at the lower end, and 2.5 cm in height.

The small volume of light source is beneficial when incorporated into a shield case to ensure that more light reaches the photodiode while minimizing ambient light impact when the shield case is placed at the soil surface. The light detector is installed at the top of the sensor case, and six LEDs are arranged circularly around the light detector. All LEDs are angled at 45° to the normal so that a beam of light from a LED is focused on a plane, resulting in a central irradiated area of approximately 8 mm in diameter at the soil surface.

During operation, the radiations from the LEDs are directed to the soil surface at a fixed distance of 15 mm. After interacting with the soil surface, a fraction of the reflected light is reflected back to the receiving detector, and the rest is lost due to scattering, absorption, and transmission. The detector has a wide angular response to incident radiation, and no light reaches the detector directly from the LEDs. To generate maximum average power, the infrared LED emits a pulse signal to produce 600 mA current for 700 µs (Fig. 2). Normally, all the LEDs at both wavelengths of 1940 and 1800 nm are under off status. When measurement is started, the