Research paper

Multiple-depth mapping of soil properties using a visible and near infrared real-time soil sensor for a paddy field[☆]

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ABSTRACT

In describing soil variability, information on the distribution of soil properties is required in both the horizontal and vertical directions. This study investigated the potential of a real-time soil sensor (RTSS) for mapping six soil properties at multiple soil depths of a paddy field. Soil spectra were acquired at three depths using RTSS. Three calibration models were developed. The first model (CM1) combined the dataset for depths of 10 and 15 cm, the second model (CM2) combined the dataset for depths of 15 and 20 cm, and the third model (CM3) combined all the three depths. CM3 was the best calibration model for all the soil properties. The generated maps exhibited variations in the distribution of all the soil properties at different depths.

1. Introduction

In precision agriculture, information on spatial and temporal soil variability is essential in order to assist farmers in making agronomic decisions for farm management. This is to ensure high crop yield and low cost production with minimal unintended environmental impact. In the conventional method of soil property quantification, the soil cores are collected at a limited number of samples and then analyzed intensively in the laboratory. This practice often results in under-sampling due to time-consuming, laborious, and costly sampling and analysis, making it impractical for mapping large field areas for precision agriculture purposes. Moreover, the capacity to detect temporal changes of these properties in soil using conventional sampling and analysis techniques is quite limited due to the large spatial variability and slow response of these properties in soil (Stevens et al., 2006). Therefore,

an improved and efficient method is required for measuring spatial and temporal variability of soil attributes. One solution to overcome the limitation found in the conventional method of soil sampling and analysis is the adoption of a visible-near infrared (Vis-NIR) sensor that is real time, cost effective and can rapidly measure soil properties. Kodaira and Shibusawa (2013) have successfully used the Vis-NIR real-time soil sensor for measuring and generating high resolution maps for multiple soil properties including moisture content, organic matter, total carbon, total nitrogen, hot-water-extractable nitrogen and available phosphorus. In other studies, Mouazen et al. (2007) investigated the potential use of the Vis-NIR sensing system for online measurement of soil properties including carbon, while Christy (2008) demonstrated that the Vis-NIR real-time sensor has potential for mapping soil organic matter.

The real-time measurement of soil properties in many previous studies, however, was only conducted in the horizontal strata (a single depth) whilst ignoring the distribution of soil variability vertically (depth direction). As claimed by Donovan (2012), vertical distribution is important for describing the variability of soil carbon because it is likely to vary with depth. Most soil carbon sampling thus defines one or more layers of soil, usually by the distance in centimeters from the soil surface. Variation in soil compositions including SOM was also found at different depths as reported by Reeves et al. (2002). Even though there are several studies that

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considered several depths including depths of 10–20 cm (Yang et al., 2011), 0–20 cm (Viscarra Rossel et al., 2010) and 50–105 cm (Ge et al., 2011), the spectra measurements for calibration model development in these studies, however, were laboratory basis which is again laborious, time consuming and expensive because the samples need to be crushed, sieved and dried prior to spectra scanning. Sarkhot et al. (2011) used a hydraulic soil probe to take soil cores and then separated the soil cores into five depths at increments of 0–10, 10–20, 20–30, 30–40 and 40–50 cm where the soil samples were oven dried before scanning the spectra in the laboratory. Only the map at the depth of 10 cm (single depth) is shown. In another study by Li (2013), the distribution of total carbon and total nitrogen are presented on maps at several depths but the maps were generated based on the laboratory analysis of a small number of samples. The resolutions of the maps were low because they were mapped using the laboratory analysis data only and no spectra were acquired to predict the value of total carbon and total nitrogen. Thus, the objectives of this study were to investigate the potential of a Vis-NIR real-time soil sensor for mapping moisture content (MC), organic matter (OM), total carbon (TC), total nitrogen (TN), hot-water-extractable nitrogen (HN), and available phosphorus (P-A) of paddy soil at multiple soil depths for precision agriculture purposes, and to describe the effect of sensing depth on the mapping of soil properties. The spatial distributions of these six soil properties were observed at three depths of paddy soil that were 10, 15 and 20 cm from the soil surface.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at an organic paddy field in Matsuyama City of Ehime Prefecture Japan (33° 8′N, 132° 8′E). This site comprises a number of small paddy fields and field no. 437 (58.3 m × 21.7 m) was selected for this study. The experiment was conducted after harvesting the paddy in autumn 2012. The average, maximum and minimum temperature of the day was 20.8, 26.3 and 14.5 °C, respectively. The soil texture of the field was described according to three depths as follows: 52.82% sand, 24.71% silt and 22.47% clay at a depth of 10 cm, 54.55% sand, 21.02% silt and 24.43% clay at a depth of 15 cm, and 66.29% sand, 11.82% silt and 21.89% clay at a depth of 20 cm.

2.2. Real-time Soil Sensor (RTSS)

The RTSS used for this study was SAS1000, SHIBUYA MACHINERY Co., Ltd as shown in Fig. 1. It is comprises of a sensor unit housing, a touch panel and a soil penetrator with a sensor probe
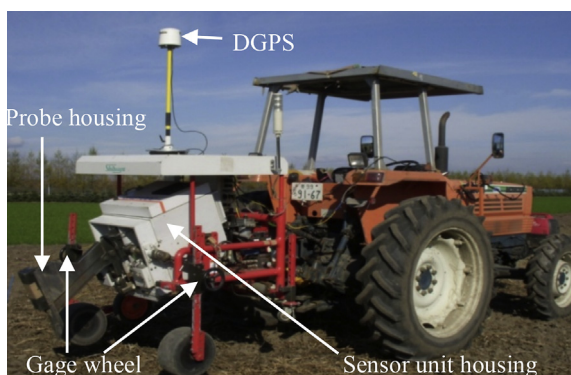

Fig. 1. Real-time Soil Sensor SAS1000.

housing. The sensor unit housing consists of a personal computer, differential global positioning system (DGPS) receiver, 150-W Al-coated tungsten halogen lamp as a light source and two spectrophotometers. The first spectrophotometer is for visible (Vis) spectra (310–1150 nm), and has a 256-pixel linear diode array, while the second spectrophotometer is for NIR spectra (900–1700 nm), and has a 128-pixel linear diode array of multiplexed InGaAs. In the probe housing, two optical fibers were used to guide the light from the light source (halogen lamp) and illuminate the underground soil surface with an area of about 50 mm in diameter. The underground soil Vis-NIR reflectance spectra were then collected through additional optical fiber probes to the two spectrophotometers. The probe housing is also equipped with a micro CCD camera to capture, record and display images of uniform soil surfaces while the RTSS running across the field. The saved images were then used to provide information for eliminating the dataset from the data analysis. By checking on the saved images, the spectra corresponding to the image that exhibited foreign objects such as stone, plant debris or larvae were identified as outliers for the calibration and prediction process. Next to the CCD camera is a laser distance sensor for monitoring distance variations between the soil surface and the micro optical devices.

The RTSS was designed with gage wheels on both sides that can be adjusted to spacings of 5 cm at depths from 5 cm to 35 cm. In this experiment, the gage wheels were initially adjusted for acquiring spectra at a depth of 10 cm. The tractor that attached with the RTSS was traveled on four transects at spacings of 5 m and a speed of 0.25 ms^{-1}. When the RTSS was running on the track, the soil penetrator tip with a flat plane edge ensured uniform soil cuts and the soil flattener following behind formed a trench with a uniform underground surface. The Vis-NIR reflectance spectra of the underground soil were acquired automatically from the bottom of the trench every 4 s, and this resulted in the Vis-NIR reflectance spectra being sampled at a distance of every 1 m. After the RTSS had completely traveled all four transects, the process was repeated for depths of 15 and 20 cm by adjusting the gage wheels.

While the RTSS was running on the track, a notification lamp was triggered at each data acquisition (every 1 m traveled). The number of spectra data were counted and displayed on the touch panel screen. When the RTSS acquired every 11th spectra data (11 m), a wooden stick was inserted into the soil. Two sets of soil samples were subsequently collected at the trench bottom of twenty wooden sticks' positions and they were packed in sealable plastic bags. This procedure was conducted for depths of 10, 15 and 20 cm. In total, there were two sets of 60 soil samples collected. However, due to the RTSS encountering an obstacle at one point at a depth of 20 cm, invalid spectra were acquired at that particular point. Hence, a soil sample corresponding to that single point was omitted from each set. Finally, only 59 soil samples of each set were collected.

2.3. Soil chemical analysis

In order to measure the chemical amount in the soil samples collected at the three depths, one set of the soil samples was transported to Tokyo University of Agriculture and Technology (TUAT) laboratory for MC and OM analysis while the other set was transported to the Agricultural Product Chemical Research Laboratory (APCRL: Federation of Tokachi Agricultural Cooperative Association, Hokkaido, Japan) for analysis of TC, TN, HN and P-A.

The first set of 59 fresh soil samples was crushed and sieved through a 2-mm sieve. Debris such as plant material and stones were removed. The samples were then stored in sealable plastic bags at 5 °C until the completion of the chemical analysis. MC was measured in fresh soil samples using the oven-dry method at 110 °C