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Incorporation of satellite remote sensing pan-sharpened imagery into digital soil prediction and mapping models to characterize soil property variability in small agricultural fields

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ABSTRACT

Soil prediction models based on spectral indices from some multispectral images are too coarse to characterize spatial pattern of soil properties in small and heterogeneous agricultural lands. Image pan-sharpening has seldom been utilized in Digital Soil Mapping research before. This research aimed to analyze the effects of pan-sharpened (PAN) remote sensing spectral indices on soil prediction models in smallholder farm settings. This research fused the panchromatic band and multispectral (MS) bands of WorldView-2, GeoEye-1, and Landsat 8 images in a village in Southern India by Brovey, Gram-Schmidt and Intensity-Hue-Saturation methods. Random Forest was utilized to develop soil total nitrogen (TN) and soil exchangeable potassium (K_{ex}) prediction models by incorporating multiple spectral indices from the PAN and MS images. Overall, our results showed that PAN remote sensing spectral indices have similar spectral characteristics with soil TN and K_{ex} as MS remote sensing spectral indices. There is no soil prediction model incorporating the specific type of pan-sharpened spectral indices always had the strongest prediction capability of soil TN and K_{ex}. The incorporation of pan-sharpened remote sensing spectral data not only increased the spatial resolution of the soil prediction maps, but also enhanced the prediction accuracy of soil prediction models.

Small farms with limited footprint, fragmented ownership and diverse crop cycle should benefit greatly from the pan-sharpened high spatial resolution imagery for soil property mapping. Our results show that multiple high and medium resolution images can be used to map soil properties suggesting the possibility of an improvement in the maps' update frequency. Additionally, the results should benefit the large agricultural community through the reduction of routine soil sampling cost and improved prediction accuracy.

1. Introduction

Rainfed agroecosystems occupy 80 million ha in arid, semi-arid, and sub-humid climate zones in India, constituting nearly 57% of the cultivated area (Srinivasarao et al., 2013b). Soil plays a pivotal role for grain output because it impacts crop growth, nutrient holding/leaching patterns, water requirements, and overall health of the soil-crop-hydrology continuum. Sustainable soil management can help reduce the risk of soil degradation and improve the food security status of indigenous farmers in poor rural smallholder farm settings in the long term. Digital Soil Mapping (DSM) is an update-to-date technique that can utilize remote sensing, geostatistics and data mining techniques to predict soil properties across various spatial and temporal scales (McBratney et al., 2003), and it has high potential to help smallholder farmers develop sustainable soil management schemes, and increase food security and soil security.

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Remote sensing images allow derivation of biophysical properties relevant for crop growth and soil conditions at different scales covering large regions (Marshall and Thenkabail, 2015; Wang et al., 2016). Spectral indices derived from remote sensing images become an important source of environmental variables in digital soil mapping with limited data (McBratney et al., 2003). Due to the limitation of relatively low spatial resolution, some multispectral images are too coarse to identify ground features and provide spectral information required in fine scale geoscientific research. Some operating earth observation satellites such as Landsat 8, WorldView-3, and SPOT have a panchromatic band that provides higher spatial resolution compared with multispectral bands. Image fusion, a classical remote sensing technique, is the combination of two or more images to form a new image using certain algorithm (Van and Pohl, 1994). It is aimed at improving spatial resolution, enhancing structural and textural details, and preserving the spectral reliability of the original multispectral data simultaneously (Zhang, 2010). Ehlers et al. (2010) classified the image fusion methods into three levels: pixel level, feature level, and decision level. Pixel level fusion methods, also called image pan-sharpening methods, are the most frequently used methods for multispectral image fusion (Ehlers et al., 2010; Zhang, 2010). According to Ehlers et al. (2010), pixel level fusion methods can also be divided into three classes. The first class is color-related methods such as the intensity-hue-saturation (IHS) method. The second class is band statistics methods such as the Gram–Schmidt (GS) method. The third class is based on arithmetic operations such as the Brovey method.

Soil prediction maps based on some multispectral indices are too coarse and cannot characterize the micro-variation of soil properties in small scale farmland. The spectral data from pan-sharpened images have the potential to be incorporated in DSM research in fine scale areas, such as smallholder farm settings. Few researchers have utilized image pan-sharpening technique in DSM research. Francés and Lubczynski (2011) utilized QuickBird and aerial orthophoto images to classify soil classes. Vaudour et al. (2013) concluded that pan-sharpened SPOT 5 image spectral has a higher prediction ability for topsoil carbon content than multispectral SPOT 4 image spectral using multiple linear regression bootstrap modeling. Many research also compared different image pan-sharpened methods and their performance. Jalan and Sokhi (2012) showed high-pass filtering (HPF), Gram–Schmidt (GS) and PANSHARP methods produced comparable pan-sharpening images with high spectral quality and spatial enhancement, while Brovey method produced the pan-sharpening images with spatial enhancement but highly distorted radiometry. Karathanassi et al. (2007) compared the 17 image pan-sharpening methods, local mean and variance matching (LMVM), least square fusion (LSF), and GS fusion methods have the highest performance in terms of peak signal-to-noise ratio (PSNR) and photointerpretation results. However, there is no paper comparing the effects of different pan-sharpened spectral indices on soil prediction models. The relationship between soil properties and spectral indices from pan-sharpened (PAN) images, and the effects of spectral indices from PAN images on soil prediction models have rarely been explored before.

Soil nitrogen depletion (Chander et al., 2014; Sahrawat et al., 2010), and soil potassium depletion (Bhattacharyya et al., 2006; Srinivasarao et al., 2013a) constrain the enhancing grain production in smallholder farms in South India. There is few DSM research incorporating environmental variables such as spectral indices to characterize soil nutrients in South India. To analyze the effects of image pan-sharpening on DSM, this research 1) fused the panchromatic band and multispectral bands of WorldView-2, GeoEye-1, and Landsat 8 images using Brovey, Gram-Schmidt (GS), and Intensity-Hue-Saturation (IHS) methods; 2) analyzed the relationships between soil properties (total nitrogen (TN) and exchangeable potassium (K_{ex})) and various PAN and MS remote sensing spectral indices; and 3) assessed the effects of the incorporation of selected PAN spectral indices on soil prediction models.

2. Materials and methods

2.1. Study area description

Kothapally (latitude 17°20′ to 17°24′N and longitude 78°5′ to 78°8′E, elevation 600–640 m) is a smallholder village located in Ranga Reddy District, Telangana State of India. It is nearly 40 km from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Center, and 74 km distance from the city of Hyderabad. The village of Kothapally is characterized by an undulating topography with an average slope of 2.5%. The Vertisols and associated soils make up 90% of the area. The annual rainfall is 802 mm (1999–2008) and soil depth ranges from 30 to 120 cm (Sreedevi et al., 2004). In the rainy season, the main cropping systems are cotton (*Gossypium hirsutum*) and rice (*Oryza sativa*). In the dry season, sorghum (*Sorghum bicolar*) is the predominant crop type. Major crop rotation is cotton-sorghum and cotton-tomato in the rainy-dry season. According to Sreedevi et al. (2004), there are 274 households composed of 1493 people in the village, and the average landholding per household is 1.4 ha. Smallholder farmers in the village utilized ground water to irrigate the crops (Sreedevi et al., 2004). The application of chemical fertilizers, pesticides and other agricultural input is not common in the village due to the limited financial resources of smallholder farmers (Wani et al., 2003).

2.2. Field sampling and laboratory analysis

A total of 255 soil samples at 0–15 cm in Kothapally were collected by ICRISAT and University of Florida Team in May 2012 (Fig. 1). Site-specific descriptions, including landform, crop types, and soil color, as well as x and y coordinates, were recorded at each sampling point. Each soil sampling location was measured by a Differential Global Positioning System (DGPS) with sub-meter accuracy (Trimble Navigation Ltd., Sunnyvale, California, USA). GPS post-correction was performed by Aimil Ltd. (www.aimil.com) located in Hyderabad, India. After being air-dried for one week, the soil samples from the study area were then sieved using a 2-mm sieve before being stored in plastic bags for future analysis. All the soil samples were analyzed by ICRISAT, for soil total nitrogen (TN) (Krom, 1980), and exchangeable potassium (K_{ex}) (Thomas, 1982). Results for soil TN and K_{ex} were reported on a concentration basis (mg kg^{-1}).

2.3. Remote sensing data

Two MS Landsat 8 images, one WorldView-2 image, one GeoEye-1 image in Kothapally were collected (Table 1). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) from the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov) was also collected. Those images were all collected from dry season. Multiple spectral indices were extracted from those remote sensing images.

2.4. Image pan-sharpening

This research fused the panchromatic band and multispectral bands of WorldView-2, GeoEye-1, and Landsat 8 in Kothapally. Three major image pan-sharpening techniques including Brovey methods (Tu et al., 2001), intensity-hue-saturation (IHS) (Kalpoma and Kudoh, 2007), and Gram–Schmidt (GS) (Laben and