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Scoping for scale-dependent relationships between proximal gamma radiometrics and soil properties

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ABSTRACT

Soil varies from location to location as a result of complex combinations of soil forming factors and processes operating at different scales and intensities. The scale-dependent variability in soil properties causes challenges for the characterization and mapping of soils. With the advent of technologies, proximal sensors such as gamma radiometrics can characterize soil spatial variability and the digital mapping of soil properties. In this study we aim to characterize scale-dependent variability of proximal gamma radiometrics and its complex relationship with soil properties at different scales using wavelet transform and wavelet coherency. We measured gamma radiometrics (γ-ray potassium (^{40}K), uranium (^{238}U), thorium (^{232}Th) and Total Count (γ-TC)) using a hand-held device in the field every 25 m along a 3.0 km transect. At each point we measured elevation (m) and land use and collected soil samples to determine key soil properties (electrical conductivity $EC_{1:5}$, pH ($CaCl_2$), soil organic carbon (SOC), cation exchange capacity (CEC), exchangeable potassium (exch. K), and Colwell P). Wavelet spectra identified significant ($P < 0.05$) variations at different scales and locations for both γ-ray and soil properties. There were significant localized variations with changes in elevation and land use also important. In most cases a 'global' Pearson correlation between the γ-ray and soil properties was not significant. In contrast, wavelet coherency provided a more powerful scale- and location-specific relationship between γ-ray, elevation and land use with selected soil properties. For example, a strong correlation (18% of the area was significant) was detected between land use and soil $EC_{1:5}$ at all scales (<100–800 m) in a low drainage depression. This correlation was due to the localized mobilization of salts and has implications for the identification of saline land. At large spatial scales (>800 m) there was significant positive correlations between γ-TC and SOC (36% by area). At medium scales (~400 m) there was significant and positive correlations between ^{40}K and CEC (23% by area), but only along the first half of the transect which was underlain with Bushy Creek Granodiorite. These findings provide an improved understanding of the spatial variability of γ-ray-soil relationships. The approach used shows the scope and significant potential to use wavelet analysis of gamma-soil property relationships that are scale-specific and would be useful for digital soil mapping. Moreover, scale-specific spatial information of soil properties aids understanding of soil formation processes and it illustrates an approach to improve future soil sampling strategies.

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1. Introduction

Soil spatial variability is ubiquitous and occurs at a range of scales. Understanding the nature and scale of this variation is important as it has implications in both managed and natural ecosystems (Biswas and Si, 2009). In the soil science context and considering the dynamics of agricultural or environmental processes, the understanding of soil variation has been attempted to better map the soil continuum. Consequently, there has been increased use and confidence with new methods capable of modelling, mapping and understanding the spatial variation of soil at the field, farm and catenary scale (Lin et al., 2005). However, the cost of sampling and laboratory analysis prohibits the use of dense sampling grids. This is because various soil properties need to be mapped. For example, with regard to soil chemical properties, salinity needs to be understood to manage constraints in tolerance to high salt concentration (Triantafilis et al., 2004). In terms of understanding the availability of nutrients soil pH needs to be measured (White, 2006). With respect to physical properties knowledge of soil the cation exchange capacity is useful as it is indicative of soil resilience

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or its shrink and swell capacity (Kabala et al., 2015). Furthermore, there is recent evidence that the variability of soil-plant relationships can be mapped (Verboom and Pate, 2015).

To enable an increased number of soil properties to be measured (with greater spatial coverage), various remote and proximal sensing methods have emerged, including; infrared spectral imaging, electromagnetic (EM) induction and electrical resistivity (Viscarra Rossel et al., 2011). One data set that is increasing in popularity in Australia is gamma ray (γ-ray) spectrometry. This is because it can detect natural radioactive emissions of γ-rays from the decay of potassium (K, %), uranium (U, ppm) and thorium (Th, ppm) from soil and rocks (Minty, 1997). Because 90% of γ-rays (Gregory and Horwood, 1961) can penetrate through 0.30–0.4 m of rocks and soil (Jaques et al., 1997) and can travel up to 100 m in air, data can be collected remotely using airborne platforms or proximally using small instruments. As such γ-ray data is available across the Australian continent and can be mapped at smaller scales.

Initially γ-ray data were collected to aid uranium exploration (Wilford and Minty, 2006). Increasingly it has found application in understanding the distribution of minerals and geochemistry and to aid geological interpretation for the location of mineral deposits (Dickson and Scott, 1997). More recently, γ-ray data has been used in pattern recognition of geomorphic units, including; Aeolian sediments (Cattle et al., 2003), ancient shorelines (Paine et al., 2004) and terraced fans (Triantafilis et al., 2013) as well as being used to develop a soil weathering index (Wilford, 2012). Over the last decade there have been an ever increasing number of studies which have reported on the correlation between γ-ray data with measured soil properties. This includes: Dierke and Werban (2012) who found negative correlations between pH, soil organic carbon and exchangeable K with Th but only for values of pH < 7, and Petersen et al. (2012) who found only moderate relationships for clay and CEC. Furthermore, success has been achieved by using γ-ray data with electromagnetic induction data to identify soil management zones at the field scale (Huang et al., 2014) or to map individual soil properties such as texture (Buchanan et al., 2012) or available water (Gooley et al., 2014).

To better understand the relationship between individual soil properties and γ-ray data, which may operate across geological units or as a function of topography, the spatial variability of these data need to be better understood. One spatial approach is to conduct wavelet analysis (Biswas and Si, 2011). For example, Lark (2005) used wavelets to account for the systematic variation in micro relief and electrical conductivity across a gilgai landscape at the field scale. In contrast, at a larger scale Zhou et al. (2016) investigated the dominant scale-specific controls of soil organic matter using the wavelet transform at the landscape scale in Northeast China and the North China Plain. These studies illustrate the value of wavelet analysis to reveal scale-dependent features as well as the spatial extent (and localized nature) of significantly correlating variables.

The overall aim of the study was to improve understanding on the nature of the spatial relationship and its scale dependency between field-measured proximal gamma radiometrics (^{40}K, ^{238}U, ^{232}Th and Total Count), elevation and land use with key soil properties (salinity ($EC_{1:5}$), pH ($CaCl_2$), soil organic carbon (SOC - %), cation exchange capacity (CEC - cmol(+)kg), exchangeable potassium (Exch. K - cmol(+)kg) and Colwell P (mg kg^{-1})). More specifically, we wanted 1) to characterize and quantify the scale- and location-specific variability in field measured gamma radiometrics, elevation and land use and soil properties and 2) to quantify the relationship between these properties at different scales and locations. Measurements were taken along a 3 km transect and a wavelet transform used to quantify variability at different scales and locations and wavelet coherency used to quantify relationship between gamma radiometrics, elevation and land use with soil properties at different scales and locations.

2. Material and methods

2.1. Study area

The study area is located at ~80 km north of Warrnambool in south-western Victoria, (37.769° S; 142.606° E) Australia (Fig. 1) and is within the Glenelg Hopkins catchment, which covers the Western Uplands according to the Victorian Geomorphological Framework (Victoria gov, 2016). The study transect is in an undulating tableland with moderate relief (~90 m) and high drainage density. There are two geological parent material units along the transect. The western half is underlain by the Bushy Creek Granodiorite, which is a gray porphyritic hornblende type. The eastern half consists of Glenthompson Sandstone, which is characterized by fine to medium-grained metaquartz, minor siltstone and flysch deposits (1:250,000 map Geological Survey of Victoria) (VandenBerg, 1997). Both geological units are from the Palaeozoic (Cambrian) era. In addition and probably of greater importance for this study, the area includes Pliocene sediments (Tertiary) which have been deposited from continental, paralic and marine origins (Baxter and Robinson, 2001). Indeed, Paine et al. (2004) highlight the geological and geomorphological complexity of the region with their identification of ancient shorelines. This area includes a range of different geologies including granite, basalt, metasediments and Permian glacial deposits and the tableland landscape unit where this study is located is highly dissected and characterized by deep lateritic weathering (VRO, 2016).

A soil and land resource survey of this area (Maher and Martin, 1987) stated that the dominant soils have a duplex profile and have weakly developed hardsetting or soft surface horizons over clay subsoils. The typical features of these soils include an A1 horizon that is a fine sandy loam of 20 cm depth (with a range from 5 to 30 cm) which is usually above a bleached layer (A2) with variable coarse gravel content. The subsoil is medium or heavy yellow clay with mottles and the depth is mostly >1 m, except in steeply sloping parts of the landscape. The dominant soil across the studied transect is an Abruptic Albic Luvisol (IUSS Working Group WRB, 2014). The landscape is characterized by agricultural land uses that comprise a mixture between

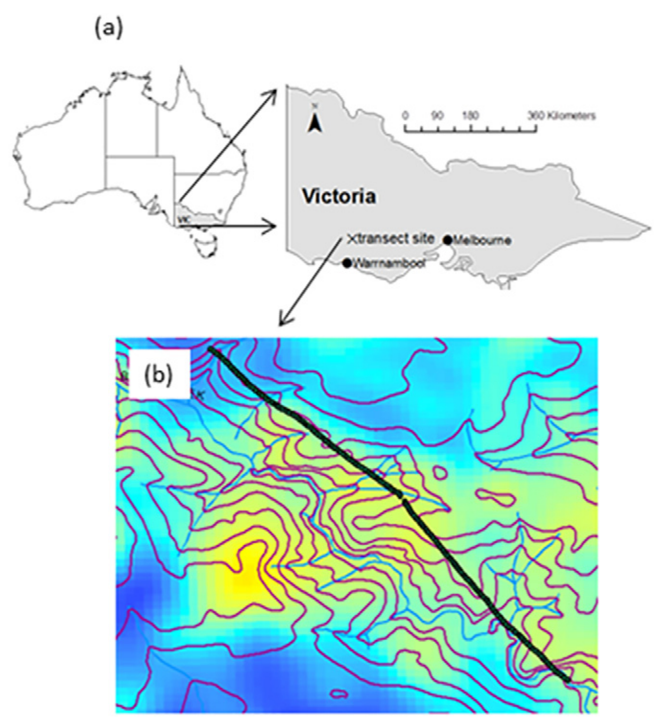

Fig. 1. Location of study area in south-western Victoria, Australia (a) and the location of the sampling points along the transect with the background colour showing the airborne gamma radiometric element potassium (b).

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