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Understanding the utility of aerial gamma radiometrics for mapping soil properties through proximal gamma surveys

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ABSTRACT

Historical aerial gamma radiometrics have been proposed to be an important covariate for characterizing soil properties because it provides information about soil parent material. Pre-existing aerial gamma radiometrics within the United States, however, can exhibit coarse spatial resolutions and therefore may be unhelpful for soil mapping studies. Therefore, the objective of this work was to test the hypothesis that aerial gamma radiometrics can reliably map soil properties. The hypothesis was tested using proximal radiometrics and soil sampling. Proximal or ground surveys were conducted within four different heterogeneous landscapes, and 112 soil samples were collected and characterized for texture (i.e. particle size fractions) and/or calcium carbonate equivalent. Proximal and soil relationships were assessed in terms of significance using Pearson correlation coefficient testing and stepwise backwards linear regression. Proximal data were then weighted and averaged within the aerial sensor field of view and subsequently tested for significance with historical aerial data using Pearson correlation tests. Proximal and aerial sensors were then compared in their ability to predict nearby measurements of clay and sand content. Relationships between texture and proximal gamma measurements were significant ($p < 0.01$) when variability in clay content was present, while calcium carbonate equivalent and proximal gamma signatures were significantly correlated when clay content variability was low. Relationships between proximal and aerial measurements were only meaningful when the latter were adequately located in geographic space. When aerial spatial positions were corrected, they significantly explained about half as much of clay and sand content variability relative to proximal gamma measurements. Therefore, aerial gamma information has value in characterizing soil spatial variability, but attention should first be given to the data quality of these historical surveys.

1. Introduction

Aerial gamma radiometrics (AGR) is an environmental covariate that has been proposed to assist in characterizing soil variability not only at the local (meter) scale but also at the regional (1000 to 10,000 km) scale because such information represents the state of the parent material in terms of its weathering intensity (Stockmann et al., 2015). Thus, AGR have a potential advantage over stationary soil sensors such as XRF and vis-NIR spectroscopy and mobile sensors such as electromagnetic induction that are relatively limited in spatial extent (Viscarra-Rossel et al., 2011; Söderström et al., 2016). In AGR, a spectrometer located at relatively high altitudes (usually 120 m) detects passively gamma radiation emitted within the soil (usually up to 30 cm depth) (Minty, 1997; Duval et al., 2005). These measurements can occur across the entire spectrum (0.4–3.0 MeV), in regions of interest (ROIs) such as potassium (^{40}K), uranium (^{238}eU), thorium (^{232}eTh) and dose rate (International Atomic Energy Agency, 2003). AGR has been applied toward geomorphology (Pickup and Marks, 2000), ecosystem (Verboom and Pate, 2015), environmental contamination (Sanderson et al., 2008) and soil mapping studies (Rawlins et al., 2009; Odgers et al., 2014; Kidd et al., 2015), mainly within Europe and Australia.

Within the United States, conterminous AGR are available in the form of archival line data and interpolated raster surfaces (Duval, 1990), but few studies have addressed the applicability of these products for predicting soil properties. Rouze et al. (in press) recently related 2-km cell interpolated AGR data with several physical and chemical soil properties. In their results, they found generally significant relationships with texture (clay and sand particle size fractions) and cation-exchange capacity, but such relationships had low r-squared values (<0.30) because of coarse AGR spatial resolution and sampling design issues.

Abbreviations: AGR, aerial gamma radiometrics; PGR, proximal gamma radiometrics; CCE, calcium carbonate equivalent; FOV, field of view.

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Therefore, it would beneficial to determine whether AGR can be used as a covariate for predicting soil properties, assuming an improved survey strategy. Previous literature has suggested that relationships between AGR and soil properties are only comparable if both sets of information have similar measurement support volumes (Ryan et al., 2000). However, aerial gamma measurements have been shown to exhibit a measurement support volume or field-of-view (FOV) greater than that of soil sample measurements (Pracilio et al., 2003). Previous methods have therefore sought to compare AGR and soil properties by either collecting a representative amount of soil samples within the FOV or by collecting ground gamma measurements on foot, but such methods are inefficient, particularly where gamma information is needed across large areas (Tyler et al., 1996; Kock and Samuelsson, 2011).

Fortunately, a more practical method that can be used to assess United States AGR can be obtained by using a mobile vehicle to collect continuous gamma radiometric measurements closer to the ground, termed proximal gamma radiometrics (PGR). This is because PGR has a much finer spatial resolution of measurement than AGR and allows for greater spatial coverage than ground sampling techniques (International Atomic Energy Agency, 2003). Literature has indicated that relationships between PGR and soil properties are both significant and meaningful. For example, Viscarra Rossel et al. (2007) used PGR in Australia to map surficial clay content as well as other soil properties associated with soil clay content such as nutrients (K, Fe), pH, and salinity from two different sites (i.e. residual and alluvial parent materials). When compared to measured clay contents of the soil surface, adjusted R^2 values within residuum and alluvial soils were 0.76 and 0.63, respectively (Viscarra Rossel et al., 2007). Most recently, Coulouma et al. (2016) found that PGR (in particular ^{232}eTh) can significantly predict clay content within Mediterranean landscapes ($R^2 = 0.72$, RMSE = 35 g kg^{-1}). PGR has also been found to significantly relate with other soil properties such as cation-exchange capacity, calcium carbonate, and pH (Taylor et al., 2010; Mahmood et al., 2013; Priori et al., 2013; Rodrigues et al., 2015). Clay content has received the most attention within soil modeling literature because nuclide concentration and particle size are negatively correlated (Megumi and Mamuro, 1977).

Collectively, these investigations suggest that AGR also have the potential to map soil properties, but only to the extent that such capabilities exist for PGR. Thus, it is important that PGR be utilized effectively in modeling soil properties. In developing these calibrations, care should be given toward choosing variables that best represent the gamma spectrum, as there have been conflicting reports regarding whether the entire spectrum (total counts or TC, counts s^{-1} or cps) or ROIs should be used (Viscarra Rossel et al., 2007; Mahmood et al., 2013).

The overall goal of this article is to improve our understanding of historical United States AGR surveys by conducting proximal gamma radiometric surveys underneath pre-existing aerial gamma radiometric point data. We hypothesize that AGR are more strongly related to soil properties than was shown by Rouze et al. (in press) by comparing AGR with proximal surveys. To test these hypotheses, three specific objectives are addressed. First, strength of relationships between laboratory-measured soil properties and proximal gamma-ray spectral data (e.g. ^{40}K, ^{238}eU, ^{232}eTh, dose rate, total counts) are assessed using Pearson correlation coefficients and multiple linear regression modeling. The second objective of this study is to compare the measurements between proximal and aerial surveys within these sites by comparing their spatial patterns in terms of visual analysis and correlations. The third objective of this study is to quantify the loss of information in predicting clay content between proximal and aerial survey measurements.

2. Materials and methods

2.1. Site descriptions

Four sites in three distinct landscapes were chosen for PGR surveys within Texas, USA and are shown visually in Fig. 1. Site A (30°39′59″N, −96°32′45″W in Bryan, TX) has an area of approximately 895 ha and contains soil forming over nearly level floodplains, with an elevation ranging from 74 to 77 m above sea level and zero % slopes (Fig. 1a). The soil is relatively young due to recent Quaternary sediment deposition by fluvial processes actively taking place within the last 2000 years, with clayey sediments deposited furthest from the river and silty sediments nearest the channel (Soil Conservation Service, 2002). The source sediments within these fluvial streams are predominantly eolian in origin (Soil Conservation Service, 2002). The land is used for croplands (cotton/corn rotation), and soils are classified as Inceptisols and Vertisols with mixed mineralogy types (Soil Conservation Service, 2002). Surface texture classes are silt loam, silty clay loam and clay. The average annual precipitation is 990 mm.

Site B (30°29′7″N, −96°50′59″W near Caldwell, TX) is located about 64 km southwest of Site A across an area of approximately 156 ha. Soils at Site B formed on uplands over discrete and interbedded shale and sandstone residuum, with an elevation ranging from 120 to 140 m above sea level and highest at the center of Fig. 1b, with slopes ranging between 1 and 12% (Soil Conservation Service, 2005). The bedrock materials were initially deposited in shallow marine environments around the Eocene Epoch when an ancient sea transgressed the Texas land mass – this geological interpretation was supported by the presence of local glauconite, an iron potassium phyllosilicate mineral located within sand-sized particle fractions (Soil Conservation Service, 2005; Harding et al., 2014). The land used for grazing and soils are classified as Alfisols and Vertisols with siliceous, smectitic and glauconite mineralogy types (Soil Conservation Service, 2005). Surface texture classes are loam, clay, sandy clay loam, fine sandy loam and loamy fine sand. The average annual precipitation is 970 mm.

Site C is located about 121 km northwest of Site A and consists of two sub-regions, termed C1 and C2, located under the same aerial transect line (Fig. 1). Site C1 (31°27′36″N, −96°52′50″W in Riesel, TX) is approximately 184 ha and contains soil formed on uplands consisting of marl residuum (159–174 m elevation and 1–5% slopes, Fig. 1c). Site C2 (31°27′50″N, −96°49′58″W) is located about 3.5 km east of Site C1 with an area of approximately 507 ha and also contains upland marl residuum as well as old alluvium landforms (138–150 m elevation with 1–3% slopes, Fig. 1d). The land use at C1 is grazing land and soils are primarily Vertisols. Site C2 land use is cropland (corn) and soils are mainly smectitic Vertisols, but Alfisols are also present to a lesser extent. The parent materials within Site C were deposited during the Cretaceous period that have since undergone erosional down cutting to form stream terraces, e.g. within Site C2 (Soil Conservation Service, 2003) (Fig. 1d). Surface texture classes at Site C1 are clay and silty clay, while Site C2 additionally has silty clay loam within the old alluvium (Fig. 1). The annual precipitation across Site C is 850 mm.

2.2. Aerial surveys

Pre-existing or historical AGR surveys are available in the form of archival point data within each of the previously described sites (Fig. 1). All sites were carried out in accordance with the National Uranium Resource Evaluation program as implemented by the USGS (Hill et al., 2009). Note that only one transect line was used at each site due to the large distance (about 5 km) between adjacent aerial survey transect lines. Aerial points were selected for this study because the gridded product and its coarse pixel resolution (2 km) resulted in too few cells for analysis.

Sites A and B were surveyed on April 20 and 21, 1977, respectively, using a Douglas DC-3 aircraft (Geodata International Inc., 1979). The survey for Sites A and B used nine NaI (Sodium Iodide) scintillation crystals, with eight of those crystals (61.3 dm^3) looking downward (4π steradian solid angle) and one crystal (6.8 dm^3) directed upward (2π steradian solid angle). The average along-line distances for Sites A and B are 65 and 63 m, respectively and the average