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

Rouze, G.S.^{1*}, Morgan, C.L.S.¹, McBratney, A.B.²

¹ Department of Soil and Crop Sciences, Texas A&M University, College Station, TX 77843-2474, United States

² Soil Security Laboratory, Department of Environmental Sciences, Faculty of Agriculture and Environment, The University of Sydney, Suite 401, Biomedical Building C81, 1 Central Avenue, ATP, Eveleigh, NSW, Australia

* Corresponding author: gregoryscottrouze@tamu.edu

Keywords

Aerial gamma radiometrics; proximal gamma radiometrics; particle size fractions; calcium carbonate equivalent; geo-positioning

Abbreviations:

AGR – aerial gamma radiometrics; PGR – proximal gamma radiometrics; CCE – calcium carbonate equivalent; FOV – field of view

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 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 are 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) are an environmental covariate that have been proposed to assist in characterizing soil variability not only at the local (meter) scale but also at the regional (1,000 to 10,000 kilometer) 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 limited in spatial extent such as electromagnetic induction (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) (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) or can be combined to create dose rate (International Atomic Energy Agency, 2003). AGR have been applied toward geomorphology (Pickup and Marks 2000), ecosystem (Verboom and Pate, 2015), environmental contamination studies (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 et al., 1990), but few studies have addressed the applicability of these products for predicting soil properties. Rouze et al. (in press) only 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 (less than 0.30) because of both coarse AGR spatial resolution and sampling design issues.

Therefore, it would be 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 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 U.S. 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}Th) can significantly predict clay content within Mediterranean landscapes ($R^2 = 0.72$, $\text{RMSE} = 35 \text{ g kg}^{-1}$). 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 Jr. 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 has 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 sec^{-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. (2017) by comparing AGR to 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) using Pearson correlation coefficients and multiple linear regression modelling. 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 was 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 Figure 1. Site A ($30^{\circ}39'59''\text{N}$, $-96^{\circ}32'45''\text{W}$ 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 meters 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 near 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, according to USDA soil taxonomy with mixed mineralogy types. Surface texture classes are silt loam, silty clay loam and clay. The average annual precipitation is 990 mm.

Site B ($30^{\circ}29'7''\text{N}$, $-96^{\circ}50'59''\text{W}$ 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 Figure 1b, with slopes ranging between 1 to 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 (Triplehorn, 1965; Soil Conservation Service, 2005). The land used for grazing and soils are classified as Alfisols and Vertisols with siliceous, smectitic and/or glauconite mineralogy types. 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 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 altitudes are 131 and 124 meters, respectively. Site C surveys were conducted on October 12, 1979 using a Beechcraft Queen Air aircraft (EG&G Geometrics, 1980). The survey used 50.3 and 8.4 dm^3 of NaI scintillation crystals for downward and upward looking directions, respectively. The average along-line distance in the study area was 68 m, and the average altitude was 114 m while traveling about 225 km hr^{-1} .

Spectral information from both contractors was collected by a pulse height analyzer every second and subsequently stored onto magnetic tape. The data were then

corrected for atmospheric radiation and altitude effects and converted to concentrations using experimentally determined sensitivity coefficients (Geodata International Inc., 1979). Positional information during these legacy aerial surveys was not collected using modern GPS. For Sites A and B, positional information was determined relative to a base point and heading using a combination of radar altimeter and a Doppler navigation system using dead-reckoning, which determines position based on velocity measurements (Kayton and Fried, 1997). These positions were then verified by selecting identifiable features on the ground (roads, rivers etc.). Within Site C, Doppler radar was not used and flight position was only determined by correlating landmark features from an intervalometer camera with associated features on topographic quadrangle maps. For both sites, these pick-points were used as inputs to recover all other points during post-processing and then subsequently coupled with spectral information (Geodata International Inc., 1979). Additional discussion regarding flying operations during this time period is provided by Bullock (1979).

Because modern style GPS navigation was absent in these surveys, the presence of potential navigational errors was assessed, as positional errors on the order of 50 to 500 meters have been reported (Luyendyk, 1997). Positional certainty within these surveys was obtained from surficial geology codes against an independent geology map - this inspection revealed that gamma points located in Site A were in error because several points within Site A were labeled as old alluvium deposits, but prior knowledge indicated that young alluvial deposits were present (Fig. 1a). A positional error was also present at Site B, although its effects were less apparent because these soils, in contrast, did not form under sharply contrasting landforms e.g. young/old alluvium (Fig.

1). In both cases, the amount of positional offset was determined by the amount needed to match geology codes, as well as nearby environmental features and their expected radiometric signatures. For example, Site A transect was shifted approximately twenty points or 1300 m east based on a nearby terrace landform with sandier (i.e. lower gamma signature) surface soils than that from our site (Fig. 1). A shift of approximately seven points, or 440 m east, was applied to site B based on the presence of forested areas attenuating gamma rays (Wetterlind et al., 2012).

2.3. Proximal surveys

Pre-existing AGR surveys were complemented with local PGR surveys using a 4 dm³ volume sodium iodide (NaI) gamma-ray spectrometer (Radiation Solutions Inc., Mississauga, Ontario, Canada). These ground sites were conducted between spring and summer of 2014, particularly when the crops (i.e. Sites A & C2) were not planted. The radiometric survey data was collected using a field vehicle, with the sensor located at a height of approximately 55 cm above the ground, giving a field of view with a radius of about 3 m (Killeen, 1979). During a survey, the spectrometer collected and stored energies between 0.4 to 3.0 MeV every second along with geo-positional information from a Wide Area Augmentation System-enabled GPS unit. The distance between individual transect lines was not constant for all sites due to the varying land-use types, varying from 20 m (Site A) to 230 m (Site C2) (Fig. 1). The vehicle speed across all sites was approximately 4.5 m s⁻¹.

2.4. Soil sampling and laboratory analysis

Proximal surveys were followed by the collection of 32, 37, 24, and 19 soil samples at sites A, B, C1 and C2, respectively. Soil samples were also collected at each site

under a specified sampling design. For example, soil sampling for Sites A and C1 were stratified using topography and aerial imagery. For Sites B and C2, the raw proximal gamma survey data was stratified for sampling. At each sampling point, soils were obtained by hand-auguring to a depth of 15 cm and bulked with four samples, each spaced 1 m apart. Proximal surveys at sites A, B, C1 and C2 were performed under relatively dry conditions. However, gravimetric water content measurements were collected from a Theta Probe (Delta-T Devices, Inc.) to ensure gamma-rays were not significantly attenuated by the presence of soil moisture, as such effects have been noted within literature (Beamish, 2013).

Soil samples were air dried to 60° C for 48 hours and ground to pass through a 2-mm sieve. Soil particle-size distribution for all samples was measured using the pipette method and wet-sieving the sand-sized fractions (Gee and Or, 2002). Inorganic carbon was only measured at Sites C1 and C2, as soils at Sites A and B were non-calcareous. Inorganic carbon was measured using a modified-pressure calcimeter method from Sherrod et al (2002). Inorganic carbon mass concentrations (g kg^{-1}) were then converted into calcium carbonate equivalent (CCE) concentrations (g kg^{-1}) by dividing inorganic carbon concentrations by the molecular weight fraction of carbon.

2.5. Data management and statistical analysis

The laboratory data and both AGR and PGR datasets were analyzed within the statistical program R (R Development Core Team, 2015). Concentrations of ^{40}K (%), 1.37-1.57 MeV), ^{238}eU (1.66-1.86 MeV) and ^{232}eTh (2.41-2.81 MeV, both in ppm) from AGR and PGR systems were then expressed as SI Units of radioactivity (Bq kg^{-1}) using the constants defined by International Atomic Energy Agency (2003). Estimates of

uranium and thorium radioactivity are assumed to be in equilibrium with the environment and hence are labeled as ^{238}eU and ^{232}eTh (Minty, 1997). In addition to the radioelements, dose rate (dose rate = $13.2 \cdot [^{40}\text{K}] + 5.48 \cdot [^{238}\text{eU}] + 2.72 \cdot [^{232}\text{eTh}]$) and total counts (0.4-3.0 MeV, counts sec^{-1}) were retrieved from both AGR and PGR systems to assess the value of enhanced gamma spectral resolution for modeling soil properties (Duval et al., 2005).

In accordance with other studies (Viscarra-Rossel et al., 2007; Mahmood et al., 2013), we observed that PGR measurements were noisy. Therefore, the raw proximal datasets were smoothed in time using a central spatial moving average of five measurements as determined by the largest apparent reduction in variance (Viscarra-Rossel et al., 2014). Additionally, proximal values outside of two standard deviations of the five-point averaged data were removed, as these readings were associated with background levels of radiation from local roads and/or water bodies. Temporally averaged PGR measurements were then interpolated onto a five-meter grid for Sites A, B and C1 and a twenty-meter grid for Site C2 using ordinary block kriging using the gstat R package (Pebesma, 2004).

To facilitate statistical modeling, each soil sample was spatially joined with a given interpolated PGR cell. The two datasets were then compared by calculating Pearson correlation coefficients and testing for significance ($p\text{-value} < 0.01$) within each site. A correction for the potential effect of soil moisture on gamma spectral measurements was applied according to Loijens (1980) based on local Theta Probe measurements, and Pearson correlation coefficients reassessed. A moisture correction did not

significantly affect the magnitude of these coefficients, and all subsequent statistical analysis was based on non-moisture corrected PGR measurements.

2.6. Statistical analysis

Statistical models were then created with respect to the individual sites, whereby stepwise backward elimination regression models were fit between multiple soil properties (clay/sand/silt contents, CCE) and PGR variables (ROIs, dose rate/total counts). Before modeling began, however, PGR variables were removed contingent on a variance inflation factor greater than or equal to five. Individual predictors of the ROI model were then eliminated if they were statistically insignificant ($p\text{-value} \geq 0.01$). The best model that resulted from any combination of these radioelements was then compared with that from similarly derived dose rate/total counts models to identify the best PGR predictor of soil properties. The suitability of the MLR and dose rate/total counts models was then assessed by investigating residual plots for homoscedasticity as well as simulating 100 spatial correlograms for residual spatial autocorrelation – this criterion ($p < 0.05$) was met about 85 to 95 % of the time. Predictors and the predictands were transformed using the maximum likelihood method of Box and Cox (1964) if residual plots revealed heteroscedasticity. These models were then validated by applying the models on an independent dataset using leave one-out cross-validation. For models within and across sites, goodness-of-fit metrics, such as the coefficient of determination (R^2), root-mean squared error (RMSE) and bias (both in g kg^{-1}) were used.

2.7. Comparison between PGR and AGR

Raw, temporally averaged PGR measurements were compared against AGR in terms of the ROIs (^{40}K , ^{238}eU and ^{232}eTh), dose rate and total counts at each site through a weighted footprint analysis. At each aerial measurement (large points in Fig. 1), an ellipsoidal geometry of axial dimensions 268 m by 378 m was created in the across-track and along-track directions, respectively. The geometry and its dimensions were selected to represent the approximate field of view (FOV) of a moving detector at the approximate altitude (120 m) of these AGR surveys (Pitkin and Duval, 1980). Within each FOV, all spatially averaged proximal measurements located were averaged using an inverse-distance weighting method with respect to the ellipsoid centers (Kock and Samuelsson, 2011). AGR points that did not lie within the PGR sampling area were removed within Site A because these points were located over non-soil features such as roads and trees. Original aerial measurements and area-weighted proximal measurements were then compared using Pearson correlation coefficients within each site.

AGR and PGR were also compared with each other in terms of their ability to model clay and sand content based on differing measurement support volumes. To do this, a subset of the shifted AGR point measurements was selected on the condition that a collected soil sample lie within the AGR FOV – this procedure resulted in 35 soil samples coupled with nearby AGR samples and spatially joined PGR measurements. In terms of distribution, 17 samples were from Site A, 12 from Site B and 6 from Site C2. These selected AGR points were then compared with interpolated PGR and non-shifted AGR measurements in their ability to predict clay and sand content across all sites.

3. Results and Discussion

3.1. Soil data

The results from soil laboratory analyses by each site are summarized in Table 1. The textural analysis confirms that Site A is predominantly silty and clayey (with means of 452/365 g kg⁻¹ silt and clay, respectively), while Site B is more sandy (means of 584 g kg⁻¹) and Sites C1 and C2 more clayey (means of 488/424 g kg⁻¹ clay, respectively) (Table 1). Site C2 shows larger variability in clay content (CV = 0.24) than Site C1 (CV = 0.08) because soil is formed from old alluvium with alluvial deposition patterns and conditions for lessivage. Unlike Sites A, B and C2, Site C1 showed the highest variability in CCE (CV = 0.36, Table 1).

3.2. Aerial and proximal surveys

Figure 1 shows the spatial variation of PGR and AGR relative to the various landform elements and are summarized further in Table 1. Figure 1a in particular shows the high frequency variability of PGR across a landscape of young alluvium. In the western half and close to the river (Fig. 1a, left), the PGR shows the greatest variability, oscillating between small-intermediate (1987-2171 cps) to intermediate-large (2371-2577 cps) values. The AGR shows similar oscillations, although there is visual discrepancy between high AGR (1877-2035 cps) and intermediate PGR (2371-2577 cps) left-central portion of the study area (Fig. 1a). In the eastern half and near old alluvium, the variability is much smaller, but the values are generally larger for both PGR (2578-4032 cps) and AGR datasets (1894-2138 cps). On average, there is greater radioactivity from PGR than AGR not only within Site A but across all sites as well (Table 1).

Figure 1b shows the variation of both PGR and AGR from a more varied landscape with varying parent materials such as quartz sandstone, shale and glauconitic sandstone. By comparison, these bedrock materials have a more extensive weathering history as reflected in both PGR and AGR signatures. For example, there was a higher amount of PGR/AGR ^{40}K variability within Site B (CV = 0.50) than Site A (CV range: 0.19–0.21) (Table 1). Site B has a higher CV value for ^{40}K relative to Site A most likely because ^{40}K decreases with increasing weathering and becomes soluble within the soil profile (Wilford, 2012). ^{40}K losses within Site B were evident, as mean PGR- ^{40}K radioactivity values were much lower within Site B (969 Bq kg $^{-1}$) than Site A (2230 Bq kg $^{-1}$) (Table 1).

In addition to within-profile mechanisms, gamma radiometrics was able to identify above-ground processes as well. For example, PGR spatial patterns within Site B presented an anomaly of high radioactivity in an area of otherwise low radioactivity (Fig. 1b, arrow). This response is most likely due to erosion of sandy A and E horizons from local stream entrenchment, leaving behind a clay-rich argillic horizon of high radioactivity (Soil Conservation Service, 2005). The relatively high slopes (6 to 12 %) derived from a digital elevation model in this area suggest that such a process is plausible.

Figure 1c and 1d show the relative uniformity of the two marl landscapes in terms of both PGR and AGR signatures. This was particularly evident at Site C1 where the PGR (<1986 cps) and AGR (<1421 cps) were for the most part small and in general exhibited little variability (Table 1). Although there is relatively lower mean radioactivity within Site C1 (1329 cps) than Site C2 (1497 cps), Site C1 has a larger mean clay content value

than Site C2 (Table 1). This suggests that radioelements within clay-sized particles are being diluted within Site C1, although its mechanism to this point has not been identified.

3.3. Soil property modeling

3.3.1. Particle size fractions

Table 2 shows Pearson correlation coefficients between PGR and soil particle size fractions, while Table 3 shows the stepwise regression model results for both clay/sand content and CCE. Figure 2 presents the results of Table 3 in plot form. We excluded silt content from stepwise modeling procedures because silt-PGR relationships were significant but inconsistent with regards to correlation direction and magnitude (Table 2). Silts are problematic in relationships with PGR because these particles usually contain a mixture of primary (low radioactivity) and secondary (high radioactivity) minerals (Buchanan et al., 2012). Additional data obtained from the National Cooperative Soil Characterization Database (available at <http://ncsslabsdatamart.sc.egov.usda.gov/>) confirmed the presence of mixed mineralogy types such as mica and montmorillonite, which contribute relatively higher and lower amounts of radiation, respectively (Bierwirth, 1996).

Clay content was positively correlated with PGR at Sites A, B and C2 because radioactivity is mainly sourced from secondary silicate clay minerals such as smectite, illite and kaolinite located within the clay-sized fractions (Bierwirth, 1996; Stahr et al., 2013). The mechanism behind this relationship has been previously established by Megumi and Mamuro (1977), who suggest that radioactivity is associated with particle size because radionuclide surface adsorption of is dependent on soil particle surface

area. Thus, clay content was not significantly related with any of the PGR variables at site C1 because clay content variability was relatively uniform (Table 1).

Sand content was significantly negatively correlated with PGR data within Sites A, B and C2 because sandy soils typically have greater proportions of quartz grains that are lower in radioactive nuclides (Wilford and Minty, 2006). Although correlations between sand and PGR relationships were similar if not greater than clay-PGR, these relationships were not always linear. For example, sand content was under predicted at Site A because soils with relatively high sand contents emitted less than expected radioactivity – this is because its source sediment (eolian silt/sand particles) can emit low ^{40}K (Wilford et al., 1997; Pickup and Marks, 2000). Sand content was well predicted within Sites B and C2 by the PGR, achieving RMSE values as low as 27 g kg^{-1} (Fig.2 and Table 3).

Relationships between soil particle size fractions and PGR were found to be influenced by the soil landscape. For example, strongest correlations occurred within sites A and C2 because these areas exhibited very little variability in topography (max $R^2 = 0.85$, Table 3). PGR within Site B and its more rugged topography were also significantly related with clay content, but correlation strengths were lower (max $R^2 = 0.61$) (Table 3). Correlation strengths were greatest within Site A because the alluvial landscape allows for radioelements to move within the soil, indicating that the PGR response is more likely to reflect soil forming processes. In contrast, correlation strengths were lower in Site B because erosion in the area (i.e. Fig. 1b, arrow) can transport surficial radioelements downslope, suggesting that PGR is more likely to represent initial parent material geochemistry (Wilford and Minty, 2006). The distinction

is subtle but important because it suggests that PGR responses are not only a function of the original parent material type but also its position on the landscape because this determines how well PGR reflects soil property variability (Wilford and Minty, 2007).

3.3.2. CCE

CCE model results are similarly shown in Tables 2-3 and Figure 3. Unlike Sites A, B and C2, PGR within Site C1 was responding to CCE variability (Tables 2 and 3). PGR relationships with CCE were established within Site C1 only because clay variation was initially absent (Clay CV = 0.08, Table 1). Regarding trend, CCE and PGR were negatively correlated because the presence of carbonates dilute overall gamma-ray signals due to their low amounts of radioactivity (Table 2) (Stahr et al., 2013). This observation was evident within the ^{232}eTh ROI channel, as it was the predominant radioelement responding to CCE variability ($\rho = -0.78$, Table 2). Unlike ^{40}K and ^{238}eU , ^{232}eTh is highly immobile during carbonate weathering (Rachkova et al., 2010; Wilford, 2012). In addition to ^{232}eTh , CCE was best predicted with total counts (validation $R^2 = 0.55$) compared to the ROI model ($R^2 = 0.33$), indicating that there is additional information within the gamma spectrum besides ^{232}eTh that contributes to CCE variability (Table 2). Future studies that aim to model CCE using PGR should consider identifying these useful portions of the gamma spectrum.

3.3.3. Comparisons between combined and individual ROIs

Table 3 compares the prediction results of the best ROI model (^{40}K , ^{238}eU , ^{232}eTh , dose rate) to results from a total counts model within each site. With respect to the PGR radioelements themselves, ^{40}K and ^{232}eTh were the most correlated with soil particle size fractions, while ^{238}eU was only useful for predicting sand and clay contents within

Site C2 (Tables 2 and 3). ^{238}eU was more poorly correlated with clay and sand content because it usually has a relatively low signal-to-noise ratio (Dickson, 1995). While our results agree with previous studies that ^{232}eTh is the better ROI predictor for modeling soil properties (Pracilio et al., 2006; Colouma et al., 2016), within our study areas additional information is provided by the ^{40}K signal.

Total counts relationships with soil properties were slightly greater than ROIs because less weight is given to ^{238}eU (Table 3). The ROI variable that was most similar to total counts was dose rate because it contains information from both ^{40}K and ^{232}eTh channels (Table 2). Total counts/soil relationships were most differentiated from ROI/soil relationships for clay/sand content within Site C2 as well as CCE within Site C1 (Table 3). Although the ROIs (except for Site B) were lower in prediction quality relative to total counts (Table 3), ROI information is nevertheless invaluable for interpreting PGR surveys in terms of landscape processes (Wilford, 2012).

3.4. Proximal and aerial gamma radiometric comparisons

Table 4 shows the Pearson correlations between AGR and PGR measurements, and Figures 4 to 6 show how they vary along their respective transect lines. The results from Table 4 confirm that measurements between both methods generally match well, particularly within Sites B and C2 (Figs. 5-6). Site A is an exception to this trend, however, as PGR measurements were much smoother between individual measurements (Fig. 4). AGR and PGR measurements within Site C1 were not significant, although previous results established that PGR Site C1 was associated with CCE (Tables 3-4). Areas such as Site C1 are problematic for AGR surveys because objects that emit low radioactivity are prone to high amounts of statistical noise

(International Atomic Energy Agency, 2003; Beamish, 2016). Thus, AGR as it stands can only map particle size fractions and not CCE.

3.5. Sources of error in aerial gamma radiometrics and need for spatial shifting

One general trend that can be observed across all sites is that AGR measurements are smaller than proximal measurements (Figs. 4-6). Aerial sensors typically register lower radiation because a larger field-of-view (FOV) smooths local heterogeneity present on the ground. AGR FOVs are primarily a function of survey altitude, although the movement of the aircraft can play a part as well (Simon and Graham, 1998; Martin et al., 2006). The extent of smoothing from AGR FOVs will depend on both the spatial dimensions and degree of heterogeneity associated with the ground source (Sanderson et al., 2008; Environmental Protection Agency, 2011). The one exception to this trend, however, was observed within Site A, where AGR measurements were greater than PGR at the west end of the survey (Fig. 4). There are several possible explanations for this discrepancy, however we conclude that rainfall was the likely reason. Rain can deposit atmospheric radon on the ground, resulting in an increase in ^{238}eU because radon is also present within the uranium decay chain (Minty and Wilford, 2004). Indeed, ^{238}eU readings from the AGR were relatively higher than PGR measurements (Fig. 4b), and historical weather data indicates that a rain event did occur the day before the AGR surveys at site A. The reader is referred to U.S. Environmental Protection Agency (2011) for an overview of all of the uncertainties associated with AGR surveys.

Figure 7 shows how much detail can be lost when there is a change in measurement support volume (i.e. FOV) between PGR and AGR surveys. For example, PGR total counts was highly correlated with clay content across Sites A, B and C2 ($R^2 = 0.77$)

(Fig. 7a, black line) because it collects gamma radiation from a much smaller measurement area and thus provides a higher spatial resolution. In contrast, AGR total counts only explained about half as much variation when corrected for position errors ($R^2 = 0.35$) (Fig. 7a, red line) because AGR measurement areas or FOV are much larger. Note that power models were fit due to the differences in soil-PGR relationships across sites.

Figure 7 also indicates that when AGR data points (i.e. samples within Sites A and B) are not spatially shifted, the degree of correlation was very poor and insignificant ($R^2 = 0.05$) (Fig. 7a, blue line). A similar result was found modeling sand content, whereby PGR, shifted AGR and non-shifted PGR produced R^2 values of 0.39, 0.23 and 0.08, respectively (Fig. 7b). It was difficult to quantify the lost information between AGR and PGR for CCE because of our limited sample size within Site C1 ($n = 5$). If the intended purpose of AGR is for soil mapping and such errors regarding spatial position are present, then applying an appropriate shift can improve the accuracy of predictions between AGR and soil properties content (Fig. 7). However, the amount of shift applied (if necessary) should be justified and have sound reasoning so that type I errors can be avoided.

As explained within the materials and methods, initial locations of AGR point measurements were found to be in error based on the apparent mismatch in geology codes within the AGR survey and an independent geology map. AGR surveys can contain points that are incorrectly geo-referenced because modern GPS techniques were not available. While the maximum amount of positional error can be up to 130 m in the direction of travel for modern AGR systems (U.S. Environmental Protection Agency,

2011), legacy AGR surveys can exhibit navigational errors on the order of 500 m, especially in areas where little variations in topography exist such as a floodplain (Luyendyk, 1997).

In addition to the geology code method, there are general guidelines that can be used to check the positional accuracy and/or amount of shift for a given AGR survey. First, compared to soil signatures, AGR measurements over large bodies of water are expected to emit relatively much lower amounts of radiation (Ahl et al., 2014). If large water bodies are not present, abrupt changes in geomorphology (i.e. Site A) indicate soil with different weathering histories and therefore abrupt changes in gamma signatures (Wilford et al., 1997). Third, heavily forested areas are a zone of gamma-ray attenuation, as tree trunks can act as an additional attenuation source in terms of its wood density and ability to hold large volumes of water (Wetterlind et al., 2012). Although previous literature has suggested that AGR can be corrected by data processing techniques (Söderström et al., 2016), consideration should first be given toward assessing the certainty of positional information provided by historical AGR surveys, and it would be interesting to determine if such positional errors are present within non-US radiometric databases.

There is still much that needs to be understood about gamma radiometrics for robust implementation as a covariate in soil mapping. While we have demonstrated that PGR surveys are more efficient in soil mapping relative to AGR surveys, PGR methods can be impractical within large areas that are difficult in access (Killeen, 1979). Modern AGR surveys can solve both challenges while providing minimal positional uncertainty, but such techniques are expensive. For example, it can cost up to 272,000 to 408,000 USD

to fly a 1:250,000 map sheet as of 2016 (Rouze et al., in press). While recent methods have sought to use optimized PGR sampling strategies across large areas (Stockmann et al., 2015), we recommend that it is worthwhile to first investigate the quality of legacy AGR surveys, and we have demonstrated that such information has inherent value for soil mapping purposes. Future studies could address the value of legacy AGR by identifying sites with multiple AGR flight lines within parent materials not present in this study.

4. Conclusions

Proximal gamma radiometric surveys were conducted within various landforms to determine to what extent aerial gamma radiometrics were reliably mapping soil properties on the ground. We have demonstrated here that proximal surveys were significantly related with soil properties such as clay, sand and CCE under sites within landforms such as young alluvium and between residual/terrace landforms. The highest correlations between proximal and soil data (0.93 and -0.95 for clay and sand content, respectively) were found for sites with parent materials exhibiting different radioelement signatures (alluvium and marl residuum). The gamma ROIs that exhibited the overall highest correlations and accuracies in predicting soil properties were (in order): total counts, ^{232}Th , dose rate, ^{40}K and ^{238}U .

Proximal and aerial gamma radiometric comparisons from our footprint analysis showed good agreement in terms of visual comparison as well as significant correlations (range r^2 : 0.40-0.97) where gamma signal variability was present. Total counts and dose rate provided the best agreement between aerial and proximal gamma radiometric measurements.

Spatial misalignment of legacy aerial point data was an issue for several sites, and were subsequently accounted for by considering nearby environmental features such as abrupt changes in geomorphology, forested areas, and large water bodies. The magnitude of shift required was found to be non-systematic within a given survey.

This body of work provides several new insights into the relationship between the field of gamma-ray spectrometry and soil science: 1) calcium carbonate equivalent can be mapped with both proximal and aerial gamma radiometrics within a uniform residuum (marl); 2) aerial gamma radiometric spatial patterns generally match proximal gamma radiometric spatial patterns when aerial data are correctly geo-positioned and thus soil properties can be mapped by aerial gamma radiometrics; 3) aerial gamma radiometric legacy data in the United States may or may not contain positional errors.

Acknowledgements

This work was funded by the U.S. Department of Agriculture Natural Resource Conservation Service (USDA-NRCS, project number 68-7482-12-528). We would also like to thank the anonymous reviewers for their helpful comments in the revision of this manuscript.

References

- Ahl, A., Motschka, K., Slapansky, P., 2014. Precipitation correction of airborne gamma-ray spectrometry data using monitoring profiles: methodology and case study. *Explor. Geophys.* 45, 8–15.
- Beamish, D., 2013. Gamma ray attenuation in the soils of Northern Ireland, with special reference to peat. *J. Environ. Radioact.* 115, 13–27.
- Beamish, D., 2016. Enhancing the resolution of airborne gamma-ray data using horizontal gradients. *J. Appl. Geophys.* 132, 75–86.
- Bierwirth, P., 1996. Investigation of Airborne Gamma-Ray Images as a Rapid Mapping Tool for Soil and Land Degradation - Wagga Wagga, NSW. Canberra. Australian Geological Survey Organisation, Record 1996/22.
- Box, G.E.P., Cox, D.R., 1964. An Analysis of Transformations. *J. R. Stat. Soc. Ser. B* 26, 211–252.
- Buchanan, S., Triantafilis, J., Odeh, I.O.A., Subansinghe, R., 2012. Digital soil mapping of compositional particle-size fractions using proximal and remotely sensed ancillary data. *Geophys.* 77, WB201–WB211.
- Bullock, S.J., 1979. Airborne Radiometric Surveys, Equipment and Practical Considerations, in: Training Course of Radiometric Prospecting Techniques. Atomic Energy Board, Pelindaba, S.A.

- Coulouma, G., L. Caner, E.H. Loonstra, and P. Lagacherie. 2016. Analysing the proximal gamma radiometry in contrasting Mediterranean landscapes: Towards a regional prediction of clay content. *Geoderma* 266: 127–135.
- Dickson, B.L. 1995. Uranium-series disequilibrium in Australian soils and its effect on aerial gamma-ray surveys. *J. Geochemical Explor.* 54 (3): 177–186.
- Duval, J.S., 1990. Modern aerial gamma-ray spectrometry and regional potassium map of the conterminous United States. *J. Geochemical Explor.* 39, 249–253.
- Duval, J.S., J.M. Carson, P.B. Holman, and A.G. Darnley. 2005. Terrestrial radioactivity and gamma-ray exposure in the United States and Canada, USGS Open-File Report 2005-1413. <http://pubs.usgs.gov/of/2005/1413/> (accessed 26 Sep. 2013).
- EG&G Geometrics, 1980. National Uranium Resource Evaluation aerial gamma-ray and magnetic reconnaissance survey, Nebraska-Texas project, Tyler, Texarkana, and Waco quadrangles of Texas, Oklahoma, Arkansas, and Louisiana. U.S. Department of Energy. Open-File Report GJBX-69-80.
- Gee, G., Or, D., 2002. Particle-size analysis, in: Dane, J.H., Topp, G.C. (Eds.), *Methods of Soil Analysis: Part 4 Physical Methods*, SSSA Book Series 5.4. Soil Science Society of America, Madison, WI, pp. 255–294.
- Geodata International Inc., 1979. Aerial radiometric and magnetic survey, Austin National Topographic Map, Texas Gulf Coast. U.S. Department of Energy. Technical Report GJBX-148-79.

Hill, P.L., R.P. Kucks and D. Ravat. 2009. Aeromagnetic and aeroradiometric data for the conterminous United States and Alaska from the National Uranium Resources Evaluation (NURE) Program of the U.S. Department of Energy: USGS Open-File Report 2009-1129. <http://pubs.usgs.gov/of/2009/1129/> (accessed 18 Jun. 2013).

International Atomic Energy Agency. 2003. Guidelines for radioelement mapping using gamma ray spectrometry data. Vienna, Austria. IAEA-TECDOC-1363.

Kayton, M., Fried, W.R., 1997. Avionics Navigation Systems, 2nd ed, Avionics Navigation Systems. John Wiley & Sons, New York, USA.

Kidd, D., Webb, M., Malone, B., Minasny, B., McBratney, A., 2015. Eighty-metre resolution 3D soil-attribute maps for Tasmania, Australia. *Soil Res.* 53, 932–955.

Killeen, P.G., 1979. Gamma-ray spectrometric methods in uranium exploration - application and interpretation, in: Hood, P.J. (Ed.), *Geophysics and Geochemistry the Search for Metallic Ores*. Geological Survey of Canada, Economic Geology report 31, Ottawa, ON, pp. 163–230.

Kock, P., Samuelsson, C., 2011. Comparison of airborne and terrestrial gamma spectrometry measurements - evaluation of three areas in southern Sweden. *J. Environ. Radioact.* 102, 605–613.

Loijens, H.S., 1980. Determination of soil water content from terrestrial gamma radiation measurements. *Water Resour. Res.* 16, 565–573.

- Luyendyk, A.P.J., 1997. Processing of airborne magnetic data. AGSO J. Aust. Geol. Geophys. 17, 31–38.
- Mahmood, H.S., Hoogmoed, W.B., van Henten, E.J., 2013. Proximal gamma-ray spectroscopy to predict soil properties using windows and full-spectrum analysis methods. Sensors 13, 16263–80.
- Martin, P., Tims, S., McGill, A., Ryan, B., Pfitzner, K., 2006. Use of airborne gamma-ray spectrometry for environmental assessment of the rehabilitated Nabarlek uranium mine, Australia. Environ. Monit. Assess. 115, 531–54.
- Megumi, K., Mamuro, T., 1977. Concentration of uranium series nuclides in soil particles in relation to their size. J. Geophys. Res. 82, 353–356.
- Minty, B.R.S., 1997. Fundamentals of airborne gamma-ray spectrometry. AGSO J. Aust. Geol. Geophys. 17, 39–50.
- Minty, B., and Wilford, J., 2004. Radon effects in ground gamma-ray spectrometric surveys. Explor. Geophys. 35, 312–318.
- Odgers, N.P., W. Sun, A.B. McBratney, B. Minasny, and D. Clifford. 2014. Disaggregating and harmonising soil map units through resampled classification trees. Geoderma 214-215: 91–100.
- Pebesma, E.J., 2004. Multivariable geostatistics in S: the gstat package. Computers & Geosciences, 30: 683-691.

- Pickup, G., and A. Marks. 2000. Identifying large-scale erosion and deposition processes from airborne gamma radiometrics and digital elevation models in a weathered landscape. *Earth Surf. Process. Landforms* 25: 535–557.
- Pitkin, J.A., Duval, J.S., 1980. Design parameters for aerial gamma-ray surveys. *Geophys.* 45, 1427–1439.
- Pracilio, G., M.L. Adams, and K.R.J. Smettem. 2003. Use of airborne gamma radiometric data for soil property and biomass assessment. p. 551–557. *In* Stafford, J., Werner, A. (eds.), *Precision Agriculture: Papers from the 4th European Conference on Precision Agriculture*. Berlin, Germany.
- Pracilio, G., Adams, M.L., Smettem, K.R.J., Harper, R.J., 2006. Determination of Spatial Distribution Patterns of Clay and Plant Available Potassium Contents in Surface Soils at the Farm Scale using High Resolution Gamma Ray Spectrometry. *Plant Soil* 282, 67–82.
- Priori, S., Bianconi, N., Fantappie, M., Pellegrini, S., Ferrigno, G., Guaitoli, F., Costantini, E.A.C., 2013. The Potential of Gamma-ray Spectroscopy for Soil Proximal Survey in Clayey Soils. *Environ. Qual.* 11, 29–38.
- R Development Core Team, 2015. *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

- Rachkova, N.G., Shuktomova, I.I., Taskaev, A.I., 2010. The state of natural radionuclides of uranium, radium, and thorium in soils. *Eurasian Soil Sci.* 43, 651–658.
- Rawlins, B.G., Marchant, B.P., Smyth, D., Scheib, C., Lark, R.M., Jordan, C., 2009. Airborne radiometric survey data and a DTM as covariates for regional scale mapping of soil organic carbon across Northern Ireland. *Eur. J. Soil Sci.* 60, 44–54.
- Rodrigues Jr., F.A., Bramley, R.G.V., Gobbett, D.L., 2015. Proximal soil sensing for precision agriculture: simultaneous use of electromagnetic induction and gamma radiometrics in contrasting soils. *Geoderma* 243-244, 183–195.
- Rouze, G., Morgan, C.L.S., McBratney, A.B., Neely, H.L., in press. Exploratory Assessment of United States Aerial Gamma Radiometrics. *Soil Sci. Soc. Am. J.* doi: 10.2136/sssaj2016.07.0206
- Ryan, P.J., McKenzie, N.J., O'Connell, D., Loughhead, A.N., Leppert, P.M., Jacquier, D., Ashton, L., 2000. Integrating forest soils information across scales: spatial prediction of soil properties under Australian forests. *For. Ecol. Manage.* 138, 139–157.
- Sanderson, D.C.W., Cresswell, A.J., White, D.C., 2008. The effect of flight line spacing on radioactivity inventory and spatial feature characteristics of airborne gamma-ray spectrometry data. *Int. J. Remote Sens.* 29, 31–46.

- Sherrod, L.A., Dunn, G., Peterson, G.A., Kolberg, R.L., 2002. Inorganic carbon analysis by modified pressure-calculator method. *Soil Sci. Soc. Am. J.* 66, 299-305.
- Simon, S.L., Graham, J.C., 1998. A comparison of aerial and ground level measurements of ^{137}Cs in the Marshall Islands. *Environ. Monit. Assess.* 53, 363–377.
- Söderström, M., Sohlenius, G., Rodhe, L., Piikki, K., 2016. Adaptation of regional digital soil mapping for precision agriculture. *Precis. Agric.* 1–20.
- Soil Conservation Service, 2002. Soil Survey of Brazos County, Texas. U.S. Gov. Print. Office, Washington, DC.
- Soil Conservation Service, 2003. Soil Survey of McLennan County, Texas. U.S. Gov. Print. Office, Washington, DC.
- Soil Conservation Service, 2005. Soil Survey of Burleson County, Texas. U.S. Gov. Print. Office, Washington, DC.
- Stahr, K., Clemens, G., Schuler, U., Erbe, P., Haering, V., Dinh Cong, N., Bock, M., Dinh Tuan, V., Hagel, H., Le Vinh, B., Rangubpit, W., Surinkum, A., Willer, J., Ingwersen, J., Zarei, M., Herrmann, L., 2013. Beyond the horizons: challenges and prospects for soil science and soil care in Southeast Asia, in: Fröhlich, H.L., Schreinemachers, P., Stahr, K., Clemens, G. (Eds.), *Sustainable Land Use and Rural Development in Southeast Asia: Innovations and Policies for Mountainous*

Areas, Springer Environmental Science and Engineering. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 31–107.

Stockmann, U., Malone, B.P., McBratney, A.B., Minasny, B., 2015. Landscape-scale exploratory radiometric mapping using proximal soil sensing. *Geoderma* 239-240, 115–129.

Taylor, J.A., M. Short, A.B. McBratney, and J. Wilson. 2010. Comparing the ability of multiple soil sensors to predict soil properties in a Scottish potato production system. p. 387–396. *In* Viscarra Rossel, R.A., McBratney, A.B., Minasny, B. (Eds.), *Proximal Soil Sensing*. 1st ed. Springer Science+Business Media B.V., Dordrecht Heidelberg London New York.

Tyler, A.N., D.C. Sanderson, E.M. Scott, and J.D. Allyson. 1996. Accounting for Spatial Variability and Fields of View in Environmental Gamma Ray Spectrometry. *J. Environ. Radioact.* 33 (3): 213–235.

Triplehorn, D.M., 1965. Origin and significance of glauconite in the geologic sequence. *Tulsa Geol. Soc. Dig.* 33, 282–283.

U.S. Environmental Protection Agency, 2011. Aerial and Ground Radiological Surveys Phosphate Mines in January 2011. Erlanger, Kentucky.

Verboom, W.H., Pate, J.S., 2015. Catena An integrated approach to mapping and understanding of vegetation : soil systems. *Catena* 126, 134–145.

Viscarra Rossel, R.A., Taylor, H.J., McBratney, A.B., 2007. Multivariate calibration of hyperspectral γ -ray energy spectra for proximal soil sensing. *Eur. J. Soil Sci.* 58, 343–353.

Viscarra-Rossel, R.A., Adamchuk, V.I., Sudduth, K.A., McKenzie, N.J., Lobsey, C., 2011. Proximal Soil Sensing: An Effective Approach for Soil Measurements in Space and Time, in: Sparks, D.L. (Ed.), *Advances in Agronomy*. Elsevier Inc., pp. 237–282.

Viscarra-Rossel, R.A., Webster, R., Kidd, D., 2014. Mapping gamma radiation and its uncertainty from weathering products in a Tasmanian landscape with a proximal sensor and random forest kriging. *Earth Surf. Process. Landforms* 39, 735–748.

Wetterlind, J., Tourlière, B., Martelet, G., Deparis, J., P.A. Saby, N., Richer de Forges, A.C., Arrouays, D., 2012. Are there any effects of the agricultural use of chemical fertiliser on elements detected by airborne gamma-spectrometric surveys? *Geoderma* 173-174, 34–41.

Wilford, J.R., Bierwirth, P.N., Craig, M.A., 1997. Application of airborne gamma-ray spectrometry in soil/regolith mapping and applied geomorphology. *AGSO J. Aust. Geol. Geophys.* 17, 201–216.

Wilford, J., and B. Minty. 2006. The Use of Airborne Gamma-ray Imagery for Mapping Soils and Understanding Landscape Processes. In Lagacherie, P., McBratney, A.B., Voltz, M. (Eds.), *Digital Soil Mapping An Introductory Perspective*. Developments in soil science. Elsevier, Amsterdam. p. 207–220.

Wilford, J., 2012. A weathering intensity index for the Australian continent using airborne gamma-ray spectrometry and digital terrain analysis. *Geoderma* 183-184, 124–142.

Table 1: Descriptive statistics of soil sample analysis with raw proximal (P) and aerial (A) gamma radiometrics collected within each site. Dose rate is in nGy hr⁻¹, ⁴⁰K, ²³⁸eU and ²³²eTh are in Bq kg⁻¹, and total counts are in counts per second.

	Range	Std. dev.	Mean	CV
<i>Site A</i>				
Soil Properties, g kg ⁻¹				
Clay	91-733	239	365	0.66
Sand	8-648	191	183	1.04
Silt	188-698	149	452	0.33
Gamma radiometrics				
⁴⁰ K (P)	481-3975	429	2230	0.19
²³⁸ eU (P)	0-468	66	141	0.46
²³² eTh (P)	0-306	38	118	0.32
Dose Rate (P)	89-416	40	236	0.17
Total counts (P)	1466-2984	255	2381	0.11
⁴⁰ K (A)	157-689	96	459	0.21
²³⁸ eU (A)	6-48	9	26	0.35
²³² eTh (A)	12-53	8	33	0.24
Dose rate (A)	28-70	8	53	0.15
Total counts (A)	1307-2035	168	1758	0.10
<i>Site B</i>				
Soil Properties, g kg ⁻¹				
Clay	11-484	145	212	0.68
Sand	290-932	210	584	0.36
Silt	54-433	82	203	0.41
Gamma radiometrics				
⁴⁰ K (P)	0-2928	484	969	0.50
²³⁸ eU (P)	0-449	61	115	0.53
²³² eTh (P)	1-362	57	362	0.46
Dose rate (P)	36-381	55	174	0.31
Total counts (P)	887-3013	455	1891	0.24
⁴⁰ K (A)	31-532	35	222	0.50
²³⁸ eU (A)	11-46	8	35	0.33
²³² eTh (A)	19-72	15	46	0.33
Dose Rate (A)	28-73	14	51	0.28
Total counts (A)	1066-2026	290	1542	0.19
<i>Site C1</i>				
Soil Properties, g kg ⁻¹				

	Range	Std. dev.	Mean	CV
Clay	399-553	37	488	0.08
Sand	84-189	25	131	0.19
Silt	326-467	33	382	0.09
CCE	146-486	103	288	0.36
Gamma Radiometrics				
⁴⁰ K (P)	162-930	109	521	0.36
²³⁸ eU (P)	0-123	17	57	0.68
²³² eTh (P)	35-148	18	86	0.35
Dose rate (P)	55-147	13	105	0.19
Total counts (P)	1301-2271	123	1858	0.07
⁴⁰ K (A)	157-188	15	166	0.09
²³⁸ eU (A)	11-19	2	15	0.16
²³² eTh (A)	28-31	1	30	0.04
Dose rate (A)	31-35	1	34	0.04
Total counts (A)	1281-1369	30	1329	0.02

Site C2

Soil Properties, g kg ⁻¹				
Clay	180-554	102	424	0.24
Sand	69-454	108	186	0.58
Silt	340-450	31	389	0.08
CCE	0-89	25	15	1.72
Gamma radiometrics				
⁴⁰ K (P)	51-1165	195	561	0.44
²³⁸ eU (P)	12-154	20	74	0.54
²³² eTh (P)	12-161	22	100	0.29
Dose rate (P)	46-168	25	122	0.18
Total counts (P)	1368-2626	164	2285	0.07
⁴⁰ K (A)	157-250	41	204	0.20
²³⁸ eU (A)	19-30	3	24	0.11
²³² eTh (A)	29-38	3	33	0.07
Dose rate (A)	34-46	4	42	0.08
Total counts (A)	1372-2578	68	1497	0.05

Table 2: Significant Pearson correlation coefficients (p-value < 0.01) between proximal gamma radiometric measurements and lab-characterized soil data. NS denotes correlation insignificance at a p-value less than 0.01.

Soil property	Dose Rate	⁴⁰ K	²³⁸ eU	²³² eTh	Total counts
<i>Site A</i>					
Clay	0.90	0.89	0.58	0.89	0.93
Sand	-0.63	-0.70	NS	-0.58	-0.64
Silt	-0.70	-0.60	-0.47	-0.74	-0.73
<i>Site B</i>					
Clay	0.72	0.64	NS	0.77	0.74
Sand	-0.75	-0.65	NS	-0.81	-0.78
Silt	0.65	0.53	NS	0.73	0.70
<i>Site C1</i>					
Clay	NS	NS	NS	NS	NS
Sand	NS	NS	NS	NS	NS
Silt	NS	NS	NS	NS	NS
CCE	-0.80	NS	NS	-0.78	-0.83
<i>Site C2</i>					
Clay	0.88	0.68	NS	0.74	0.87
Sand	-0.91	-0.75	NS	-0.80	-0.95
Silt	NS	NS	NS	NS	NS
CCE	NS	NS	NS	NS	NS

Table 3: Leave one out cross validation performance in predicting various soil properties with selected proximal gamma predictors.

Site	Covariate(s)	R ²	RMSE g kg ⁻¹	Bias g kg ⁻¹
<i>Clay</i>				
A	²³² eTh+ ⁴⁰ K	0.85	90.4	-5.8
	Total Counts	0.84	93.3	-6.6
B	²³² eTh	0.44	117.3	-13.9
	Total Counts	0.38	125.4	-18.0
C2	²³⁸ eU + ²³² eTh	0.50	69.1	0.3
	Total Counts	0.67	55.1	1.8
<i>Sand</i>				
A	²³² eTh	0.09	194.5	-27.7
	Total Counts	0.20	165.3	-29.7
B	²³² eTh	0.61	127.1	-1.3
	Total Counts	0.56	135.8	-1.2
C2	⁴⁰ K + ²³² eTh	0.68	58.4	-6.0
	Total Counts	0.93	26.7	-1.9
<i>CCE</i>				
C1	²³² eTh	0.33	84.7	-4.8
	Total Counts	0.55	67.1	-6.1

Table 4: Significant Pearson correlation coefficients (p-value < 0.01) between aerial and proximal gamma measurements for dose rate, ^{40}K , ^{238}eU and ^{232}eTh .

Variable	ρ			
	<i>Site A</i>	<i>Site B</i>	<i>Site C1</i>	<i>Site C2</i>
N =	86	33	11	25
^{40}K	NS	0.68	NS	0.89
^{238}eU	NS	NS	NS	NS
^{232}eTh	0.36	0.92	NS	0.91
Dose Rate	0.52	0.96	NS	0.65
Total Counts	0.53	0.95	NS	0.95

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure captions

Figure 1. Location of study areas within the United States and the state of Texas. The lower case letters presented on the Texas map correspond with Sites a) A, b) B, and c) C1 and d) C2. Within each site, aerial (larger colored circles) and proximal (smaller colored circles) raw total count measurements (counts sec^{-1}) are underlain with geological parent materials according to local county soil surveys. The uppercase letters (A, A' etc.) within each site correspond with the beginning and end of the aerial transects. Soil sampling locations are color coded by amount of clay content (g kg^{-1}) as well as calcium carbonate equivalent (g kg^{-1}) within Site C1.

Figure 2. Predicted versus observed clay (black circles) and sand (grey triangles) contents within Sites (a) A, (b) B, (c) C2. In all cases relationships were modeled using proximal total counts (TC) because it produced the highest prediction accuracies.

Figure 3. Predicted versus observed CCE contents (g kg^{-1}) within site C1. The proximal variable that was the most accurate in predicting clay/sand content is labeled in the legend (TC - Total Counts).

Figure 4. Transect across Site A containing aerial (dashed line) and proximal (solid line) (a) ^{40}K , (b) ^{238}eU , (c) dose rate (DR), (d) ^{232}eTh and (e) total counts (TC) measurements. Refer to Figure 1 for locations of these points within the study area (A and A').

Figure 5. Transect across Site B containing aerial (dashed line) and proximal (solid line) (a) ^{40}K , (b) ^{238}eU , (c) dose rate (DR), (d) ^{232}eTh and (e) total counts (TC) measurements. Refer to Figure 1 for locations of these points within the study area (B and B').

Figure 6. Transect across Site C2 containing aerial (dashed line) and proximal (solid line) (a) ^{40}K , (b) ^{238}eU , (c) dose rate (DR), (d) ^{232}eTh and (e) total counts (TC)

measurements. Refer to Figure 1 for locations of these points within the study area (D and D').

Figure 7. Comparison between proximal (black) and aerial (red, blue) gamma total counts in predicting clay content for Site A (circles, $n = 17$), Site B (triangles, $n = 12$) and Site C2 (squares, $n = 6$). Aerial total counts are then divided into models where spatial shifts were not implemented (blue) and where spatial shifts were implemented for Sites A and B (red).