Estimating soil properties with a proximal gamma-ray spectrometer using windows and full-spectrum analysis methods

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Abstract

Our objective was to evaluate a proximal gamma-ray spectrometer to find quantitative relationships between radiometric data and soil properties, using energy windows and full-spectrum analysis methods in two study fields. Relations between radiometric data and soil properties, such as clay content, total nitrogen, phosphorus, potassium, organic matter and magnesium were variable across fields and methods. Validation of models across the fields indicated that full-spectrum method outperformed the windows method and predicted clay content, nitrogen and pH. We conclude that radiometric data combined with full-spectrum method can be used to estimate and predict different soil properties.

Keywords: gamma-ray sensing, soil properties, energy windows, full-spectrum analysis.

Introduction

Collection of fine-scale information on soil properties, using conventional soil sampling and laboratory analyses, is time consuming and expensive. Gamma-ray (radiometric) sensors have the capability to scan soils with high spatial resolution and to explain variations in soil properties. Conventionally, radionuclide (RN) activities are found by summing the intensity of gamma-ray counts over three relatively broad energy windows (EWs) of the energy spectrum surrounding the peaks of three radionuclides, such as ^{40}K, ^{238}U and ^{232}Th (IAEA, 2003). Although a certain amount of relevant information can be lost in the EWs method, this serves as a simple and reference method for radiometric data analysis. A proximal gamma-ray spectrometer, the Mole[1], was developed for the full-spectrum analysis (FSA) method and to the best of our knowledge no attempts have been made to evaluate it with simple EWs method. Our objective was to evaluate the Mole to find quantitative relationships between radiometric data and soil properties, using EWs and FSA methods, in two study fields.

Materials and methods

Study fields

This study was conducted at Broekemahoeve, Lelystad (52°32'35.67"N, 5°34'26.50"E), The Netherlands. The soil was quite young because it was reclaimed from the North Sea some 50 years ago. Total study area was 5.5 ha, which comprised a conventionally managed and an organic field, separated by 100 m. The texture of the study fields was sandy loam with a varying amount of small stones and seashells.

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[1] The Mole is a gamma-ray spectrometer developed and commercially used by The Soil Company, Leonard Springerlaan 9, 9727 KB, Groningen, The Netherlands.

Gamma-ray data acquisition, soil sampling and laboratory analysis

Gamma-ray data were acquired using the Mole with CsI-(Tl) scintillation detector (Van Egmond et al., 2010). The spectrometer was driven in fields at about 1.2 m/sec and at 0.5 m height. Gamma-ray data were collected at 1 Hz from about 5,000 points from both fields together with the associated GPS locations. For spectrometer calibration, soil samples were taken from four selected points in each field up to a depth of 30 cm. We measured integrated gamma-ray spectra from each sampling point for five minutes to acquire more stable and de-noised spectra. Soil samples were analysed for clay content, organic matter (OM), total nitrogen (TN), phosphorus (TP), potassium (TK), magnesium (Mg) and pH.

Data analysis

Multichannel data were transformed to spectral energy data. In the EWs method, radionuclide (RN) concentrations were determined using the stripping method (IAEA, 2003). Sensitivities and stripping factors were computed from standard spectra of RNs (Van Egmond et al., 2010). In the FSA method, RN concentrations were determined with the method proposed by Hendriks et al. (2001). RN concentrations determined with EWs and FSA methods were linearly regressed to soil properties to expose correlations between them. Regression models of each field were validated with soil property data of the other field. Leave-one-out cross-validation was used on samples of combined fields.

Results

Description of gamma-ray spectra

Raw gamma-ray spectra measured every second were very noisy (Figure 1a). Integrated spectra measured for five minutes, however, removed most of the statistical noise (Figure 1b). Overall gamma-ray count-rate was very low. There were two visible peaks of ^{40}K (at 1.46 MeV) and ^{137}Cs (at 0.662 MeV). There were two other very flat and hardly visible peaks of ^{238}U (at 1.76 MeV) and ^{232}Th (at 2.61 MeV). Higher energy channels after 1.90 MeV collected either very low or zero counts as shown in Figure 1 (a, b).

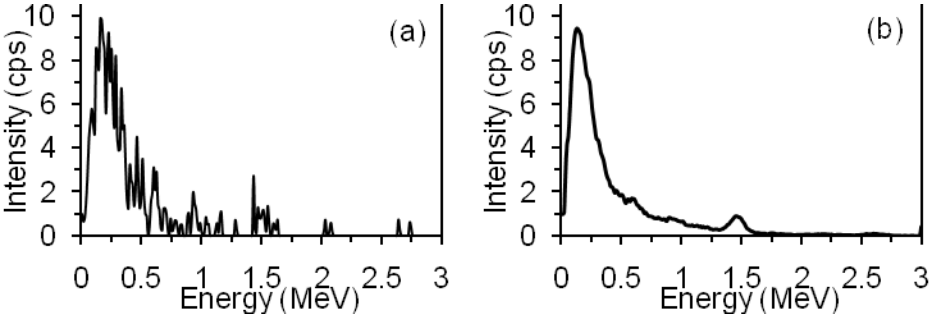

Figure 1. Examples of spectra measured (a) every second and (b) for five minutes.

Relations between radiometric data and soil properties

RN concentrations determined with EWs and FSA methods were significantly linearly correlated (R≥0.80) with each other. Relations between RN data and soil properties were variable across fields and methods as shown in Table 1. When combining fields, however, the strength of relations was decreased and new correlations were also identified in each method (Table 1). Clay content, unlike other soil properties, always showed more or less some correlation with ^{232}Th in individual as well as in combined fields in each method. Results of validation and leave-one-out cross-validation are shown in Table 2.

Table 1. Correlations between radiometric data and soil properties

Soil property	Full-spectrum analysis method						Energy windows method					
	Conv.		Organic		Combined		Conv.		Organic		Combined	
	RN	R^2_{adj}	RN	R^2_{adj}	RN	R^2_{adj}	RN	R^2_{adj}	RN	R^2_{adj}	RN	R^2_{adj}
Clay (%)	Th	0.98**	Th	0.83	Th	0.54*	Th	0.26	Th	0.66	Th	0.46*
OM (%)	K	0.96*	TC	0.21	U	0.30	U	0.88*	Cs	0.19	Cs	0.47*
TN (mg/kg)	Th	0.74	U	0.99**	U	0.50*	K	-0.13	U	0.82	U	0.54*
TP (mg/kg)	TC	0.29	U	0.91*	U	-0.12	Cs	0.94*	U	0.64	Cs	-0.12
TK (mg/kg)	K	0.41	U	0.72	U	-0.07	U	0.27	U	0.82	K	-0.15
Mg (mg/kg)	Cs	0.69	U	0.10	U	0.50*	Cs	0.15	U	0.48	U	0.29
pH	Cs	0.63	Cs	0.71	Cs	0.19	U	-0.28	Th	0.23	Th	-0.02

** Relations are significant at 0.01 level; * relations are significant at 0.05 level.

Table 2. Validation of models across fields and cross validation for combined fields

Field	Full-spectrum analysis method			Energy windows method		
	Soil property	R^2	RMSE	Soil property	R^2	RMSE
Conventional	Clay content (%)	0.98	0.92	Clay content (%)	0.51	0.57
	TN (mg/kg)	0.69	54.37	TN (mg/kg)	0.01	62.93
	TP (mg/kg)	0.13	13.22	TP (mg/kg)	0.03	10.71
	TK (mg/kg)	0.05	5.15	TK (mg/kg)	0.51	4.59
	pH	0.75	0.05			
Organic	Clay content	0.83	0.66	OM (%)	0.26	0.41
	OM (%)	0.13	0.68	TP (mg/kg)	0.46	12.69
	TN (mg/kg)	0.55	116.77			
	Mg (mg/kg)	0.08	21.34			
	pH	0.81	0.25			
Combined	Clay content	0.49	0.46	Clay (%)	0.03	0.70
	TN (mg/kg)	0.31	48.02	OM (%)	0.17	0.15
	Mg (mg/kg)	0.37	7.77	TN (mg/kg)	0.40	44.26

Discussion

The low number of gamma-ray counts is due to the soil having very young parent materials, which has a sandy or sandy loam texture and leached profile. Very low number of counts in ^{238}U and ^{232}Th windows indicates that the soil is lacking ferruginous material. A relatively high signal of ^{40}K indicates that there are freshly weathered granite parent materials, which are rich in K feldspar (Cook et al., 1996). High correlation between RN concentrations determined by EWs and FSA methods shows that both methods can be used to find relations with soil properties. Good correlations between radionuclide data and different soil properties suggest a potential role of gamma-ray spectroscopy in soil property mapping. The correlation between clay content and ^{232}Th indicates that ^{232}Th is absorbed or adsorbed on the clay minerals and this is consistent with previous finding (Cook et al., 1996; Pracilio et al., 2006; Van Egmond et al., 2010). And this ^{232}Th can serve as an indicator for measurement of clay content. Other soil properties, such as OM, TN and pH show mixed results because they may not have direct relations with RNs. Although the results in both methods are comparable, the FSA method outperforms the EWs method most of the times because it accounts for RN concentrations from the entire spectrum; supporting the findings of Hendriks et al. (2001). Low correlations in the EWs method can be attributed to non-removal of background, use of limited spectral information and finding correct sensitivities and stripping factors for EWs. Correlations between radiometric data and soil properties are very site-specific and the Mole should be calibrated in each field. Validation and cross-validation results indicate that the FSA method predicted clay content, TN and pH across the fields better than EWs.

Conclusions

The very low number of gamma-ray counts proves that the soil is very young. Integrated spectra for five minutes remove most of the statistical noise. Strong correlations between radionuclide data and different soil properties suggest a potential role of gamma-ray spectrometry in modelling and mapping soil properties. The strength of relationships is stronger in individual fields than when combining them. Variable results across fields and methods suggest that gamma-ray models are very site-specific. Both EWs and FSA methods are comparable, but FSA outperforms EWs in most cases, which is confirmed by validation and cross-validation results. The FSA method, therefore, can maximise the ability of the Mole to estimate soil properties. For better understanding of relationships between soil properties and radiometric data, more samples for calibration and validation should be taken on fields having small variations in soil properties.

Acknowledgement

We acknowledge Higher Education Commission (HEC), Pakistan, for providing a scholarship for this PhD study.

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