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Proximal gamma-ray spectrometry for site-independent in situ prediction of soil texture on ten heterogeneous fields in Germany using support vector machines

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Dedicated to Professor Dr. Armin Skowronek on the occasion of his 70th birthday.

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ABSTRACT

Gamma spectrometric field measurements may provide high resolution information on topsoil texture. Yet, calibrations for the estimation of texture data usually have to be done site-specifically. The lack of site-independent calibrations thus limits the easy and universal use of proximal gamma-ray sensing in soil mapping and precision agriculture. Our objective was to develop a study site-independent prediction model for topsoil texture from gamma-ray spectra. We surveyed ten study sites across Germany with 417 reference samples (291 for calibration, 126 for test set-validation), providing soils from a broad range of parent materials and with widely varying soil texture. First, study site-specific models were calibrated by a linear regression approach. These models provided reliable estimations of sand, silt, and clay for most of the study sites. Second, study site-independent models were calibrated via i) linear regression and ii) support vector machines (SVM), the latter being mathematical methods of data pattern recognition. Based on the non-linear relationship between gamma spectrum and soil texture, which varied widely between the different parent materials the linear models are not appropriate for satisfactory soil texture prediction (averaged R^2 of 0.73 for sand, 0.61 for silt, and 0.18 for clay and averaged absolute prediction errors of 9 to 5%, respectively). In contrast, the SVM calibrated prediction models revealed reliable performance also for site-independent calibrations. With the non-linear SVM approach we were able to include all sites in one single prediction model for each texture fraction although the different mineralogical composition of their parent materials led to complex and partly opposing relationships between gamma features and soil texture. Site-independent predictions via SVM were often even better than site-specific linear regression models. The site-independent SVM calibrated predictions yielded an averaged R^2 of 0.96 (sand), 0.93 (silt), and 0.78 (clay), and corresponding averaged absolute prediction errors of 2 to 4%, respectively. To summarize, (i) non-linear prediction models are a feasible approach for capable site-independent texture estimations across a wide range of soils and (ii) gamma spectrometry-based texture predictions are a valuable input for applications that require highly resolved texture information at low costs and efforts.

1. Introduction

The demand for rapid and reliable soil sensing techniques and methods increases remarkably since site-specific management and sustainable land use require high resolution information on soil properties (Viscarra Rossel and Adamchuk, 2013). Such information is, e.g., needed for spatially resolved fertilization or plant

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protection measures (Patzold et al., 2008; Gebbers and Adamchuk, 2010). Conventional methods based on laboratory soil analyses are time consuming, expensive and often fail to provide the demanded spatial resolution (Viscarra Rossel and Adamchuk, 2013). Gamma spectrometry has emerged to be a capable technique to provide information on various soil properties of the topsoil, in particular on soil texture. Many studies dealing with this technique revealed that calibrations for the estimation of texture data should be done strongly site-specific (Viscarra Rossel et al., 2007; Dierke and Werban, 2013). This confinement limits the easy and site-independent use of gamma spectrometry. Gamma studies on the landscape or national scale with varying objectives are available for Canada (e.g. Dent et al., 2013) and Australia (e.g. Cook et al., 1996; Viscarra Rossel et al., 2007; Minty et al., 2009). However, surveys for European soils with a more general approach and thus dealing with texture prediction on study sites from different parent materials are scarce (Petersen et al., 2012; Priori et al., 2014).

Rocks and soils contain varying amounts of different radionuclides emitting gamma photons with each discrete energy level being characteristic of the gamma-ray source. This forms the basic principle of gamma spectrometry. Since approximately 90% of the above ground measured radiation originates from the uppermost 0.3–0.5 m of the soil (Cook et al., 1996), gamma data provide integrated information on the topsoil, at least on arable land. The only naturally occurring radionuclides abundant in soils and bedrock which produce sufficient energy and intensity to be efficiently detected by proximal gamma measurements are ^{40}K, ^{238}U and ^{232}Th. These radionuclides are monitored via so-called Regions of Interest (ROIs) with defined energies from 1.37 to 1.57 MeV for ^{40}K, 1.66–1.86 MeV for ^{238}U, and 2.41–2.81 MeV for ^{232}Th. Another gamma feature of interest are the Total Counts (TC), ranging from 0.4 to 2.81 MeV (Minty, 1997). Monitoring these ROIs forms the most common approach of analysing the gamma spectra.

Quality and quantity of radionuclides in soil are driven by the mineralogy and geochemistry of the parent material and by pedogenesis (Dickson and Scott, 1997; Wilford et al., 1997). Since these are factors and processes that determine or at least influence major soil properties, several studies surveyed the relationship between gamma data and soil properties. Studies of airborne gamma spectrometry reveal correlations between gamma data and soil group i.e. soil classification (Rawlins et al., 2007; Triantafilis et al., 2013) as well as soil moisture (Carroll, 1981). Proximal gamma spectrometry was used to survey gravel content (Pracilio et al., 2003), plant available potassium content (Wong and Harper, 1999), pH and organic carbon content (Dierke and Werban, 2013) as well as soil texture (Klooster van der, 2009; Mahmood et al., 2011; Petersen et al., 2012). According to Megumi and Mamuro (1977), soil texture contributes more to the gamma-ray signal than other soil constituents like organic matter. The authors state that a decrease in particle size yields an increase in radionuclide concentration due to elevated specific surface sorption capacity. Besides surface sorption, ^{40}K, ^{238}U, and ^{232}Th

Table 1
Sand, silt, and clay contents at the study sites as determined by conventional laboratory analysis, parent materials of the surveyed soils and reference soil group (RSG according to IUSS Working Group WRB, 2015; PPSD = Pleistocene periglacial slope deposits; CV = coefficient of variation; 1 ha ≙ 10.000 m^2).

Study site	Fraction	Min	Max	Mean	CV	Parent material & reference soil group (RSG)
Ascheberg	Sand [%]	21	80	57	26	Cretaceous marls partially covered by aeolian sand, Pleistocene fluvial sediments and Pleistocene glacial till; RSG:
n = 45	Silt [%]	9	21	15	20	Cambisols, Stagnosols
approx. 8 ha.	Clay [%]	9	55	26	50	
Cologne	Sand [%]	41	53	46	7	Upper Pleistocene and Holocene fluvial sediments; RSG: Cambisols, Luvisols
n = 25	Silt [%]	26	38	34	9	
approx. 1 ha	Clay [%]	16	21	18	6	
Holzendorf	Sand [%]	36	81	61	11	Pleistocene glacial till; RSG: Cambisols, Luvisols, Stagnosols
n = 81	Silt [%]	11	40	23	17	
approx. 35 ha	Clay [%]	5	21	14	21	
Kraatz	Sand [%]	34	78	57	16	Pleistocene glacial till; RSG: Cambisols, Luvisols, Stagnosols
n = 39	Silt [%]	16	37	26	19	
approx. 25 ha	Clay [%]	6	27	16	38	
Scheyern	Sand [%]	19	66	37	35	Tertiary sediments covered by Pleistocene loess deposits with var. thickness; RSG: Cambisols, Luvisols
n = 20	Silt [%]	23	54	43	21	
approx. 5 ha	Clay [%]	9	31	20	30	
Siebeldingen	Sand [%]	11	56	25	48	Pleistocene fluvial sediments, loess and loess loam of the Pleistocene and Holocene, small area with clayey Keuper;
n = 60	Silt [%]	22	69	49	24	RSG: Luvisols, Cambisols, Regosols
approx. 25 ha	Clay [%]	14	35	24	21	
Wesseling	Sand [%]	13	65	26	50	Pleistocene fluvial sediments, partially covered with loess; RSG: Cambisols, Luvisols
n = 42	Silt [%]	26	71	59	20	
approx. 8 ha	Clay [%]	9	19	15	13	
Hilberath	Sand [%]	12	37	25	28	**PPSD** consisting of Devonian sand, silt & clay stones intens. weathered during Mesozoic & Tertiary, partially covered
n = 42	Silt [%]	40	65	53	13	by Quaternary loess; RSG: Cambisols, Stagnosols
approx. 3 ha	Clay [%]	14	28	21	14	
Schleidweiler	Sand [%]	14	42	24	33	**PPSD** containing clayey sandstone of Mesozoic Tertiary weathered Muschelkalk, sandstone of Upper Bunter
n = 36	Silt [%]	41	55	50	8	Sandstone, and loess; RSG: Cambisols, Leptosols
approx. 4 ha	Clay [%]	14	37	23	26	
Vinxel	Sand [%]	6	24	12	42	**PPSD** rich in Tertiary trachyte tuff, partially covered by loess loam deposits with variable thickness; RSG: Stagnosols
n = 27	Silt [%]	52	87	65	14	
approx. 5 ha	Clay [%]	4	39	22	32	