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Application of airborne gamma-ray imagery to assist soil survey: A case study from Thailand

Ruamporn Moonjun [a,b,]*, Dhruba Pikha Shrestha [a], Victor G. Jetten [a], Frank J.A. van Ruitenbeek [a]

[a] Department of Earth Systems Analysis, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
[b] Land Development Department, Ministry of Agriculture and Cooperatives, Phaholyothin Road, Chatuchak, Bangkok 10900, Thailand

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ABSTRACT

Airborne gamma-ray imagery (AGRI) provides coarse-resolution (approximately 400 × 400 m pixel) spatial information on gamma-ray emitting elements, i.e. potassium (K), thorium (Th) and uranium (U), in the upper half meter of the soil. These radioelements are a potential information source for soil mapping since their abundance is related to soil geochemistry, specifically the chemical composition of parent materials and their weathering products resulting from geomorphic and pedogenic processes.

The aim of this study was to evaluate the potential of AGRI for improving digital soil survey process in two phases: (1) a preliminary phase, where hypotheses of soil-landscape relationships are developed, and (2) a phase where soil map unit boundaries are placed or revised. The study also evaluated the match between AGRI and existing lithologic, geopedologic, and soil series maps. The study was conducted in a well-characterized complex soil landscape: the 560 km^2 upper Pa Sak watershed in Petchaboon province, Thailand. The relationship between gamma-ray data and geological units was examined with box-and-whisker plots and confirmed by rock and soil samples. Rock and soil sample classifications were compared with the gamma-ray image and to typical radio-element responses found in the literature.

To interpret AGRI data in terms of regolith and soil genesis, we compared AGRI to two existing soil maps: geopedologic and soil series maps. First, the geopedologic map was split into four maps according to the geopedologic hierarchy: landscape, lithology, relief, and landform; at the latter (lowest) level, soil units are also associated. Secondly, soil series and geopedologic soil units were used to examine the distribution of radio-element response to selected soil characteristics: parent material, texture, mineralogy, and thickness. The interpretations from best correlation in both soil maps were described in terms of the radioelement changes during pedogenic and geomorphic processes, based on a review of literature and supported by soil samples.

In the hypotheses-generating stage, AGRI provided useful information in three forms (single signal, ratio, and ternary images enhanced with a hill shaded DEM) by relating these to lithology, material transport, and internal pedogenetic processes. AGRI correlated well with the classes of the geopedologic map (1:50,000) at the two higher levels (landscape and lithology) but to a lesser degree at the two lower levels (relief and landform in geopedologic approach). In the mapping stage, AGRI showed deficiencies in the soil series map (1:50,000) made by conventional aerial photo analysis and limited field surveys, especially in inaccessible areas but also in low-relief terraces and flood plains, which provided a basis for future field sampling to correct these deficiencies. AGRI suggested new boundaries, differentiating topsoil properties and the presence of plinthite, despite its coarse resolution.

Clustering of gamma ray and elevation data (DEM) was carried out using fuzzy logic to generate various classification layers. Final map was produced using total weighted inverse distance of all the classes in a 3 by 3 window. Class label was assigned to the one with the largest total inverse distance over the entire set of fuzzy classification bands. The result shows relatively higher classification accuracy for soil parent material differentiation (overall accuracy of 72%) as compared to the classification for soil types (67%).

1. Introduction

Soil survey is the process of representing soil types, properties or functions as a map over an area of interest (Soil Survey Staff, 1993). Since the soil can only be observed directly or sampled over a tiny

* Corresponding author at: Department of Earth Systems Analysis, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands.
E-mail address: ruampornm@gmail.com (R. Moonjun).

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fraction of its extent, soil survey is based on inferences from these limited observations, backed by understanding the processes involved in soil genesis and landscape evolution. Aerial photos have been extensively used to understand soil landscape relationship and to delineate boundaries of presumed soil differences in order to map soil (Bennema and Gelens, 1969; Goosen, 1967; McBratney et al., 2000; Zinck, 1989). Recently the advancement in digital soil mapping using an array of techniques including GIS, digital elevation model (DEM), multivariate statistical, geo-statistical, neural network, and fuzzy logic claims to increase the mapping efficiency (Behrens et al., 2005; Grimm et al., 2008; Lagacherie, 2008). Co-variables that cover the entire spatial extent at some reasonable resolution, e.g., DEM derivatives and remotely-sensed imagery, have proven to dramatically improve the quality of a soil survey using digital soil mapping (DSM) approaches (McBratney et al., 2003). One possible source of co-variables is airborne gamma-ray data (AGRD). This measures natural radioactive emanations of Uranium-238 (^{238}U), Thorium-232 (^{232}Th), and Potassium-40 (^{40}K) decay series from the upper part of the Earth's surface (Minty, 1997; Rawlins et al., 2009; Sini et al., 2007). AGRD has been widely used in geological mapping and to study rock weathering and lithology (An et al., 1995; Carrier et al., 2006; Grasty, 1993; Jaques et al., 1997; Paradella et al., 1997; Schetselaar et al., 2000). Airborne gamma-ray imagery (AGRI) is the interpolated map from AGRD acquired along flight lines, fully covering a study area at some horizontal resolution, typically 400 m. Gamma ray radiation can penetrate about 50 cm of rock or soil (IAEA, 2003). AGRI is often available as the result of mineral exploration studies and this source may do double duty to allow inference of soil and regolith properties as well as to help understand the soil-landscape process over the generally quite large area covered by the airborne survey.

Wilford and Minty (2007), in their review of the application of AGRI to soil survey, showed that AGRD generally relates to bedrock mineralogy and its weathering state as influenced by geomorphic stability and the climate of a region (Lacoste et al., 2011; Pickup and Marks, 2000, 2001; Rawlins et al., 2007; Schuler et al., 2011; Tunstall, 2003; Wilford, 2002, 2011; Wilford et al., 1997). These are related to soil-forming factors such as parent material, climate and time.

Previous applications of AGRI in support of soil surveying have been used primarily to understand the geochemistry and weathering of soil parent materials. Cook et al. (1996) correlated AGRI with the distribution of soil forming materials in southwestern Australia. Dickson and colleagues related radioelement concentrations to the geochemical composition of rocks and soils (Dickson et al., 1996; Dickson and Scott, 1997). Wilford and colleagues summarized the radioelement responses of rocks and soils in terms of geochemical components, pedogenic processes and geomorphic processes (Wilford, 2007; Wilford and Minty, 2007). Accordingly, high K is typically associated with acid igneous rocks (including granite, rhyolite and pegmatite), while low K contents are typical for mafic minerals and associated mafic to ultramafic rocks (e.g. basalts, dunites, serpentinite and peridotites). Thorium (Th) is associated with granite, pegmatite and gneiss. High uranium (U) is associated with pegmatites, syenites, radioactive granites and some black shales. U and Th are found in accessory and resistant minerals such as zircon, titanite (sphene), apatite, allanite, xenotime, monazite and epidote. During pedogenesis, K concentrations often decrease with increased weathering, due to leaching of cations. In contrast, U and Th are associated with more stable weathering products in soil profiles, as U and Th released during weathering are readily absorbed into clay minerals, Fe and Al-oxides and soil organic matter. In addition, U and Th are also associated with resistant minerals that persist in soils. These results show that AGRI is a valuable data source to differentiate parent materials, i.e., the lithology of the primary bedrock or transported materials in which the soil develops, as revealed by its geochemical signature (Rawlins et al., 2007). This may be an improvement over the use of geological maps, which are typically at coarse resolution and which are aimed at the stratigraphy and geological age rather than lithology, let alone details of the geochemistry. A second soil-forming factor is time, which is related to the degree of weathering. AGRI may be able to differentiate geomorphic surfaces developed from the same original lithology on the basis of relative weathering, specifically the depletion in K and the relative enrichment in Th.

Applications of airborne gamma-ray data are not all free from limitations. One of the problem is due to similar responses of gamma-ray signals in different regoliths as shown in some studies (Cook et al., 1996; Wilford et al., 1997). The variation of the gamma-ray signal is also influenced by soil moisture content which makes it difficult to interpret. Also, the area between flight lines, is likely to be undetected, because of the relatively poor spatial resolution of the survey data. The suggestion is that, gamma-ray data should not be used in isolation, but should be used in combination with other data particularly terrain attributes, such as slope and relief.

In Thailand, the Land Development Department (LDD), Ministry of Agriculture & Cooperatives, is the agency responsible for soil survey, agricultural development and rural land use planning. It produces soil series maps at 1:50,000 and 1:25,000 scales, as well as detailed farm planning maps at 1:4000. LDD is currently transitioning to DSM methods to improve the quality of soil maps and mapping efficiency. It focusses on soil physical and chemical properties for agriculture and soil conservation advice to the farmers. Since AGRI is related to soil composition properties LDD wants to make its optimum use. Currently, AGRI is available for the entire country. The question thus arises as to how this valuable data source can be used to improve soil survey at semi-detailed and detailed scales.

This study therefore aimed to answer the following questions:

1. How much of the variation in bedrock and soil parent material can be explained using AGRI?
2. How much of the variation in soil characteristics can be explained by AGRI?
3. To what extent can AGRI explain soil pattern in terms of soil parent material, weathering, and pedogenic processes over landscape?
4. Can AGRI assist with delineating soil mapping units or refining boundaries found by other survey methods?

The study is applied in a case study in Pa Sak watershed in central Thailand. Data used are soil series map, geopedology map and a map showing geology/soil parent material information. The gamma ray sensor data of the measurement of the natural radiation from decay series of potassium (K), thorium (Th) and uranium (U) in the upper 45 cm of the Earth's surface is used. The three-channel data is further enhanced spatially by digital image analysis technique from which three products e.g. single channel data, band ratio and colour composites were used in the analysis. It is described as follows.

2. Materials and methods

2.1. Study area

We selected a study area based on its varied soils, physiography, geology and land use, the availability of field observations and covariate maps. The chosen area is the upper Pa Sak watershed, in Lom Kao and Lom Sak districts, Petchaboon province, Thailand (Fig. 1), bounded by 101° 30′ - 101° 45′ E and 16° 45′- 17° 15′ N and covering 560 km^2. The area is a horst-graben, the result of active tectonic processes, denudation and sedimentation, with complex physiography composed of valleys and quaternary terraces along the Pa Sak (eastern) and Numpung (western) rivers, hilly piedmont and lower slopes of surrounding mountains, with elevations ranging from 140 to 590 m above sea level. The climate is humid tropical, influenced by north-eastern and southwestern monsoons, with distinct differences between dry and hot (Oct–Apr) and wet (May–Sep) seasons. Average annual precipitation is 1095 mm (Lom Sak station), of which 80% falls during the monsoon period. Average annual temperature is 28 °C with the highest