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Soil and soil quality mapping for an extreme relief region using detailed fuzzy slope forms

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Abstract

Slope forms at different positions are often gradual which reflects the nature of a slope. Some studies have computed different fuzzy slope positions for digital soil mapping. However, there has not been a system calculated for a large area with extreme relief conditions. This study examines all possible slope forms that can be achieved for a large area of 860 km^2 with extreme relief conditions as a soil-forming parameter for fuzzy soil mapping. This fully achieved slope form system together with slope gradients can be used to find out rules for variations of organic matter content at different slope positions and slope angles as a very important index for soil and soil quality mapping. Firstly, a classification of five major slope positions (ridge, upper-, middle, foot slope, and valley) was defined. Nine basic slope forms (FAO, 2006) were computed as nine fuzzy slope forms for each of the three middle major slope positions. This resulted in 29 fuzzy slope forms extracted for a single slope. Secondly, soil mapping was carried out using SoLIM software (Soil and Land Inference Model). To prepare for the model, calibration of different soil groups based on their distinctive forming combinations of environmental parameters was carried out. The development of a soil database based on 123 soil profiles resulted in 7 major reference soil groups. The soil information was collected with information of slope, elevation, geology, and land use types. Soil prototypes or distinctive combinations of soil-forming parameters were defined for every soil group. These prototypes were then set as fuzzy rules in SoLIM to derive a soil map of 7 major soil groups. Thirdly, soil quality indices were calculated for every soil profile in which slope form-dependent organic matter content played a very important role. From these calculations, soil quality prototypes were defined based on the distinctive combinations of the forming parameters and set as fuzzy rules. SoLIM was then applied to derive a map of different quality classes. This soil quality map spatially depicts different soil quality variations for the area and can be used for many purposes, such as land evaluation, land use planning.

Key words: Slope forms, organic matter content, extreme relief, fuzzy rules, prototypes, SoLIM, soil mapping, soil quality mapping

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1. Introduction

Northwestern Vietnam is a mountainous region and home to almost three million people from many different ethnic minorities. The region has remained the poorest region over the whole country for many years with the highest poverty rate. It has a wide range of elevations, strong relief variations, land use patterns, climatic patterns, land cover, and petrography. The geological patterns of the area are ophiolite complex, intrusion complexes, volcanic rocks, terrigenous and carbonate sedimentary rocks ranging from Proterozoic age till now (Khuong, T. H., 2010a). Swiddening and slash-and-burn agriculture had had a long cultivation history of people in mountainous regions and they had been claimed to be sustainable (Dao, B. M., 2000). These cultivation practices worked very well in providing efficient subsistence to local people and sustaining the land use systems of the area (Vien et al., 2004). However, due to population growth and immigration happening over decades, like many other mountainous regions, the population in the northwest has risen remarkably recently, creating a severe stress on cultivated soils in covering the food demand for the growing population. Moreover, upland agriculture has been shifted towards meeting markets' demands, or market-orientation, i.e. intensification of cash crops like maize as a leading income crop (Clemens et al., 2010). This has promoted more intensive uses of soils and deforestation to widen arable land on hill slopes. Consequences have then arrived quickly represented by serious flooding due to increasing deforested area, increasing soil degradation due to soil erosion and over exploitation of soils and decreasing productivity of the cultivated soils (Toan et al., 2001, Wezel et al. 2002). The demand to mitigate these facts is to drive cultivation practices towards sustainability. Some solutions to achieving the sustainable development goal are to recover the lost forested area and importantly to adapt new suitable crops that not only bring high income to local people but also function to mitigate soil degradation and recover soil quality. To do so, a good knowledge of soil resources and soil quality must be necessarily achieved (Igue, A.M, 2000).

2. Objectives

Because of its prominent terrain characteristics, i.e. steep slopes and strong relief variations, the geomorphology must be thoroughly described in the linkage with the existence of different soils and their quality levels. Based on this, a hypothesis was proposed for the research which states ***slope forms are very important in capturing spatial variations of soils and their fertility levels and if they are correctly spatially delineated, loss of soil information can be minimized and spatial soil gradation can be better seen as a continuum.***

The overall goal of this study over the last 4 years was to develop a detailed soil information system for the northwestern mountainous district of Yen Chau using SOTER database upscaled from Cong's work (2011). From this upscaled SOTER database, a soil map and a soil quality map will be generated for Yen Chau district using Soil and Landscape Index Model (SoLIM). To achieve this goal, the following objectives have been identified:

- Derivation of a detailed slope form system for the area. The result will be a map consisting of all possible slope forms that will be used later as one of the soil-forming environmental parameters in the SoLIM model in mapping the variations of different soils and the quality of these soils.

- Development of a SOTER database for Yen Chau district that rules the formation of soils through unique combinations between soils and environmental conditions such as landforms, slope forms, slope gradients, parent materials.
- Application of SoLIM in deriving the soil map for Yen Chau based on the relationships between soils and terrain characteristics from the SOTER database.
- Calculation of soil quality indices and studying their relationship with the environmental parameters for the development of a soil quality map for Yen Chau applying SoLIM.

3. Methodology

3.1. SOTER database

The construction of SOTER database is illustrated in Figure 1:

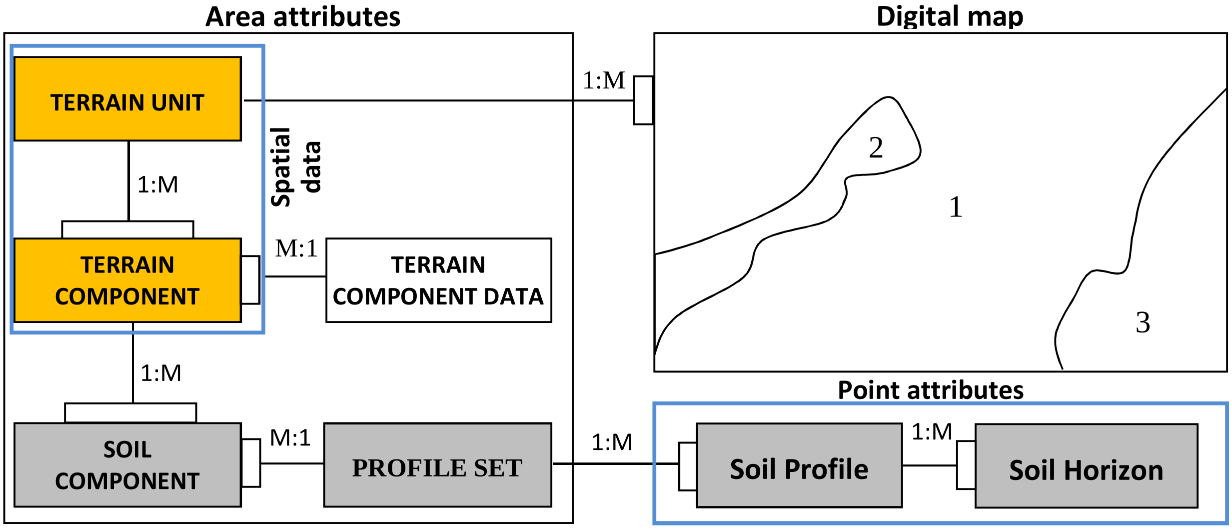

Figure 1. SOTER data structure (Weller and Stahr, 1995)

SOTER units reveal unique combinations of soils and terrain characteristics and they can be mapped. The information of these units can be stored in two ways: geometry and attribute data in which an attribute characterizes an object or a geometric shape. Geometry data are stored in a Geographic Information System (GIS). Attribute data are structured progressively in the order of terrain units, terrain components and soil components, known as SOTER differentiating criteria (van Engelen, 1995; Oldeman, 1993). The structure of a SOTER database is well illustrated in Figure 1, in which:

- **Terrain units** are general description of physiography and parent material. Physiography represents landforms of the earth's surface. When observing terrain characteristics, one should be able to capture as fully as possible the major landforms. The major landforms can then be subdivided in combination with parent material or lithology. Terrain units characterize an area through combinations of landforms and lithology. A terrain unit can have one or more terrain components. In Yen Chau, there are 8 geological units: Volcanic 1, Volcanic, Volcanic 3, Limestone, Sedimentary rocks, Sedimentary K_2yC_1, Sedimentary K_2yC_2, Quart-rich metamorphic rock.

- **Terrain components** are the of terrain units by taking into account different parameters like surface forms, slope categories, mesorelief, surface drainage, ground water, etc. A terrain component can have one or more soil components. For its extreme relief conditions, there are 29 slope forms defined and derived for Yen Chau (Table 1).

Table 1: Definition of 29 slope forms for Yen Chau

Slope form code				**Contour (Horizontal) curvature**		
				Convex-**V**	*Straight*-**S**	*Concave*-**C**
1	Ridge (RDG)					
2	Upper slope (UP)	**Profile (Vertical) curvature**	Convex **V**	UP-VV		
3					UP-VS	
4						UP-VC
5			Straight **S**	UP-SV		
6					UP-SS	
7						UP-SC
8			Concave **C**	UP-CV		
9					UP-CS	
10						UP-CC
11	Middle slope (MD)	**Profile (Vertical) curvature**	Convex **V**	MD-VV		
12					MD-VS	
13						MD-VC
14			Straight **S**	MD-SV		
15					MD-SS	
16						MD-SC
17			Concave **C**	MD-CV		
18					MD-CS	
19						MD-CC
20	Foot slope (FT)	**Profile (Vertical) curvature**	Convex **V**	FT-VV		
21					FT-VS	
22						FT-VC
23			Straight **S**	FT-SV		
24					FT-SS	
25						FT-SC
26			Concave **C**	FT-CV		
27					FT-CS	
28						FT-CC
29	Valley (VLY)					

- **Soil components** contain information of soils of the area and are characterized by soil profiles. Every soil component has one or more fully described and analyzed reference soil profile. One soil profile should have maximum five subjacent horizons to the depth of at least 150 cm. A soil horizon should not exceed 50cm in depth. In the soil database, each horizon must be characterized with physical and chemical properties. Reference profiles are represented on maps as points given by unique coordinates.

The SOTER database of Yen Chau comprises of 123 soil profiles, 95 SOTER units, 123 soil components, and 10 major soil groups. The formation of each of the major soil groups is studied through unique combinations of environmental variables that are used as input for the soil and soil quality mapping models using SoLIM. The environmental parameters affecting the formation as well quality of soil in Yen Chau are determined as geology, slope inclination, slope form, elevation, slope aspect, climate, and land use history.

3.2. Soil mapping using SoLIM

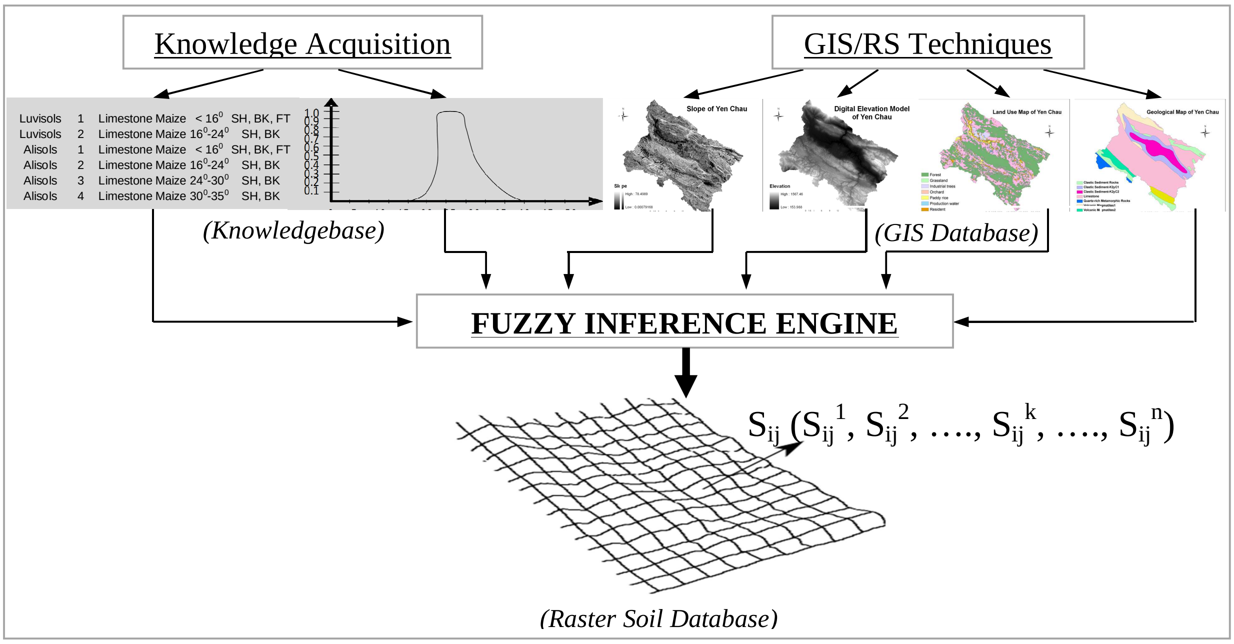

Figure 2. Fuzzy Soil Inference Process (adopted from Zhu et al., 2003)

A fuzzy set is defined (Zimmermann, 1976) as: If $X = \{x\}$ is a collection of objects denoted generically by x then a fuzzy set A in X is a set of ordered pairs: $A = \{x, \mu_A(x)\}\ x \in X$

where x is an object which belongs to the set of object X, $\mu_A(x)$ is called the degree of membership of x in A which maps X to the membership space M (when M contains only the two points 0 and 1, A is non-fuzzy and $\mu_A(x)$ is identical to the characteristic function of a non-fuzzy set). The range of the membership function is a subset of the nonnegative real numbers whose supremum is finite.

The inference process is illustrated in Figure 2. The inference engine is operated using a raster data approach in which fuzzy similarity values are calculated for every grid cell. Zhu et al. (1996) assumed that the formation of a soil class at a cell is controlled by the least optimal environmental variable for the soil class at that cell. Thus, fuzzy intersection (or fuzzy minimum operator: $\mu_N(x) = \min\{\mu_A(x), \mu_O(x)\}, x \in X$) is used to calculate the integration of these influences from the environmental variables. The inference engine takes a set of environment al variables derived from a GIS package for calculating the optimality curves. Then the minimum operator takes these optimal values for calculating the membership value for one instance of that cell. In case the soil class has more than one instance, the set of environmental variables and the minimum operator are used again to calculate optimal values and membership values of these instances.

After all the instances of this cell are calculated for membership values, the maximum operator ($\mu_N(x) = \max\{\mu_A(x), \mu_O(x)\}, x \in X$) is used to calculate the final membership value of that cell, i.e. finally how similar the value of the cell to the conceptual value of that soil class. This process goes on to other cells till it completes computing for all of the cells of the study area. Till here, a thematic similarity map is produced for a single soil class. The engine then moves on to calculate for the rest of the prescribed soil classes and more similarity maps are created. The calibration for soil mapping and soil quality mapping is based on the relationships between soil groups and defined soil quality classes and the environmental parameters which are studied once the SOTER database is completed for Yen Chau.

Finally, the inference engine can technically merge these similarity maps into one map which assigns each cell with a value of one prescribed soil class based on the highest similarity value to this prescribed soil class. This technique is called Hardened Map in SoLIM. The final maps are the soil and soil quality maps that delineate the spatial distribution of all of soil classes and quality degrees for the area to be mapped.

4. Results

Figure 3 shows the results of soil map and soil quality map of Yen Chau. The model is only applied for arable land on sloping land because soils within this area are affected by the environmental conditions mentioned above. Other land uses are rather dependent on the practice behavior of the locals or are not for agriculture. For instance, paddy fields are basically formed based on the need of the local people for rice and Anthrosols are not an interest of this research. Forests, fresh water, orchards, grassland, and residence are stable land-use patterns and are not the focus for digital soil mapping.

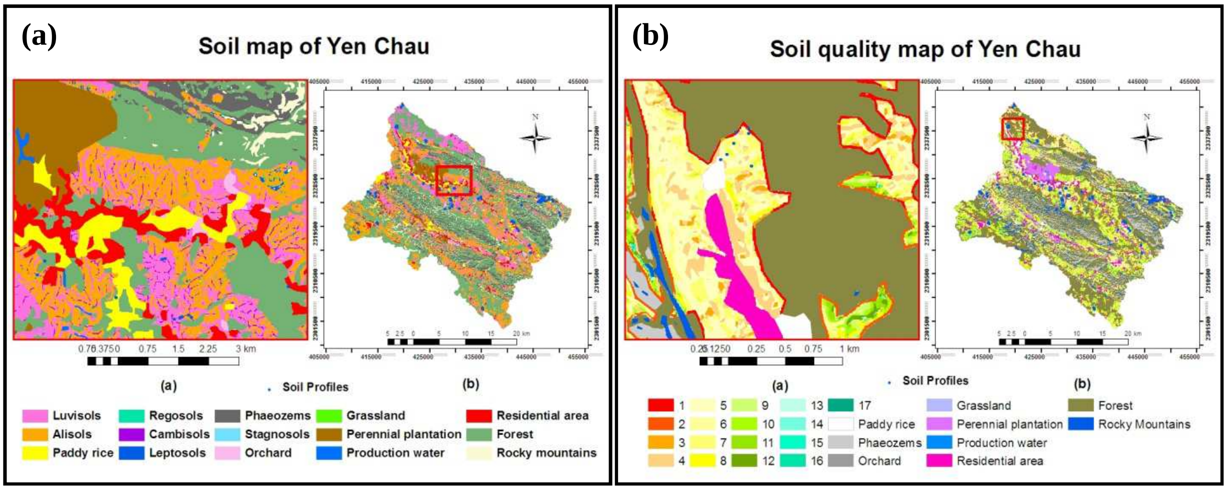

Figure 3. Result maps of the study

Figure 4 shows a general trend of increasing soil quality via N-P-S values corresponding with increasing OM content. However, the low positive correlation of $r^2 = 0.186$ shows that the overall trend of the data does not evolve so obviously.

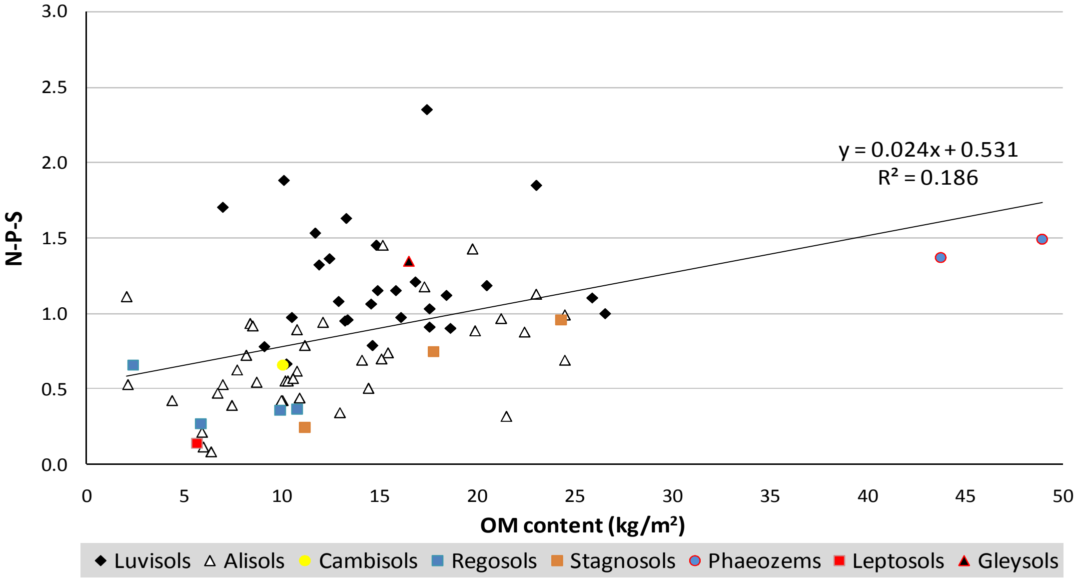

Figure 4. The relationship between the OM content and the sum parameter N-P-S for the soil profiles that have full information of OM, Nt, P_{Bray1}, and S-value.

Apparently, different soils with different properties and characteristics play a very important role in this matter. S-value has the most influential role in deciding the quality of different soils. The content of the other quality indices, i.e. OM content, N_t, and P_{Bray1}, is rather dependent on the duration of land use, slope positions and forms, and slope gradients. The content of basic cations in the soil depends more strongly on parent materials in which VO_1 has the highest stocks of bases among the 8 geological units. Moreover, Luvisols are soils that have very high content of bases.

5. Discussion

- Beyond slope inclination and geology, slope position and surface forms (slope forms) play an important role in the genesis of soils and soil quality. On a single slope, soils at upper slope positions and straight forms tend to have better quality than the rest.
- Soil organic matter is a very important indicator to determining soil quality. The N-P-S graph in Figure 3 shows a positive correlation in which soils having high OM content tend to have better quality.
- The content of organic matter rather depends on clay content, land use history and slope inclination, and slope forms. With the characteristic of strong relief variations of the region, the OM content is found to be highest at upper slope positions having straight slope forms. These locations have youngest land use age and least effects of soil erosion for their short erosive slope lengths.
- The content of basic cations represented by the S-value is found to be highest in Volcanic 1 and is strongly influenced by soil pH, elevation (lower at higher altitude).

- It is an ongoing research project and the soil and soil quality mapping models need to be validated for further conclusions, i.e. map accuracies.

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