Predicting Soil Properties from Landscape Attributes with a Geographic Information System

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ABSTRACT

Soil property maps are often critical layers in geographic information systems (GIS), particularly when used in land management decisions. Unfortunately, the soil maps of the highlands of Northern Thailand are mostly described as slope complexes for which soil characteristics and properties are not available. In this study, landscape attributes (land use types, topographic attributes, and climatic data) derived from remotely-sensed data and GIS technology were used to express our understanding of the distribution of soil materials in the Wat Chan watershed, Chiang Mai province Northern Thailand. Analyses of 107 soil samples in the landscape showed that values of topsoil properties were higher than those in the subsoil except for clay content and exchangeable magnesium (Mg). The variation for topsoil properties was also higher than that in subsoil except the variation in soil Mg. Analysis of the soil landscape indicated that elevation, slope, land use, and annual rainfall were the attributes most highly correlated with measured soil properties. Compound topographic index (CTI), which is an index that refers to a steady state of soil moisture and profile curvature, showed some influence on soil nitrogen (N) and organic matter (OM) in this landscape. Multi-linear regression analysis for predicting soil properties from landscape attributes revealed that sand, silt, N, OM, extractable phosphorus (P), and bulk density variable could be predicted in this landscape as indicated by t-test with R^2 ranging from 0.40 to 0.55.

Key words: Soil properties, Landscape attributes, GIS, CTI

INTRODUCTION

In recent years, a major focus of attention in Thailand for resource managers has been the deforestation processes in the northern highlands. Uncontrolled and unwarranted deforestation is perhaps the greatest of all ecological dangers that can de-stabilize crop production, sustainable productivity and food security. This attention has led to a call for sustainable land resource management for enhanced productivity and performance of land resources, while minimizing any negative effects on the environment. Soil information, one of the important factors for evaluation of sustainable land resource management, could be useful for resource managers in providing a basis for assessment and restoration (Syers, 1995). With accelerated land and environmental degradation of tropical forests caused by deforestation, maps of soil information have become valuable tools for land use planning and natural resource management.

Soil property maps are critical layers in geographic information system (GIS), particularly for land management decisions because questions on land use and soil conservation require increasingly accurate information on soil properties and their geographical location. In the past, soil resources in the highlands of Northern Thailand were seldom investigated due to the complexities of the landscape. These complexities cause soil properties to exhibit different and complex scales of variation (Beckett and Webster, 1971; Burrough, 1993), which require costly investments of time and money for conventional survey. Understanding the soil distribution patterns in relation to landscape attributes (such as land use types and topographic attributes) is seen as a step to improve the accuracy of prediction of soil variables at unsampled locations.

As a result of the demands for more precise information in support of soil resource inventories, there have been many attempts to characterize the spatial variability of measured soil attributes (Trangmar, 1984; Loague and Gander, 1990). These attempts led to the development of parametric mapping that has been devoted to methods of interpolation or surface fitting (e.g. inverse distance weighed and trend surface interpolation) to provide predictions of soil properties in soil survey (Webster and Oliver, 1990). However, these methods concentrated on the characterization of patterns, rather than on the linking the patterns to the underlying processes. Quantitative interpolation techniques (e.g. kriging) often ignore pedogenesis while methods based on pedogenesis, on the other hand, have lacked a consistent quantitative framework.

Soil-landscape analysis is based on fundamental principles that complex spatial patterns are related to basic underlying controls on the type and intensity of soil development. This type of analysis enables soil scientists to accurately predict soil types and their associated properties using the relationships between soil and landscape attributes. Soil-landscape attributes are natural terrain units resulting from the interactions of five factors affecting soil formation, namely parent material, climate, organisms, relief and time (Jenny, 1941). Wilding and Drees (1978) reported that a gradual or distinct change in soil properties depended on identifiable landforms, geomorphic elements or the dominant soil formation factors. So soil-landscape study should provide a consistent framework within which to derive soil property values for use in predictive models and land use interpretations in the landscape, and provide a baseline from which future studies may assess the impacts of land use practices.

The objective of this study is to quantify relationships between landscape attributes generated from remotely sensed data and GIS technology and measured soil properties and to use the resulting soil-landscape models to predict soil properties in the Wat Chan landscape.

MATERIALS AND METHODS

The study area

The study area is located in Ban Chan, Mae Chaem district, Chiang Mai province, Thailand between 19˚ 02’ and 19˚ 16’ North latitude and between 98˚ 16’ and 98˚ 20’ East longitude. The area is populated with Karen, the largest ethnic group in Northern Thailand. This watershed includes highland forested vegetation, which is composed of hill evergreen forest (e.g. Fagaceae, Bombacaceae and Rubiaceae families), pine forest (e.g. *Pinus merkusii and Pinus kesiya*) and dry dipterocarp forest (e.g. *Shorea obtusa* Wall., *Shorea siamensis* Miq. and *Dipterocarpus tuberculatus*). Judging by the increasing hill tribe populations, one possible factor increasing deforestation is that forests have been cut by human for agricultural activities, building material and fuelwood (A Progress Report of Sustaining Land Resource Management for Agriculture and Forestry in the Tropical Small Watershed Environment, surveyed in July 1993 - June 1994, unpublished). Agricultural land in this landscape is mostly used for field crops such as corn, red kidney bean, upland rice and paddy rice.

Elevation in this watershed ranges from 800 to 1,500 meters above sea level. Average annual rainfall ranges from 800 - 1,500 mm while minimum and maximum daily temperature is approximately 8 and 42 degrees Celsius, respectively.

Most soils in this area have been classified as soil series complexes (Soil survey maps, Department of Land Development) for which soil characteristics and properties are not available. Based on the preliminary survey completed in parts of the Mae Chaem watershed (A Progress Report of Sustaining Land Resource Management for Agriculture and Forestry in the Tropical Small Watershed Environment, July 1993 - June 1994, unpublished), most soils are formed on residuum or colluvium derived from several kinds of parent rocks such as granite, shale, sandstone, limestone and metamorphic rocks. These soils range from recently developed, very deep soils to highly weathered ones such as Alfisols, and Ultisols.

Landscape attribute acquisition and processing

Remotely sensed imagery of the study area for February 1996 was obtained from the Landsat 5 Thematic Mapper (TM). Prior to analysis, the image was rectified to a universal transverse mercator (UTM) projection with a pixel resolution of 25 m using nearest neighbor rules provided by the IDRISI image processing software (Eastman, 1997). Preliminary results of the classification indicated that composite images of band 3,4,5 of the image provided the best image for the unsupervised classification. The ISOCLUS module, an iterative self-organizing unsupervised classifier based on a concept similar to the ISODATA routine of Ball and Hall (1965) in the IDRISI software was used to classify land use. Ground control points were collected and used as training sites. The mean and variance/covariance of training sites were calculated and used to estimate the posterior probability that a pixel belongs to each class (the supervised classification based on maximum likelihood algorithm) of the 1996 image. Accuracy of land use classification by these processes was about 85% (unpublished data).

An elevation map for the study area was derived from a topographic map (1:50,000 scale) and stored in the computer in digital format using ARC/Info GIS software (ESRI, Inc. 1995). The vector file was then transformed into a raster image (Digital Elevation Model, DEM) for image analysis using TOPOGRID. The DEM image was used for hydrological and terrain analysis in order to obtain watershed boundaries, stream networks and topographic attributes (e.g. slope, aspect, plan and profile curvature, upslope distance and compound topographic index (CTI)). The attributes slope, aspect, plan curvature and profile curvature were calculated with ARC/Info's GRID function CURVATURE, which implemented algorithms developed by Zevenbergen and Thorne (1987).

Rainfall data obtained from two hundred weather stations in Chiang Mai province were used to interpolate rainfall data for the whole area by the Inverse Distance Weight (IDW) algorithm in ARC/Info software.

Stratification of sample locations

Elevation, slope, aspect, plan curvature (concavity across the slope), profile curvature (concavity down the slope) and compound topographic index (CTI) images generated from the DEM were used to classify the landforms in this landscape, which were later used to select sample locations.

A major assumption of the landform classification is that the topographic attributes follow a Gaussian distribution. Log transformations consequently were applied to each image to normalize the data. An iterative self-organizing unsupervised classifier that identifies natural groupings of data points was used to form landform classes. This classification of the data was accomplished using ISOCLUSTER and MLCLASSIFY in ARC/INFO GRID. Landform classes were then overlaid with the1996's land use image to generate a land unit image. One hundred and seven sample points were selected for collecting soil samples based on the land unit image. Differential GPS measurements were used to locate sample points in the landscape. Soil samples were taken from the soil plow layer (topsoil) at the depth of 0-20 cm, and subsoil at the depth of 20-40 cm in August - November, 1997. A composite soil sample was obtained by mixing and sub-sampling six samples of representative topography and mixed together to represent the location.

Laboratory Analyses

Soil samples were air-dried and passed through a 2-mm mesh to remove rocks and roots. Selected soil chemical and physical analyses were conducted at the laboratory of Department of Soil Science and Conservation, Faculty of Agriculture, Chiang Mai University, Thailand.

Soil pH was measured with a glass electrode in 1:1 soil suspension in water and in 1*M* KCl (McLean, 1982). Delta pH was calculated as pH (KCl) minus pH (H_2O) to provide an estimate of net electrostatic charge of soil material. Total N was determined using Kjeldahl methods (USDA, 1967). Extractable P was determined by the Bray II method (Bray and Kurtz, 1945). Exchangeable cations were extracted with neutral 1*M* NH_4OAc (Thomas, 1982) and atomic absorption was used to determine Ca and Mg and flame photometry for K and Na. The sum of cations was obtained by summing exchangeable Ca, Mg, K and Na. Soil organic matter was determined by the Walkley-Black Method (Nelson and Summers, 1982). Exchangeable Al was determined following extraction with non-buffered 1*M* KCl (USDA, 1967) whenever pH < 5.0-5.5.

Soil samples taken by the core method were used to measure percent moisture at field capacity (FC, 0.03 MPa) and at permanent wilting point (PWP, 1.5 MPa) by the pressure chamber method (Klute, 1965). Water holding capacity then was determined by subtracting percent moisture at PWP from FC. Percent of sand, silt and clay were determined by the pipette method (Gee and Bauder, 1982).

Data Compilation and Statistical Analysis

Exploratory data analyses were performed for all landscape attributes and soil properties measured. Correlation was tested among landscape attributes and between landscape attributes and measured soil properties. Approximation of each variable to a normal distribution was determined from QQ plots in Splus (S-PLUS, 1997). Data were transformed to normal distribution and subsequent statistical analyses were performed on transformed values, where necessary.

Recent studies using linear models revealed the possibility of predicting a soil property from easy-to-measure morphological properties (e.g. McKenzie et al., 1991; and Gessler et al., 1995). Manrique et al., (1991) have reported progress in using multi-linear regression models in predicting soil water characteristics from soil physical and chemical properties. These predictions were extended to the traditional model of soil variation that assumed spatial correlation between soil properties and topographic attributes. Stepwise model selection was used to choose the best model of each soil property in considering prediction error and the reduction in residual standard error. Statistical modeling was performed by using generalized linear models with normal errors (McCullagh and Nelder, 1983).

RESULTS AND DISCUSSION

Statistical distribution of soil properties

Descriptive statistics of soil properties calculated from 107 samples for topsoil and subsoil revealed that values of topsoil properties in this landscape were higher than those in the subsoil except for clay content and magnesium (Mg)(Tables 1 and 2). The variation in topsoil properties was also higher than that in subsoil except the variation in soil Mg that was greater in the subsoil layer.

Soil texture in the entire landscape ranges from sandy loam (77.1, 11.8 and 11.1% of sand, silt and clay, respectively) to clay (35.1, 3.20 and 61.7% of sand, silt and clay, respectively). Sand and silt contents of the topsoil were higher than there in the subsoil while there was an increase in clay content with depth in this landscape. Clay content of the topsoil ranged from 11.1 to 54.2 % while that of the subsoil from 18.6 to 60.9 %.

Soil in this landscape tended to be loose and porous as soil bulk density ranged from 0.851 to 1.76 g/cm^3 for both topsoil and subsoil. The value of topsoil bulk density was lower than that of the subsoil. The topsoil bulk density was positively correlated with sand content (R = 0.65) while negatively correlated with organic matter content (R = - 0.87, Table 3). This indicated that high sand content mostly led to high soil bulk density. Water holding capacity ranged from 3.5 to 19% by weight. There was a positive correlation between soil water holding capacity and bulk density in the topsoil.

Table 1. Properties of topsoil (0 - 20 cm) in the Wat Chan watershed, 107 samples.

Soil Properties	Min.	Mean	Max.	Std Dev.
Sand (%)	35.0	53.3	77.4	11.3
Silt (%)	6.70	17.3	32.6	6.34
Clay (%)	11.1	29.4	54.2	7.60
pH (KCl)	4.07	4.66	5.78	0.282
pH (Water)	4.73	5.31	6.15	0.254
Total N (%)	0.041	0.107	0.328	0.057
P (mg kg^{-1})	0.771	10.7	53.5	10.9
K (mg kg^{-1})	29.13	132	349	63.9
Ca ($cmol_c$ kg^{-1})	0.272	1.35	7.01	1.03
Mg ($cmol_c$ kg^{-1})	0.181	0.409	0.498	0.071
Na (mg kg^{-1})	15.5	28.5	62.3	6.23
Sum of cations ($cmol_c$ kg^{-1})	0.741	2.22	8.32	1.16
OM (%)	0.772	3.30	8.15	1.59
EC (dS m^{-1})	2.85	7.50	24.3	3.83
Bulk Density (g/cm^3)	0.851	1.35	1.75	0.210
Water Holding Capacity (%)	3.50	8.86	19.1	2.13

Table 2. Properties of subsoil (20 - 40 cm) in the Wat Chan watershed, 107 samples.

Soil Properties	Min.	Mean	Max.	Std Dev.
Sand (%)	33.1	43.1	68.1	7.85
Silt (%)	0.210	13.5	29.7	4.95
Clay (%)	18.6	43.4	60.9	7.28
pH (KCl)	3.93	4.48	5.43	0.202
pH (Water)	4.73	5.23	5.99	0.198
Total N (%)	0.021	0.060	0.179	0.028
P (mg kg^{-1})	0.359	3.05	25.4	3.62
K (mg kg^{-1})	31.8	104	279	45.5
Ca ($cmol_c$ kg^{-1})	0.158	0.746	4.43	0.622
Mg ($cmol_c$ kg^{-1})	0.095	0.385	0.500	0.081
Na (mg kg^{-1})	21.4	29.6	50.9	4.31
Sum of cations ($cmol_c$ kg^{-1})	0.526	1.53	5.31	0.710
OM (%)	0.331	1.43	4.05	0.622
EC (dS m^{-1})	2.00	4.01	16.3	1.94
Bulk Density (g/cm^3)	0.755	1.37	1.76	0.173
Water Holding Capacity (%)	3.96	7.37	12.6	1.47

Table 3. Correlation matrix of selected soil properties, the Wat Chan watershed, Thailand

a) Topsoil

	Sand (%)	Silt (%)	Clay (%)	OM (%)	BD (g/cm^3)	WHC (%)
Sand (%)	1.00					
Silt (%)	-0.76	1.00				
Clay (%)	-0.84	0.30	1.00			
OM (%)	-0.53	0.74	0.17	1.00		
BD (g/cm^3)	0.65	-0.71	-0.38	-0.87	1.00	
WHC (%)	0.38	-0.34	-0.27	-0.39	0.44	1.00

b) Subsoil

	Sand (%)	Silt (%)	Clay (%)	OM (%)	BD (g/cm^3)	WHC (%)
Sand (%)	1.00					
Silt (%)	-0.43	1.00				
Clay (%)	-0.79	-0.22	1.00			
OM (%)	-0.28	0.53	-0.06	1.00		
BD (g/cm^3)	0.49	-0.46	-0.21	-0.76	1.00	
WHC (%)	0.20	-0.29	-0.02	-0.14	0.08	1.00

Remark : OM = Organic matter content
BD = Soil bulk density
WHC = Soil water holding capacity

The reaction of soils in this landscape was mostly acidic with pH measured in H_2O ranging from 4.7 to 6.2 while KCl-pH ranged from 3.93 to 5.78 and was consistently less than that measured in H_2O. This indicated that the soil was net negatively-charged. There was no significant difference in pH between the topsoil and subsoil. Most of the measured pH values were higher than 5.5 and only four subsoil samples measured less than 5.0.

Compared with soil nutrient values listed by Landon (1990), values of all soil nutrients in these samples (N, P, K, Ca, Na, Mg, sum of cations, and OM) ranged from very low to very high. The topsoil is a general guide of nutrient status of soils because it is a major zone of root development and carries much of the nutrients available to plants. This study has shown that most topsoils contain more nutrients than the subsoil. The variation of the topsoil nutrients was also higher than that of the subsoil in this landscape except for Mg, probably because topsoil is subject to manipulation and management.

Landscape Attributes and Soil Property Relationships

Landscape attributes and properties of the topsoil and subsoil were significantly correlated (Tables 4 and 5). The landscape attributes most highly correlated with topsoil and subsoil properties were elevation, slope, land use and annual rainfall. These topographic attributes heavily influence water movement through and over the landscape, which probably most strongly influenced soil processes within a landscape (Hugget, 1975; Pennock et al., 1994). Correlation between CTI and soil properties such as organic matter content and water holding capacity were significant in this analysis as well.

Table 4. Correlation matrix between landscape attributes and topsoil properties, the Wat Chan watershed, Thailand

Soil Properties	Elevation (masl)	Slope (degree)	Aspect (direction)	Plan [1]	Profile [2]	CTI [3]	Landuse [4]	Rainfall [5]
Sand (%)	-0.48 **	-0.28 **	0.12	0.03	-0.07	0.11	-0.07	-0.54
Silt (%)	0.62 **	0.37 **	-0.11	0.00	0.01	-0.14	-0.03	0.47
Clay (%)	0.19 *	0.09	-0.08	-0.05	0.10	-0.04	0.14	0.41
pH (water)	0.06	0.02	0.05	-0.05	-0.14	0.01	-0.24 **	-0.07
pH (KCl)	0.07	0.03	0.05	-0.09	-0.07	0.03	-0.08	-0.22
Total N (%)	0.58 **	0.38 **	-0.15	-0.04	-0.07	-0.19 *	-0.05	0.47
P (mg kg^{-1})	-0.14	-0.26 **	0.16 *	0.02	0.02	0.06	-0.06	-0.64
K (mg kg^{-1})	0.33 **	0.23 **	0.03	-0.05	-0.07	-0.02	-0.10	0.25
Na (mg kg^{-1})	0.10	-0.15	0.04	0.08	-0.03	0.06	-0.12	0.08
Ca ($cmol_c$ kg^{-1})	0.24 **	0.22 **	-0.06	-0.06	-0.10	-0.02	-0.26 **	0.23
Mg ($cmol_c$ kg^{-1})	-0.17 *	-0.04	-0.08	-0.18 *	0.12	0.10	-0.10	-0.23
Sum of cations ($cmol_c$ kg^{-1})	0.26 **	0.22 **	-0.05	-0.07	-0.09	-0.01	-0.25 **	0.23
OM (%)	0.58 **	0.39 **	-0.11	-0.04	-0.05	-0.21	0.01	0.51
EC (dS m^{-1})	0.29 **	0.21 *	0.00	0.07	-0.18 *	-0.10	-0.27 **	0.22
Bulk Density (g/cm^3)	-0.45 **	-0.31 **	0.11	0.05	0.01	0.17	0.02	-0.54
Water Holding Capacity (%)	-0.33 **	-0.24 **	0.06	-0.15	0.06	0.22 **	-0.13	-0.26

Remark: * significant difference at P = 0.05
** significant difference at P = 0.01

[1] Plan - Plan curvature or the slope concavity perpendicular to the slope
[2] Profile - Profile curvature or the slope concavity down or with the slope
[3] CTI - Compound Topographic Index – the wetness index
[4] Land Use - Categories of land use types
[5] Rainfall - Annual rainfall in mm.

Table 5. Correlation matrix between landscape attributes and subsoil properties, the Wat Chan watershed, Thailand

Soil Properties	Elevation (masl)	Slope (degree)	Aspect (direction)	Plan [1]	Profile [2]	CTI [3]	Landuse [4]	Rainfall [5]
Sand (%)	-0.48 **	-0.28 **	0.12	0.03	-0.07	0.11	-0.07	-0.54
Sand (%)	-0.49 **	-0.24 **	0.05	0.06	-0.06	0.16 *	-0.07	-0.38
Silt (%)	0.54 **	0.35 **	-0.10	0.01	-0.03	-0.08	0.01	0.40
Clay (%)	0.16 *	0.02	0.01	-0.07	0.08	-0.11	0.07	0.14
pH (water)	0.13	-0.06	0.03	0.00	-0.13	0.01	-0.27 **	-0.04
pH (KCl)	0.05	-0.09	0.10	0.00	-0.01	0.06	-0.08	-0.38
Total N (%)	0.46 **	0.35 **	-0.20 *	-0.04	-0.07	-0.18 *	-0.13	0.50
P (mg kg^{-1})	-0.21 *	-0.17 *	0.13	-0.01	0.04	0.14	-0.01	-0.49
K (mg kg^{-1})	0.19 *	0.08	0.11	0.01	-0.06	0.03	-0.11	-0.18
Na (mg kg^{-1})	0.25 **	0.00	0.02	0.07	0.05	-0.02	0.04	-0.09
Ca ($cmol_c$ kg^{-1})	0.07	0.04	-0.06	-0.01	-0.08	0.08	-0.31 **	0.05
Mg ($cmol_c$ kg^{-1})	-0.03	0.06	-0.03	-0.15	-0.07	0.05	-0.14	-0.10
Sum of cations ($cmol_c$ kg^{-1})	0.10	0.05	-0.03	-0.02	-0.09	0.08	-0.30 **	0.00
OM (%)	0.41 **	0.27 **	-0.17 *	-0.02	-0.08	-0.16 *	-0.05	0.52
EC (dS m^{-1})	0.18 *	0.14	-0.02	0.06	-0.19 *	-0.06	-0.39 **	0.20
Bulk Density (g/cm^3)	-0.40 **	-0.21 *	0.21 *	0.04	0.01	0.17 *	-0.03	-0.57
Water Holding Capacity (%)	-0.32 **	-0.08	-0.08	-0.14	0.03	0.03	-0.02	0.10

Remark: * significant difference at P = 0.05
** significant difference at P = 0.01

[1] Plan - Plan curvature or the slope concavity perpendicular to the slope
[2] Profile - Profile curvature or the slope concavity down or with the slope
[3] CTI - Compound Topographic Index - the wetness index
[4] Land Use - Categories of land use types
[5] Rainfall - Annual rainfall in mm.

There was a highly negative correlation between sand content and elevation, slope and annual rainfall in both topsoil and subsoil samples (P = 0.01). This resulted from a higher percent sand at low elevations, as well as less slope and lower annual rainfall. In contrast, silt content was positively correlated with elevation, slope and annual rainfall in both topsoil and subsoil samples. So distribution of soil particles in this landscape appears related to hydrological and erosional processes.

In this steep, rugged, mountain landscape, water is probably the main agent that loosens and erodes the soil. The amount of annual rainfall increased with increasing elevation in this landscape (R = 0.22, Table 6) and consequently higher elevations experience stronger leaching conditions. With respect to physical soil properties, both the texture and structure play a dominant role. Soils with high content of very fine sand or silt are highly susceptible to interrill and rill erosion (Wishmeier et al., 1971) while an increasing clay content generally lowers the susceptibility of soils to interrill erosion (Meyer, 1981). However, organic matter, which typically is the major agent in the formation of aggregates in surface soil horizons, might be a reason that slows the movement of aggregated small soil particles.

Numerous studies showed increased aggregation of fine particles with greater amounts of organic matter in soil (Parton et al., 1987 and Richter et al., 1990). Those studies also revealed that aggregates of fine soil with organic matter were more stable (Anderson et al., 1981) and might be difficult to detach by raindrops. Kemper and Koch (1966) found a marked increase of aggregate stability up to an organic matter content of about 2%. According to the highly positive correlation between organic matter content and elevation (R = 0.58), there should be more aggregation of soil particles at higher elevations. This may be a reason why sand particles moved further downslope than soil aggregates and left small particles at high elevations and slope areas. The results of this movement should be that sand particles accumulated at lower elevations and less-steep slope with low annual rainfall. Such a process was supported by Alberts's observation (1980) that soil particles larger than 0.5 mm were high in rill and interrill sediments and less than 5% of that sediment was composed of clay.

Table 6. Correlation matrix of landscape attributes, the Wat Chan watershed, Thailand

	Elevation	Slope	Aspect	Plan	Profile	CTI	Landuse	Rainfall
Elevation	1							
Slope	0.475	1						
Aspect	-0.111	-0.184	1					
Plan	0.012	-0.201	0.095	1				
Profile	-0.133	0.097	-0.026	-0.458	1			
CTI	-0.294	-0.601	0.227	-0.215	0.171	1		
Land Use	0.203	0.299	-0.124	-0.149	0.245	-0.149	1	
Rain	0.216	0.358	-0.142	-0.028	-0.026	-0.211	0.013	1

$R_{0.05} = 0.16$, $R_{0.01} = 0.22$

There was a highly significant positive correlation between clay content and annual rainfall in the topsoil. A significant positive correlation also occurred between elevation and clay content (P = 0.05). There was, however, no correlation between measured clay content and landscape attributes in subsoil samples. So silt and clay content were highest at high elevations with high annual rainfall. This suggests that the surface particle sizes seemed to be distributed according to the expected effects of erosion while the subsoil did not appear to be affected by erosional processes in this landscape.

Soil bulk density of topsoil and subsoil was negatively correlated with elevation, slope and amount of annual rainfall. The variation of soil bulk density is likely related to soil texture and organic matter. With highly aggregated soil that mostly occur at high elevation, steep slopes and higher amounts of annual rainfall, then soil bulk density was likely to be low in this landscape characteristic -which was supported by a significant correlation between soil texture and landscape attributes.

Soil organic matter and N content were both positively correlated with elevation, slope and annual rainfall. This probably was a result from high input of organic matter and a slower decomposition rate in the cooler and wetter high elevations with higher rainfall. This would account for the higher organic matter content and the corresponding larger values of soil N. Consequently, it appears that low temperature at high elevation might be an important factor controlling organic matter and N content distribution. Rainfall was also positively correlated with soil organic matter and N content in this landscape.

There also was a highly positive correlation between the sum of cations and slope and annual rainfall, which was similarly correlated with organic matter and N content. This can be explained that the cation exchange capacity of organic matter is higher than that of low activity clays. Thus the sum of cations was highest at higher elevation with higher annual rainfall, which also contained the most organic matter.

A highly negative correlation between P and annual rainfall and slope was observed in this landscape. Considerable erosion had occurred resulting in a movement of soil from the upper to lower slopes. This, in turn, probably led to a decrease in soil profile depth on the upper slopes and an increase on the lower slopes. This process also led to low P content in the steep slopes where the low P subsoil was exposed. High amounts of rainfall also contribute to P transport through the soil profile (Whitington, 1994).

Several variables were not related to landscape attributes. There was no correlation between pH, Na and Mg in topsoil samples and landscape attributes in this landscape. Aspect, plan and profile curvature were also not the main topographic attributes that correlated with soil attributes.

Most of the measured chemical properties of subsoils (pH, K, Na, Ca, and Mg) were not correlated with landscape attributes. This might be because most of the soil nutrients in the topsoil were influenced by topography in this landscape and by the movement of water.

Statistical Models of Soil Properties

Landscape attributes (topographic attributes, land use types and annual rainfall) were used to predict measured soil properties. Degree of slope and CTI were log transformed before analysis. Tables 7 and 8 present the intercepts, coefficients and standard errors (in parenthesis) of independent variables, and the R^2 of the best predictions of measured soil properties in the topsoil and subsoil, respectively. The correlation among landscape attributes indicated that independent statistical tests could not be carried out on single attributes.

The regression equations presented in Table 7 predict sand, silt, nitrogen (N), organic matter (OM), extractable P (P), and bulk density (BD), explaining from 40% to 55% of the variability. Other predictions of measured soil properties with R^2 less than 30% were not considered, even though there were significant correlations between those soil properties and landscape attributes.

Elevation and annual rainfall were the most significant predictors of measured sand content in this landscape. Concavity of the profile curvature was an additional attribute that helped explain silt content besides elevation and rainfall. This suggests that silt content was likely to accumulate at high elevations with concave morphology. Silt was not likely to accumulate at low elevations (footslope) as mentioned in the above section.

CTI and land use were additional landscape attributes besides elevation, slope and annual rainfall that explained variation in OM and N content in this landscape. The high potential moisture content (high CTI value) in open land tended to be associated with high content of OM and N. This implied that in areas where there were uniform moisture conditions, the average total OM and N content tended to increase. Buckman and Brady(1969) states that effective soil moisture exerts a very positive effect on the accumulation of organic matter and nitrogen in soils. This is especially true for the grasslands.

Sand, silt, nitrogen content (N), organic matter content (OM) and bulk density (BD) of subsoil samples, were predicted from 33% to 47% of the variability of measured subsoil properties (Table 8).

Based on the soil-landscape study in the Wat Chan watershed, relationships between sand, silt, OM, N, P and BD and landscape attributes could be used for prediction of soil properties in this landscape until a detailed survey becomes possible.

Table 7. Predicted soil properties of topsoil (0 - 20 cm) using topographic attributes in the Wat Chan watershed (values in parenthesis are standard errors).

Soil Properties	**Intercept**	**Elevation (m)**	**Log(Slope) (degree)**	**Log(CTI)**	**Landuse**	**Rainfall (mm/year)**	R^2
Sand (%)	440 (50.5)	-0.0595 ** (0.0108)		-1.86 (1.265)		-0.284 ** (0.0444)	0.46
Silt (%)	-155 (25.2)	0.0463 ** (0.0054)			-1.408 ** (0.503)	0.116 ** (0.0227)	0.55
Clay (%)	-162 (40.2)				1.121 (0.752)	0.163 ** (0.0352)	0.19
pH (water)	5.07 (0.177)				-0.0706 * (0.0307)		0.08
pH (KCl)	8.68 (1.44)					-0.0030 * (0.0013)	0.05
Total N (%)	-1.43 (0.246)	0.0004 ** (0.0001)	0.0150 * (0.0066)	0.0176 * (0.0078)	-0.0135 ** (0.0048)	0.0010 ** (0.0002)	0.52
P (mg kg^{-1})	424 (48.9)					-0.364 ** (0.0431)	0.40
K (mg kg^{-1})	-786 (352)	0.262 ** (0.0763)	20.7 * (9.430)	25.2 * (11.2)	-16.4 ** (6.81)	0.558 (0.309)	0.22
Ca ($cmol_c$ kg^{-1})	-10.4 (5.58)	0.0032 ** (0.0012)	0.421 ** (0.150)	0.410 * (0.177)	-0.457 ** (0.108)	0.0085 (0.0049)	0.25
Mg($cmol_c$ kg^{-1})	1.41 (0.395)					-0.0009 * (0.0003)	0.09
Na (mg kg^{-1})	16.9 (7.67)	0.0151 (0.0078)	-1.86 * (0.720)				0.07
Sum of cations ($cmol_c$ kg^{-1})	-11.1 (6.20)	0.0039 (0.0013)	0.479 (0.166)	0.487 (0.197)	-0.510 (0.120)	0.0093 (0.0054)	0.26
OM (%)	-44.4 (6.82)	0.0102 ** (0.0015)	0.369 * (0.183)	0.473 * (0.217)	-0.265 * (0.132)	0.0327 ** (0.0060)	0.53
EC (dS m^{-1})	-27.2 (20.5)	0.0126 ** (0.00441)	0.698 (0.429)		-1.63 ** (0.395)	0.0259 (0.0181)	0.24
Bulk Density (g/cm^3)	8.09 (0.940)	-0.0009 ** (0.0002)				-0.0051 ** (0.001)	0.41
Water Holding Capacity (%)	41.5 (11.4)	-0.0074 ** (0.0024)				-0.0220 * (0.0103)	0.17

Remark : * = t-value significant at $P < 0.05$, ** = t-value significant at $P < 0.01$

Table 8. Predicted soil properties of subsoil (20-40 cm) using topographic attributes in the Wat Chan watershed. (values in parenthesis are standard errors).

Soil Properties	Intercept	Elevation (m)	Log(Slope) (degree)	Log(CTI)	Landuse	Rainfall (mm/year)	R^2
Sand (%)	223 (37.6)	-0.0418 ** (0.0079)				-0.120 ** (0.0339)	0.33
Silt (%)	-109 (23.6)	0.0314 ** (0.0051)	0.971 (0.632)	1.669 ** (0.749)	-0.732 (0.457)	0.0794 ** (0.0207)	0.41
Clay (%)	28.7 (8.93)	0.0140 (0.0085)					0.03
pH (water)	4.40 (0.250)	0.0005 * (0.0002)			-0.0700 ** (0.0214)		0.11
pH (KCl)	9.72 (1.05)	0.0003 (0.0002)				-0.0043 ** (0.0009)	0.16
Total N (%)	-0.700 (0.129)	0.0001 ** (0.0000)	0.0063 (0.0034)	0.0069 (0.0041)	-0.0087 * (0.0025)	0.0006 * (0.0001)	0.47
P (mg kg^{-1})	109 (18.3)					-0.0933 ** (0.0161)	0.24
K (mg kg^{-1})	639 (253)	0.149 ** (0.0535)			-8.27 (4.834)	-0.567 * (0.227)	0.11
Ca ($cmol_c$ kg^{-1})	1.61 (0.427)		0.213 * (0.0938)	0.176 (0.111)	-0.266 ** (0.0682)		0.14
Mg($cmol_c$ kg^{-1})	0.467 (0.050)				-0.0149 (0.0087)		0.05
Na (mg kg^{-1})	52.7 (24.1)	0.0150 ** (0.0050)				-0.0342 (0.0217)	0.09
Sum of cations ($cmol_c$ kg^{-1})	1.09 (0.978)	0.0014 (0.0009)	0.228 (0.107)	0.245 (0.128)	-0.317 (0.0778)		0.16
OM (%)	-17.2 (2.89)	0.0025 ** (0.0006)			-0.0859 (0.0555)	0.0145 ** (0.0026)	0.37
EC (dS m^{-1})	4.06 (2.29)	0.00496 * (0.00218)	0.393 (0.210)		-1.07 ** (0.197)		0.25
Bulk Density (g/cm^3)	7.33 (0.793)	-0.0007 * (0.0002)	0.0377 (0.0162)			-0.0047 ** (0.0007)	0.44
Water Holding Capacity (%)	-1.10 (7.95)	-0.0063 ** (0.0017)				0.0132 (0.0072)	0.15

Remark : * = t-value significant at $P < 0.05$, ** = t-value significant at $P < 0.01$

CONCLUSIONS

Topography is known to play a critical role in modifying both the microclimate and the hydrological conditions within a landscape. In particular, the role of topography on the movement of water and the consequent redistribution of materials carried within the water can influence or control the type and intensity of soil processes within a landscape. Analysis of the relationships between soil and landscape has shown several significant relationships between measured soil properties and characteristics of landscape attributes in this landscape. Prediction of some soil properties was estimated, based on regression analysis. This method offers a promising, cost-effective means of creating high-resolution maps needed for soil-specific management.

The results indicated that significant correlations between quantified topographic attributes and measured soil properties exist. Elevation, slope, land use and annual rainfall in this landscape were the attributes most highly correlated with soil properties measured at 107 locations. Physical properties of soil (such as soil texture and bulk density etc.) were better predicted by this method than were chemical properties (soil nutrients and pH) perhaps, because physical properties are less subject to change by farming than chemical properties.

CTI and profile curvature showed some influence on the variation of N and OM content in this landscape. More attention should be focussed on stratifying samples within watershed. Sample points should properly represent the landscape attributes (such as CTI, plan and profile curvature etc.) which are involved in the landform classification. These might be used as criteria for further study in soil-landscape modeling either by adding more sample sites or looking for other factors such as soil temperature and pedotransfer functions to explain soil properties (Bouma and Lanen, 1985). Drainage conditions, differential transport and deposition of eroded material and leaching, translocation and re-deposition of mobile chemical constituents also affect soil properties. These soil-landscape processes should be considered to further improve the prediction of soil chemical properties.

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