GEOGRAPHICAL ANALYSIS OF LANDSCAPE IN THE WAT CHAN WATERSHED, NORTHERN THAILAND

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ABSTRACT

Deforestation, one of the important problems in the tropical forest, can affect the accelerated land degradation that lead to decreased soil productivity and agricultural production. Geographical attributes in the landscape, such as land use types, topographic attributes, and soil information play important roles in determining the landscape structure and functions. This study used spatial analysis, such as GIS overlay and a non-parametric test of land use dynamics to provide a historic documents of deforestation and land use dynamics in the Wat Chan watershed, between 1974 and 1996. Soil-landscape relationships were used to express our understanding of the distribution of soil materials in relation to geomorphologic features.

The method of a non-parametric trend analysis for land use change permits extracting a probability of change in land use and helps illustrate that about 0.76% of the landscape can be identified as cycled land. Regressing the probability of land use change on physical attributes and topographic attributes indicated that increased land use change from forest to open lands were associated with short distances to villages, short distances to forest edge, high elevation and high CTI ($R^2 = 0.74$).

Analysis of soil landscape indicated that elevation, slope, land use, and annual rainfall were the attributes most highly correlated with measured soil properties. CTI and profile curvature showed some influence on the variation of N and OM in this landscape. Coefficients of sand, silt, N, OM, extractable P, and bulk density variable were highly significant as indicated by t-test with R^2 ranged from 0.40 to 0.55.

Multiple criteria analysis was used to characterize degradation of sub-watersheds based on landscape attributes that are influencing erosion. Only two sub-watersheds were characterized as extremely low degradation while five sub-watersheds were characterized as high degradation. The most of sub-watershed were classified as low and moderately degraded.

Results illustrate that spatial analysis and GIS can improve understanding of geographical distribution in the Wat Chan watershed in both spatial and temporal aspects. This knowledge of landscape attributes and their spatial and temporal variation are important components for efficient management of resources in the Wat Chan watershed, Northern Thailand.

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CHAPTER I

Introduction

In recent years, concerns about potential extinction of species has been joined by alarm about possible future global warming caused by "greenhouse gases" such as the carbon dioxide released by deforestation. In developing countries, on-site effects caused by deforestation can further include increased erosion potential, soil nutrient loss and a reduced quality of forest are considerable problems in mountainous areas. Southeast Asia, a region that possesses one-fifth of the world's tropical forest, has been affected by deforestation for many reasons including increased population pressure, infrastructure development and commercial logging (Rainforest Action Network, 1993). The pattern and rate of deforestation varies from place to place and time to time depending on human activity, topography, and infrastructure. This disturbance from forest cutting can affect the timing and magnitude of stream flow (Swanson et al., 1992) and the accelerated land degradation can lead to decreased soil productivity and agricultural production.

Background

For the past two decade, Thailand located in Southeast Asia has been facing problem of land degradation, especially in the highlands. The country occupies an area of 513,00 km^2 with population of about 60 million. About 80 percent of the population is engaged in agriculture, and farmers in most rural areas are poor. As population increases, farms become smaller and more fragmented as land is divided among siblings with each generation. This has created growing numbers of farmers with too little land to feed their families or with no land at all. Many of these farmers have, of necessity, cleared land for new farms in the forests. Fox et al. (1995) reported that between 1954 and 1976 closed canopy forest cover in Northern Thailand declined from 76 percent to 56 percent of the landscape. Forest statistics in all of Thailand have shown that forest cover has decreased from 46.1 million ha. to 10 million ha. from 1961 to 1992 (Charuppat, 1994).

The highlands of Thailand, exemplified by the Wat Chan area of the Mae Chaem watershed, often are complex landscapes with different forests depending on geographical features and biophysical characteristics such as slope, aspect, elevation, and soil characteristics. The natural vegetation is a mix of pine, evergreen and deciduous broadleaf forests. The pine-dominated forests appear to occupy the less fertile soils with lower moisture holding capacity. The valley bottoms have been converted to paddy, and the more gentle slopes have been or are being converted to upland crops. The soils are highly weathered but appear moderately fertile except on the steepest slopes and ridgetops that are occupied by pine.

The complexity of the landscape has led to variability in opening land for agricultural activities also causing variation in crop productivity. A preliminary study of the Wat Chan watershed during an agronomic survey of biophysical characteristics revealed that only 13% of the total rice cultivated area in the 1993 growing season was upland rice, and 87% was paddy rice. Upland rice grain yield ranged from 0.9 t/ha to

4.6 t/ha with an average of 2.2 t/ha. (A Progress Report of Sustaining Land Resource Management for Agriculture and Forestry in the Tropical Small Watershed Environment, July 1993 - June 1994, unpublished). Each farm household managed several plots of upland rice ranging from one to ten plots with the average of 3.2 plots. In the 1993 season, the area of upland rice cultivation averaged 0.4 ha. per household.

Farmers continue to practice shifting cultivation. However, the 1993 survey indicated that farmers have shortened the fallow period from 15 years to an average of 3.23 years. Only 34% of farm households cultivated upland rice in the same plot every year. Grain yield of those plots ranged from 1.0 t/ha to 2.8 t/ha with an average of 1.8 t/ha. Soil analysis revealed a very low level of available phosphorus (P), ranging from 4.2 to 11.6 mg kg^{-1} (Bray II method). Surveying ninety five households in four villages revealed that, generally, farmers in this area don't have enough rice for consumption. The strategies that farmers have chosen when they are faced with rice deficits were expanding paddy fields by encroaching on forests, and using manure or chemical fertilizer.

Soil resource, one of the components of landscape study in the tropical highland areas, is usually detrimentally affected by deforestation. These changes can result in long-term degradation of environmental quality (Pimental et al., 1987). The decline in soil productivity and quality of the watershed with the loss of forest is likely to be a serious problem for agricultural activities in the area because organic material plays a crucial role in soil ecosystems and usually declines with deforestation. Besides the loss of forest products, services, and habitats, fallow periods which allow forests to regenerate are shortened because of land scarcity. Such land pressure can lead to use of land even in sloping, infertile areas which causes further depletion of soil fertility. The depletion of soil fertility due to repeated use of land for agricultural activities varies depending on the landscape characteristics such as slope, aspect, land use and soil properties and on the soil management. Soil attributes, such as soil texture and structure, organic carbon, nitrogen, phosphorus and potassium are related to the quality of soil, and can all affect plant growth. Variability in these attributes, however, is affected by environmental factors such as rainfall amount and distribution, temperature, parent material of the soil, topography and characteristics of the plant community growing in the soil.

In the past, soil resource in the highlands of Thailand was seldom investigated due to the complexities of the landscape. These complexities cause soil properties to exhibit different and complex scales of variation (Beckett et al., 1971; Burrough 1993), which require costly investments of time and money for conventional soil survey. So, lack of soil information, especially quantitative information on spatial distribution, in this area hinders the development of effective environmental management strategies, hinders implementing sustainable farming systems and results in increased human-induced soil degradation.

Spatial Landscape Study for Watershed Resource Management

Landscape attributes such as land use types, topographic attributes and soil information are critical factors for managing watersheds. However, potential land productivity, and existing land use and practices are not always in concert with each other. In some circumstances the degradation of the watersheds reduces soil productivity and loss of other resources. Landscape characterization is needed to assess for resource potential and proper utilization to assist planning for development. Spatial information is needed that considers land use type, topographic and soil attributes of the landscape.

To obtain this information, a framework for integrated watershed study was developed (Figure 1.1). This study uses spatial analysis to quantify sub-watershed characteristics in the Wat Chan watershed, Northern Thailand. The objectives of the study were to: 1) Characterize land use pattern and change and establish relationships between land use pattern and change and landscape attributes, 2) Establish soil-landscape relationships to estimate soil properties in unsampled locations, 3) Characterize and utilize watershed attributes to enable others to restore and manage degraded sub-watershed on a sustainable bases.

Figure 1.1 A framework for using landscape characteristics and dynamics to improve management of the Wat Chan watershed, Thailand.

CHAPTER II

Literature Review

Importance of Landscape Study

Recently, land degradation has been viewed as a more comprehensive subject which seems to be a part of the environmental crisis of the modern world (Eckholm, 1976). It has a serious impact especially in the developing countries of the world and on the poorest people because of lack of the appropriate management in those areas. Deforestation is considered one of the primary causes of land degradation. It is not possible to conserve all forest since people have to have food as well as other agricultural and forest products. Uncontrolled and unwarranted deforestation, however, is perhaps the greatest of all ecological dangers that cause the unstable crop productivity. It is difficult to give general guidelines on the quality and kind of deforestation which is allowable under certain conditions unless local and regional possibilities and requirements are determined through an integrated process of land evaluation. This has led to landscape study for land use planning and for sustainable resource management.

The landscape can be defined as the surface of the earth with all its phenomena including landforms, soil, vegetation and attributes that are influenced by humans (Vink, 1983). These characteristics are not static because most of processes taking place influence the conditions of life for human beings and for other organisms. Thus the study of the landscape may be summarized as the study of the relationships in space and in time between phenomena and processes in the landscape including communities of plants and humans.

The concept of Landscape Study

A growing concern over the loss of biodiversity due to deforestation has spurred land managers to seek better ways of managing landscapes from a variety of spatial and temporal aspects. A number of developments, such as an approach to the study of the landscape, which interprets it as supporting both natural and cultural ecosystems, have made it possible to analyze and manage entire landscapes to meet manager's objectives.

One new approach, involving "ecosystem geography", is the study of the distribution pattern, structure and processes of differentiation of ecosystems as interacting spatial units at various scales, which we will describe as "landscape ecology." The developing field of landscape ecology (Forman and Gordon, 1986) has provided a strong conceptual and theoretical basis for understanding landscape structure, function and change (Naveh and Lieberman, 1994). Landscape ecology embodies a way of thinking that many see as useful for organizing knowledge about land management. A major focus of landscape ecology is quantifying the relationships between landscape attributes and ecological process. Much emphasis has been placed on developing methods to quantify landscape attributes (Turner and Gardner, 1991). Land classification for land use planning is seen as a part of applied landscape ecology. Land classification, land evaluation and land use planning all have to use landscape attribute maps as basic documents. They do this by extrapolating and predicting the potential use of land on the basis of its attributes which is whether the resource base is static and static land suitability or a dynamic resource base but static land suitability.

Landscape attributes are important factors that lead to the understanding of processes in the described areas. Exploratory data analysis of those attributes might provide the new perspective in managing resources. Knowledge of landscape change and stability is important for the planning and management of critical and significant natural landscapes as well as highly managed areas. Zheng (1997) studied change of forests between 1972 and 1988 in the Changbai Mountain of China and North Korea and found that the loss of forest cover was strongly associated with timber harvesting at lower elevations which is important in a restoration strategy. Such knowledge is particularly important when the landscapes in question are in close proximity to areas undergoing rapid change. A number of landscape assessments have been widely implemented in many areas in the world. For example, Friedman and Zube (1992), presented an approach to the assessment of spatial and temporal changes in land use at both landscape and vegetation community scales. Their study led to the measurement of landscape stability. So generating landscape attribute maps for quantifying landscapes in space and time is an important step for land use planning and resources management.

Importance of Scale in Landscape Study

The effects of the various components of the landscape are superimposed on each other over different scales because ecosystems in the landscape are often nested within each other and because of the many linkages among components within systems.

So modification of one component may affect the operation of the system as a whole. Managing one landscape without considering scale effects may lead to problems dealing with diverse information from several single-resource inventories.

Analysis and study at different scales allows us to answer different questions that help resource managers to identify and solve problems in the landscape. For example, without considering farm level objectives, a study on the improvement of rice grain yield at the field scale might not be able to answer a question at the farm level with the objective of increasing or sustaining farm income. In the interpolation issues, models developed from one gram of soil in the laboratory might not be appropriate for interpolation to several million kilograms of soil in a hectare of farmland. So a comprehensive inquiry into land management requires an approach that employs a nested set of scales (Blaikie and Brookfield, 1987). In this context, there is a need to study at various scales between the global and local scale, which are appropriate to answer questions and predict consequences of management choice.

Landscape study also should not be limited to individual-resource issues alone, such as rice production. It should be managed as an integrated entity considering the full range of biotic and abiotic characteristics. Resource data for several levels of planning, ranging from the national to the local level are needed. Local activities must be based not only on the local ecological conditions but also on how such local conditions fit into a higher level of organizational hierarchy. This is because relationships with adjoining areas partially determine the response of a parcel of land to management. A disturbance to a large system affects smaller component systems. For example, logging on the upper slopes of an ecological unit may affect small systems downslope, such as stream or riparian habitats. The structure of the landscape in a large scale view is likely to reflect the relationships among elements in systems differently from the small scale view even though it is the same environment. For example, the relationship between topography and land cover usually is a major relationship at the landscape scale. While processes of soil erosion that are related to soil nutrient movement and pollutant transportation in the mountainous area are usually focused at the watershed scale. Consequently, selecting the scale of a study area depends on the management objectives.

So consideration of studied scales will help researchers develop the appropriate information (qualitative or quantitative information) for landscape study that can be useful for defining and solving the problem.

Landscape Attributes in Watershed Study

Landscape attributes can be defined based on any phenomena located in the landscape such as landform, soil and vegetation. They are important in determining the processes taking place in the landscape. In order to obtain landscape attributes to meet modern requirements, such as estimating soil erosion, sediment and pollutant transportation, for watershed study, a parametric approach (such as division and classification of land on the basis of selected attribute values) should be considered for the operation involved. With the numerical criteria of a parametric approach, it will be possible to use these landscape attributes to evaluate watershed characteristics quantitatively. Spatially-explicit, quantitative information of surface geometry, for example, can be defined as slope gradient, slope direction, plan curvature and profile curvature based on a contour map, while information on vegetation structure can be shown as the pattern and rates of landscape change. Spatial soil properties can be quantified by surface interpolation or soil-landscape evaluation based on appropriately measured soil samples. So land use types, topography and soil information are important landscape attributes for landscape study at the watershed scale.

Land Use Characterization and Change in the Landscape

Land use in the landscape embraces all forms from agricultural uses to nature conservation in addition to urban and industrial land uses. Land use type and magnitude is an important component of landscape diversity. It contributes to a variety of wildlife habitats through influencing vegetation diversity and edge (Franklin and Forman, 1987). Change in spatial characteristics of forest openings that are the results of disturbance usually results in a significant forest fragmentation (Skole et al., 1993; Wallin et al. 1994) and this may have a significant impact on biological diversity (Pulliam, 1988).

Soil erosion and transportation of sediment and non-point source pollutants are likely to relate to the alternation of landscapes by human activities in forested area and has generated great interest in recent years. Patterns of deforestation may change considerably in space and time (Knight 1987) that makes it difficult to determine a characteristic landscape mosaic (Christensen 1991). One of the highest priorities of communities with land use change is to improve monitoring on-going changes of landscape attributes. So detecting rates and patterns of land use change is considered an important issue in landscape study for land use planning and resource management.

In the past, land use maps could be obtained from land surveys and inventories. This might be become a serious problem if large spatial extent and different time periods of land use are needed for the landscape study. This would be more difficult to study since landscape attributes are consistently changing. With emergence of remote sensing technologies in combination with the increasing availability of remotely sensed data, the extent and accuracy of land use characterization for landscape study could be improved (Spies et al. 1994). Often remotely sensed data is a main source of information for evaluating use.

Topographic Attributes in the Landscape

Topography plays an important role in the hydrologic response of a watershed to rainfall and has a major impact on fundamental hydrologic, geomorphologic and biological processes active in the landscape. It can effect the organic matter and nutrient storage in soil (Raghubanshi, 1992) by influencing microclimate, runoff, evaporation and transpiration. Estimating the influence of topography on these processes is essential for land-management endeavors that affect or disturb the surface of the landscape.

The topography of the landscape can usually be grouped into distinct segments based on topographic attributes. Topographic attributes can be divided into primary and secondary attributes. Primary attributes are composed of elevation (m), slope gradient (%), aspect (slope direction), slope length, profile curvature and plan curvature

(Pennock et al., 1987) that can be directly calculated from a Digital Elevation Model (DEM) image by using spatial analysis capability of GIS. Slope gradient together with aspect is a major determinant of the radiation regime of a landscape that affects the water balance of the system. Field studies of the effects of slope curvature on moisture contents and movement have been completed by Anderson et al. (1978), and Sinai et al. (1981). Anderson et al. (1978) found that the throughflow following rainfall was strongly convergent into concave (in both plan and profile curvature) elements, leading to soil saturation and discharge of water into adjacent streams. The secondary attributes that have potential use in predicting the spatial distribution of soil properties are the wetness index, the stream power index and the sediment transport capacity index (Moore et al, 1991). The wetness index has been used to characterize the spatial distribution of zones of surface saturation and soil water content in the landscape (Moore et al., 1993). While Gessler et al. (1996) used this index as a rational and quantitative sampling strategy to develop a robust statistical model as a soil-landscape model and found a relationship between this index and soil properties such as organic matter content.

Based on topographic attributes, topographic evaluation for characterizing landform is essential for understanding of the physical, chemical, and biological processes that occur within the landscape. Pennock et al. (1987) presented a classification of distinct, three dimensional landform elements, derived from topographic attributes. Their study also found relationships among these landform elements and selected soil morphological properties.

At present, the computed topographic attributes can be accurately generated from a digital elevation model (DEM) image by using spatial analysis algorithms that can support spatially distributed hydrological and ecological modeling of the landscape. Blaszczynski (1997) presented geographic information systems (GIS) based methods for mapping and classification of a landscape surface based on topographic attributes such as slope, plan, and profile curvature which can simplify the complexity of taxonomic schema for landforms. This method can be used with spatial modeling and GIS capability for the automated extraction of completely new information from an existing property map. This is particularly the case with topographic data traditionally available as elevation contour maps. From a contour map, various types of information, such as watershed boundaries, slope gradients, aspect and more, can now be derived (Jenson et al. 1988).

Soil Attributes in the Landscape

In a landscape study, soil property maps are critical layers in the 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.

The practice of conventional soil survey for mapping soil classification has been described elsewhere (Dent and Young, 1983; and Landon, 1984). A soil surveyor uses the dominant soil-forming factors to infer soil variation by applying the knowledge of the relationship between soil variables and more easily observed attributes such as terrain and vegetation. Over the past several decades, qualitative models have aided soil surveyors describe the distribution of soils in landscapes. They also contribute to the understanding of soil genesis where soil surveys are not completed.

A number of studies attempt to aid in the design of soil maps as well as to define variability within soil map units. The majority of the studies of soil map unit variability have concentrated on the taxonomic variability of soils within soil map units and has been spurred by the adoption of soil taxonomy (Soil Survey Staff, 1975). Little work, however, has centered on the interpretative variability of soil attributes of given area of soil properties within soil map units. However, in the context of land evaluation and management, greater interest lies in understanding the physical and chemical processes of soil formation within relatively short time frames and assessing the interactions between natural processes, environmental change, and anthropogenic impacts. This has led to the requirement of spatially explicit, quantitative soil attributes.

Wilding and Drees (1983) summarized the magnitude of variability observed in various investigations from 1970 to 1980 and found that the variability of soil properties increases as map scales become smaller. They also noted that most soil properties in the map units have a coefficient of variation of 25 to 40 percent. As a consequence of these studies, it has been suggested that, in addition to taxonomic purity, attention should be given to the variability of interpretations and their influence on use and management (Bouma, 1987, De Gruijter 1985).

In recent years, several investigators have developed methods to improve the spatial characterization of soil properties to overcome these limitations in current soil survey procedure. Such methods include soil landscape models which incorporate digital elevation models and the *catena* concepts to estimate various soil map unit attributes (Moore et al. 1993), geostatistical models to produce maps of selected soil attributes and associated variance structure from point observations (Bregt et al. 1991), expert systems to map soil landscape features using local knowledge and environmental database (Skidmore et al. 1991) and a rule-based system to map soil properties (Cook et al. 1996).

In areas without a soil inventory, awareness of the variability of soil attributes in soil classification especially at the landscape level should be considered. This is because soil properties vary across the landscape, due to the modifying effects of topography on soil forming and geomorphic processes (Coleman et al. 1983). This has led to the development of soil landscape evaluation for mapping soil attributes. Relationships between topography and soil properties have been investigated by Milne (1953), Aandahl (1948), Ruhe and Walker (1968), and Aguilar and Heil (1988). So soil-landscape relationships might be of further use and helpful in soil inventory.

Spatial interpolation of soil information

A number of methods have been used for interpolating soil attributes such as prediction based on local soil classification, interpolation and surface fitting, and soil-landscape correlation. Selecting methods for soil parametric mapping depends on many factors such as landscape characters, time and budget condition, and objectives of the study.

Soil mapping based on local soil classification. It is widely assumed that properties of the sampled profiles apply to the complete mapping unit. The soil properties are assumed to vary in concert across the unit. However, the assumption of high soil property covariance is seldom tested even though it controls the reliability of prediction (Butler, 1980). It may be appropriate in particular landscapes that have low spatial variability but in others the assumption may fail altogether (Webster and Butler, 1976). Major limitations of soil inventories and associated databases are related to nature and quality of numerical data describing soil physical and chemical properties. These data are usually summarized for a typical pedon, and without quantitative information on the spatial distribution of properties within map units. Traditionally, numeric values of soil properties are extrapolated to similar landscape positions from the location of the typifying pedon sampled for laboratory characterization. In addition, probability distribution functions of these variables are derived from the experiences of others when needed for some form of simulation modeling. This might be an inaccurate representation of actual soil information.

Soil mapping based on interpolation and surface fitting. In recent years, quantitative soil information has become necessary because environmental modeling has become important due to the role of soil in regulation of environmental quality. This has led to the development of spatial interpolation of soil information based on measured soil properties. Most effort in the development of parametric mapping has been devoted to quantitative interpolation techniques, such as inverse distance weighted interpolation, trend surface interpolation and kriging to provide predictions of soil characteristics across survey area (Webster and Oliver, 1990). These methods are based on spatial relationships of sample values to be considered in interpolation. These developments take into account both the systematic and random characteristics of spatial distribution variables so that quantitative tools can be used for their description and optimal, unbiased estimation. Interpolation and surface fitting are appropriate when areas are intensively sampled and there are few major discontinuities (Webster 1985). A limitation until recently has been the exclusion of information on soil-landscape relationships. Inclusion of such information makes sense where no discernable relationships are apparent among the more easily observed environmental attributes (e.g landform, topography, and land use). However, in complex landscapes, soil formation is influenced by parent material, climate, vegetation, topography, and time (Jenny, 1941). So methods that concentrate on characterization of pattern (e.g. kriging), rather than on the linking of pattern to process often ignores pedogenesis and lack a consistent quantitative framework.

Soil mapping based on soil landscape correlation. The potential for correlating soil attributes with topographic attributes and land use types has physical meaning (Moore et al., 1993; and McKenzie and Austin, 1993). These relationships express our understanding of the distribution of soil materials in relation to geomorphologic features such as drainage networks, geological structure or chronology (Lammers and Band, 1990). These relationships can be used for soil landscape study to enable more reliable estimates of soil attributes that have land use implications and related to map units or landform elements contained within map units. Soil landscape models also aid in the extrapolation of detailed soil patterns determined in small sample areas to the wider area. It is standard practice in free and integrated survey for pedologists to use quantitative models for mapping soils that rely on related factors as explanatory variables (e.g. landform, local drainage, vegetation, parent material etc.) Soil distribution is predicted on the basis of relationships. These mental and verbal models can be complex and have considerable predictive power.

A number of studies have explored soil-landscape relationships. To relate soil attributes with landscape feature, Webb and Burgham (1997) found that relocation of topsoil material from upper to lower slopes is attributed mainly to the effects of cultivation operations, or directly, through the promotion of soil erosion. Topographic evaluation for simplifying landform for soil-landscape study was used by De Bruin and Stein (1998). They used fuzzy c-means clustering of topographic attributes derived from digital elevation model to represent zones in the soil-landscape and found a high degree of association between wetness index and measured topsoil clay. Currently, soil-landscape models can easily be used for landscape management because landscape attributes are simple to measure and due to the emerging of GIS technology with the spatial analysis algorithms. So soil-landscape models are a promising development for landscape study.

Use of Landscape Attributes in Watershed Studies

Spatially explicit, quantitative information is necessary for both landscape and watershed scale studies for sustainable watershed resources management and includes land use types, topography and soil information. Spatial analysis at the watershed scale is one of the important scales that attempts to provide a more complete understanding of landscape-scale processes, balancing economic and ecological priorities for planning. As we consider that a watershed is an ecological unit, the analysis of a watershed is then intended to address these shortcomings by providing a systematic procedure for characterizing the physical and biological processes active within a watershed. Watershed analysis can also support decision making; it is intended only to generate the information required to make informed choices about potential land management impacts in a spatially-distributed context.

Many studies attempt to understand landscape structure for various objectives. Ekasingh et al. (1995) used Geographic Information Systems (GIS) in combination with remote sensing analysis to study spatial patterns of landscape in Northern Thailand in order to provide indices for prioritizing watersheds and communities in small-scale natural resource and development planning. Detecting change in the landscape can be performed by overlaying two time periods of spatial pattern images in the landscape. This technique can be used to help understand the effects of land use changes on hydrological processes for watershed management. GIS, combined with modeling capacities, will provide a valuable approach for identifying and ranking critical areas. For example, Hamlett et al.(1992) used GIS-based technology combined with a pollutant generation and transport model to rank watershed areas for agricultural pollution prevention based on runoff index, chemical use index, sediment production index and animal loading index.

CHAPTER III

Land Use Characteristics and Dynamic in the Wat Chan Watershed

INTRODUCTION

Deforestation is one of the problems that has been occurring in temperate and tropical regions throughout history. In recent years, much attention has been focused on tropical forests, where as much as 50% of the original forest may have been lost to deforestation in the last two decades, primarily as a result of agricultural expansion.

The highland area, especially the Wat Chan watershed, Northern Thailand, is a complex landscape that usually comprises different forests depending on geographical features and biophysical characteristics. Increasing population density, small-scale subsistence farming practice (such as shifting cultivation etc.) and infrastructure development (such as road networks and electricity lines) in the landscape seem to be the main causes of the change in land use from year to year (Methi et al., 1995). The preservation of watersheds by the government is mostly based on the watershed classification system in Thailand, which seldom considers the relationship between the landscape attributes and the farmers' utilization of land. Such incorrect classification will mislead the watershed management at the landscape level.

Landscape characteristics and dynamics are significant to a range of themes and issues central to the study of global environmental change. Quantifying spatial landscape characteristics and dynamics will provide relationships among attributes in the landscape. Land use, one of the major attributes in the landscape, can be changed spatially and temporally by human activities determined by decisions that are mostly based upon physical attributes (such as transportation networks, location of villages and resource accessibility etc.) and topographic attributes in the landscape. These changes can impact natural resources in the landscape on a sustained basis. The roles of land use pattern and change are important at both local and global scales. For example, land-atmosphere-climate interaction (Salati and Nobre, 1991; Giambelluca and Ziegler, 1995), hydrology and the movement of materials (e.g. soil and nutrients) (Swanson and Franklin, 1992), the potential for significant climate change as a result of increases in atmosphere CO_2 concentration (Woodwell et al. 1978; Adams et al. 1990), physical and chemical soil properties (Neill et al.1995; Arrouays, 1994), biological diversity (Ehrlich and Wilson, 1991; Zampella et al. 1997) and sustainable productivity (Sinha and Swaminathan,1991). So analysis of the recent history and present patterns of land use offers a present day baseline for assessing future landscape patterns.

Tools for Land Use Characterization and Change Analysis

Resource managers in Thailand face a number of formidable land use problems. Examples include deforestation and sustainable development of land and water resources. To meet these challenges, any rigorous analysis of land management alternatives must include consideration of spatial interactions between people and their environments. Analysis of land use characteristics and dynamics for the complexities of ecosystem management at a landscape level requires a wide variety of information on both spatial and temporal scales. To obtain this information without suitable tools is costly in time and resources. The resulting range of alternatives considered will be limited as well.

Satellite remote sensing has made it possible to collect a wide spectrum of data on natural resources in a reliable and systematic manner. Resource satellites can assist resource managers in taking timely action and measure the cost effectiveness of their intervention objectively.

Remote sensing relies on the measurement of reflected light from the land surface over areas from several to hundreds of kilometers. Reflected light is modified by many parameters of biological interest, including canopy chemistry (primarily pigments and water), canopy architecture and the proportion of vegetation on the soil surface. These measurements are made over 100% of the sampled surface, typically at a regional scale that is larger than that ecologists measure in the field. This allows researchers to begin determining the interaction between resources within the sampled region and at scales that are meaningful to the management of resources of interest.

GIS (Geographic information systems) is a powerful tool for collecting, storing, retrieving, transforming, and displaying spatial data to enable a suite of spatial analyses and geographic comparisons (Burrough, 1986). GIS data layers, each representing different kinds of mapped information, can be analyzed through Boolean overlay operations, standard database query and summary, and through a host of specialized algorithms including interpolation, neighborhood, surface and geophysical analyses. Because the data can be accessed, transformed, and manipulated interactively they can be used to study environmental processes or to analyze the results of trends, or anticipate the possible results of a planning decision.

The development of remote sensing techniques during the last two decades, in combination with the increasing availability of remotely sensed images and new methods in spatial modeling and GIS, have increased the extent and accuracy of assessing rates, pattern, and direction of regional change (Cohen et al.1995).

Land Use Characterization and Change Analysis

Complexity in mountainous areas is one of the factors that causes difficulty in understanding spatial patterns and changes of the landscape. It is necessary to gather both spatial and temporal information. A spatial analysis is necessary to characterize spatial patterns and dynamics of land use and other attributes of the landscape. There have been many attempts to characterize the spatial variability of land use. These attempts have concentrated on the characterization of pattern, rather than on the linking of the pattern to an underlying process.

By merging GIS and remote sensing technologies, the relationships between topographic attributes, such as elevation, slope, and aspect and land use pattern can be studied to increase understanding the structure of the landscape (Fox et al. 1995). Topographic attributes that most concern landscape characterization are elevation, slope, aspect, compound topographic index (CTI, the index that explains soil wetness based on topography), plan curvature (surface morphology along the contour lines) and profile curvature (surface morphology across the contour lines) (Moore et al.1993).

These topographic attributes can be easily calculated from an elevation map with the spatial analysis capabilities of GIS.

Spatially dynamic change analysis in the landscape is a challenging task especially in areas influenced by humans. Spatial change analysis with GIS is most commonly carried out through the overlay of spatial data sets representing data at two points in time. Change is then represented as the difference between two data sets (Lo and Shipman, 1990; Ripple et al. 1991). Because only two data sets are used, the primary weakness of this method of change analysis is the inability to describe non-linear trends over time. In order to improve change analysis, Schlagel and Newton (1996) used a raster GIS with a non-parametric test for trend to apply to a subset of animal waste management coverages and found that from 1983 to 1990, significant increases in the rate of disposal occurred on 18 percent of the land within 100 meters of Jewett Brook. With this method, non-systematic or random variation in manure application rate from year to year and the cyclical changes in application rate due to crop rotation were filtered out leaving only those fields with significant trends.

This chapter uses a spatial analysis approach to quantify landscape characteristics and dynamics in the Wat Chan Watershed, Northern Thailand. The change and pattern of land use from 1974 through 1996 is evaluated by the non-parametric Mann-Kendall trend statistic together with GIS technology. The objectives of this study were; 1) Compare methods of land use change analysis by overlaying spatial land use data representing data at two points in time and a non-parametric test for trend; 2) Determine relationships between land use, land use change and topographic attributes of the landscape and 3) Predict a probability of land use change due to change in physical attributes and topographic attributes within the Wat Chan watershed. The land use dynamics and topographic attributes will be used for further study in the description and indexing of degraded sub-watersheds in chapter 5.

MATERIALS AND METHODS

Study Area

The study area is located in Ban Chan, Mae Chaem district, Chiang Mai Province, between 19° 02’ and 19° 16’ North latitude and between 98° 16’ and 98° 20’ East longitude (Figure 3.1). 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*). Many types of forest are located in almost the same circumstances in this landscape. Most of the dry dipterocarp forests are hardwood trees that are suitable for timber and building material. Fuelwood is the dominant energy source in this landscape and farmers obtain it from all types of forest depending on the availability of the wood around the villages. Judging by the increasing hill tribe populations, one possible factor increasing deforestation is that forests have been cut by humans for agricultural activities, building material and fuelwood (A Progress Report of Sustaining Land Resource Management for Agriculture and Forestry in the Tropical Small Watershed

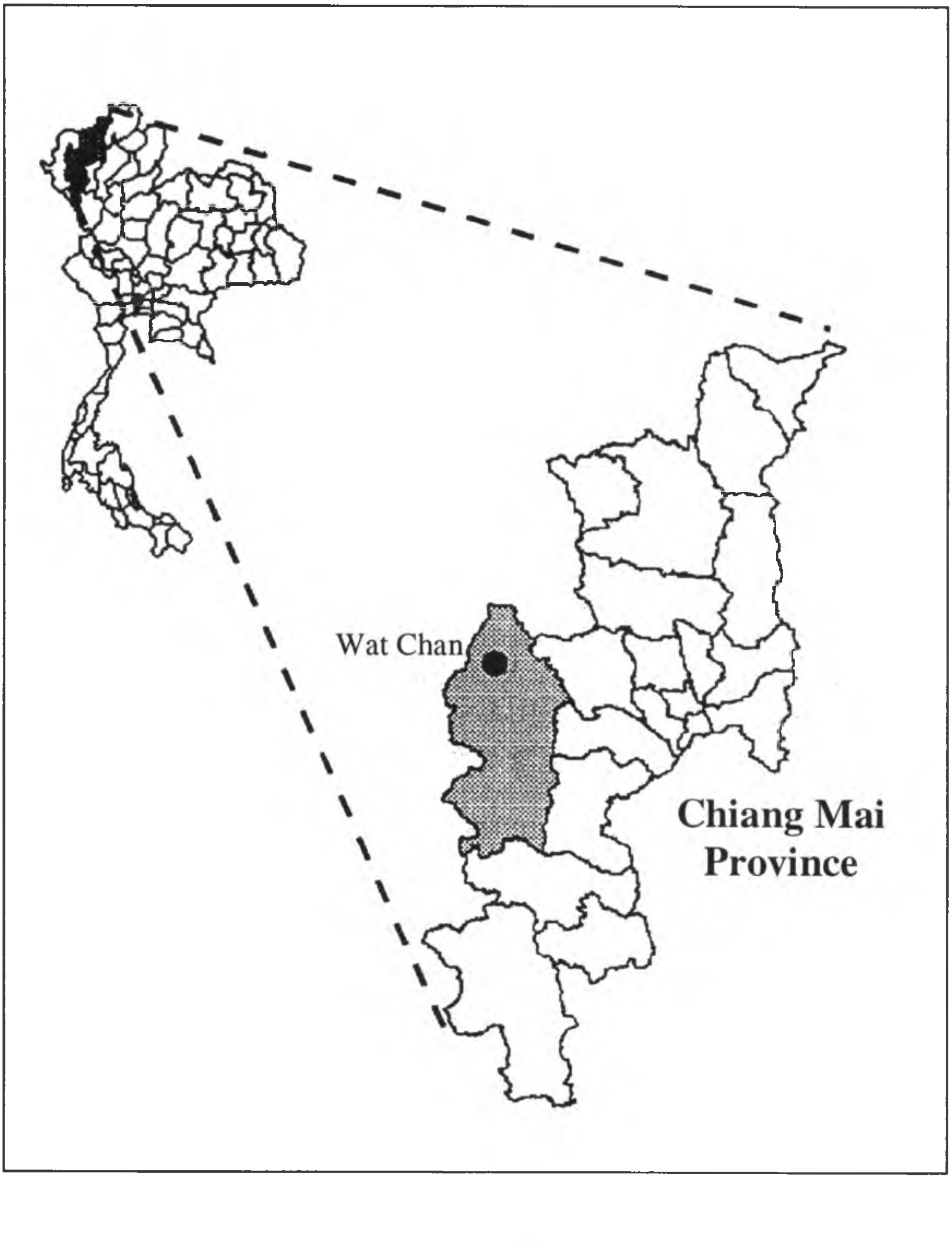


Figure 3.1 The study area

Environment, July 1993 - June 1994, unpublished). Agricultural land in this landscape is mostly used for field crops (e.g. corn, red kidney bean, upland rice) and paddy rice.

Elevation of this watershed ranges from 800 to 1,500 meters above sea level. Average annual rainfall ranges from 800 - 1,500 mm. and minimum and maximum daily temperature is approximately 8 and 42 degrees celsius, respectively (Statistics of Agriculture in Thailand, 1995).

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 different 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 soils such as Alfisols, and Ultisols. At the suborder level, the soil moisture regime is the most important soil characteristic used as criteria to distinguish soils in the mountains.

Data Acquisition and Processing

Remotely sensed images of the study area for January 1974 and 1982 were obtained from a Multi-spectral Scanner (MSS) and those for February 1990, March 1992, February 1994 and February 1996 were obtained from the Landsat 5 Thematic

Mapper (TM). Prior to analysis, all images were rectified to a universal transverse mercator (UTM) projection with a pixel resolution of 25 m using nearest neighbor rules provided by IDRISI image processing software (Eastman J.R., 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 using the six images. 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). Then the algorithm and experience from the 1996 classification were applied to the other images.

An elevation map for the study area derived from a topographic map (1:50,000 scale) was 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 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.

A road map was generated from data collected by a differential Global Positioning System (GPS) technique with an error of 25 – 50 m. The clusters of villages were digitized from air photo interpretations because image classification could not satisfactorily distinguish the village site.

Spatial Analysis of Land Use Characteristics and Dynamics

Standard database queries and summaries were used to group and calculate descriptive statistics for each landscape attribute. Summary statistical data of patch structures for all land use classes included; 1) area of each land use class (ha); 2) percent of the landscape; 3) number of patches; and 4) mean patch size (ha).

To detect change in the landscape, land use categories were grouped into two types; 1) forest (composed of pine, dry dipterocarp and hill evergreen forest) and 2) open land (paddy field, field crop and fallow). Two methods of detecting change in land use in the study area were compared in this analysis;

1) The classified image from 1974 was cross-tabulated with the 1996 image for detecting rates and patterns of land use change. Net change of these land use classes between 1974 and 1996 were calculated on the basis of whether each pixel changed. The sum of pixels that changed from one land use type to another type was calculated for the entire landscape. So only net change was detected by this method.

2) The Mann-Kendall test (a non-parametric test for zero slope of the linear regression of time-ordered data versus time, Gilbert, 1987) was used to estimate the probability of land use change from 1974 through 1996. Gilbert (1987) presents the procedure to calculate the Mann-Kendall trend statistic to estimate land use change over multiple time periods :

- Determine the sign of all n(n-1)/2 possible differences :

$\text{sign}\ (x_i - x_k) = +1 \quad \text{if}\ x_i - x_k > 0$

$\text{sign}\ (x_i - x_k) = 0 \quad \text{if}\ x_i - x_k = 0$

$\text{sign}\ (x_i - x_k) = -1 \quad \text{if}\ x_i - x_k < 0$

x_i = land use status of pixel x at time i

x_k = land use status of pixel x at time i-1

Step 1, 1) Calculate a difference image for all pairs of images by subtracting the earlier time period from the later time period. 2) Each difference image was then reclassified twice. The first reclassification generated a binary image containing the value +1 for all positive values in the difference image and zero for all other values in the image. The second reclassified image contains the value of –1 for all negative values of the subtraction, and zero for all other values. 3) An additional overlay is then used to sum the binary images for positive and negative values separately.

- Compute the Mann-Kendall Statistic according to the following expression :

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} sign(x_i - x_k)$$

Step 2, 1) Calculate a single image containing the Mann-Kendall trend statistic by adding the image containing the negative total to the image containing the positive total. 2) Compare the value for each pixel obtained with a tabled critical value for a generated probability of land use change (see Hollander and Wolfe, 1973) for areas that are in transition to forest (positive sign) and transition from forest (negative sign).

Since only six images covering a 22 year period were available for this study, the following assumptions were taken: 1) There were no land use changes between the available images, 2) The weight of changing from forest to cropland and cropland to forest is the same, each was given a weight of 1.

Areas that were in transition from forest (forest to crop land), transition to forest (crop land to forest) and no-transition were expected to be identified with this analysis. The following three possible changes were lumped in the "no-transition area" 1) stable forest lands, 2) stable crop lands and paddy fields, and 3) cycled land or land for which the images indicated the same land use for 1974's and 1996's image. In order to identify the above three categories, the following methods were employed: 1) To distinguish lands of unchanged forest from unchanged crop land the image was reclassed to a value of zero (no-transition) in the Mann-Kendall image to the value of one and all other values were reclassified to a value of zero. This image was then overlaid (multiplication operation) with land use image of 1974. Pixels of the stable forest lands, crop lands and paddy lands retained their same value while the value of pixels of other land became zero. 2) To distinguish the cycled land, a zero value in the image of the positive total and the negative total were reclassed to a value of one. Then the two reclassified images were summed together. The value of zero in the resulting image was considered land with a cycled landuse.

Land Use Change Modeling

The depletion of forest has demanded the attention of policymakers during the 1980's and 90's. Understanding what drives deforestation is important in order to respond appropriately. Several studies have identified factors contributing to deforestation. Pfaff (1996) found that increased road density, greater distance from economic centers, better soil, and high population density were the most important factors to increase deforestation in the Brazilian Amazon. In the Wat Chan watershed study, distance to a forest edge, proximity to a road, proximity to villages, elevation, degree slope, CTI, plan curvature and profile curvature were tested as factors to predict the change in land use.

To predict land use change, a probability of transition from forest based on the land use change analysis from 1974 through 1996 (calculated by method II) was regressed on landscape attributes in order to predict land use change. A logistic model was fitted to the landscape attributes to determine the relationship between the transition probability of land use and landscape attributes (physical factors and topographic attributes).

The following statistical model was fitted

$$\text{Logit(fcprob)} = b_1 + b_2X_1 + b_3X_2 + b_4X_3 + \ldots + b_nX_n$$

Where fcprob is a transition probability of the land use change from forest to crop land

X_n are landscape attributes.

RESULTS AND DISCUSSION

Spatial Pattern of the Landscape

A land use image taken in 1996 (Figure 3.2) shows that the landscape in the Wat Chan watershed was dominated by hill evergreen and pine forest. About 16% of the landscape was occupied by agricultural land and about 2% was stable paddy fields in 1996. About 84% of the total area was covered by forest composed of hill evergreen forest, dry dipterocarp forest and pine forest (Table 3.1).

Summary statistics of the topographic attributes in this highland landscape revealed that about 53% of the landscape was located on slopes of 20% or steeper (Table 3.2). About 94% of the area remained in forest (Table 3.3). Due to the steep slopes in this landscape, the surface water is likely to flow quickly to a stream and then out of the watershed quickly drying the soil surface in upslope areas. This is suggested because 85% of the area has CTI values (wetness index) less than 4.0. About 57% and 51% of the total area was characterized by plan and profile concavity, respectively.

Rates and Patterns of Land Use Changes in the Landscape

A strong trend in land use change is revealed by the six year images of the landscape occurred during the 22-year study period (Figure 3.3). It is clear that rates of land use change are varying non-linearly in this region (Figure 3.4). Spatial Change of land use from one type to another was different by time period as follows;

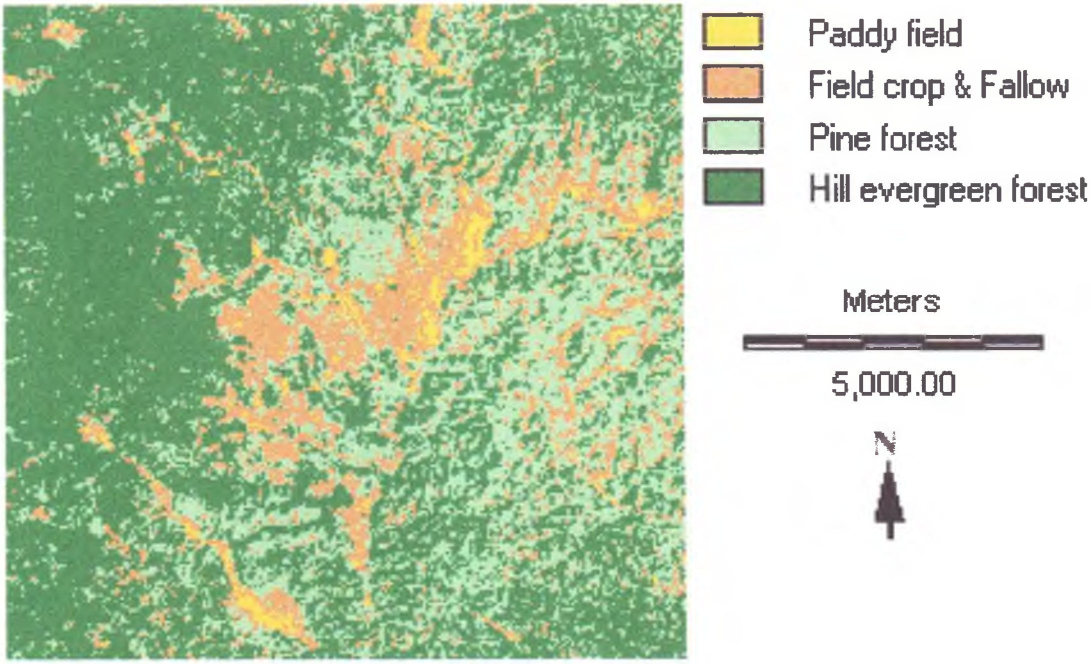


Figure 3.2 Land use classes of the Wat Chan watershed in 1996.

Table 3.1 Land use pattern in the Wat Chan watershed in 1996.

Land Use	Area (ha)	(%)
Paddy field	240	1.91
Field crop & Fallow	1745	13.9
Pine forest	3763	30.0
Hill evergreen forest	6790	54.2
Total	**12538**	**100.0**

Table 3.2 Topographic attributes of the Wat Chan watershed.

Aspect	**Area (ha)**	**(%)**
N	1541	12.29
NE	1829	14.59
E	1657	13.21
SE	1703	13.58
S	1889	15.07
SW	1640	13.08
W	1178	9.39
NW	1102	8.79

CTI (Wetness index)	**Area (ha)**	**(%)**
0-2	8132	64.9
2-4	2925	23.3
4-6	810	6.46
6-8	340	2.71
8-10	173	1.38
10-12	102	0.81
12-14	48.0	0.38
14-16	9.13	0.07

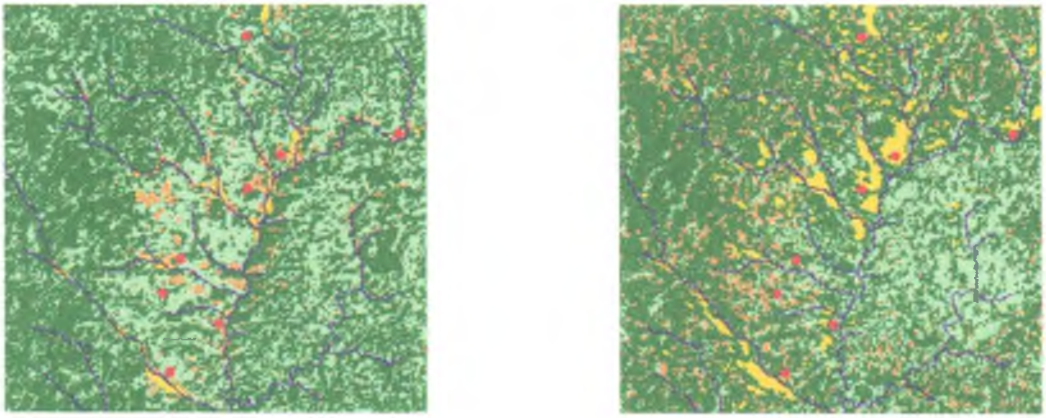
Plan curvature	**Area (ha)**	**(%)**
Convex	5397	43.1
Concave	7141	57.0

Profile curvature	**Area (ha)**	**(%)**
Convex	6106	48.7
Concave	6432	51.3

Slope Classes (%)	**Area (ha)**	**(%)**
0-3	927	7.39
3-8	1705	13.6
8-20	3270	26.1
20-35	3122	24.9
>35	3514	28.0

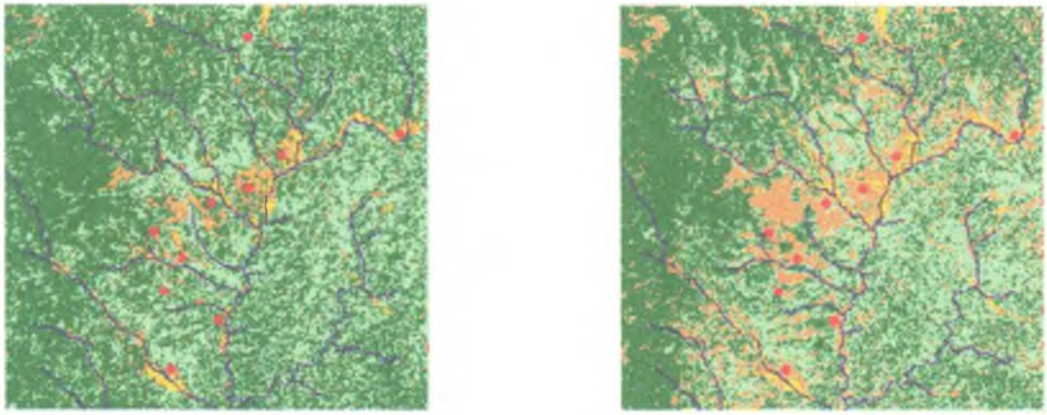
Table 3.3 Forest and agriculture land on different slope classes in 1996

Slope	Agriculture		Forest	
	(Area)	(%)	(ha)	(%)
> 20 %	406	6.10	6230	93.9
< 20 %	1579	26.7	4323	73.3



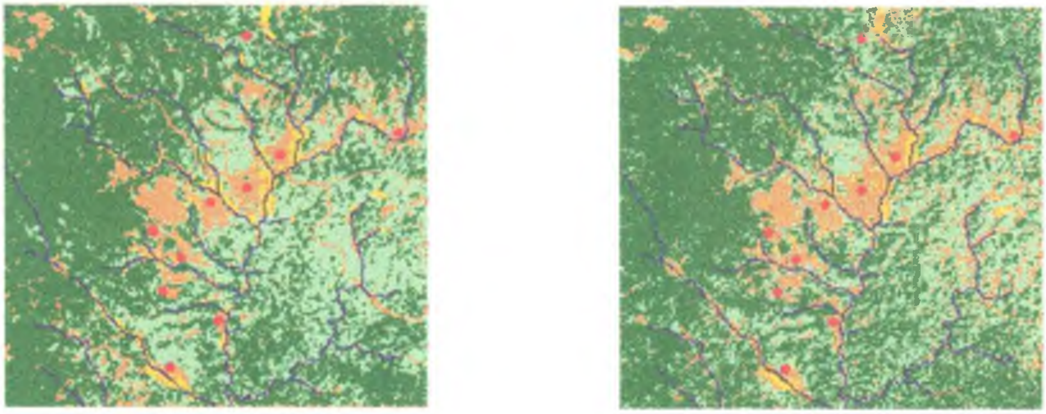
Land use classes, 1974

Land use classes, 1982



Land use classes, 1990

Land use classes, 1992



Land use classes, 1994

Land use classes, 1996

🟨 Paddy field

🟧 Field crop & Fallow

🟩 Pine forest

🟩 Hill evergreen forest

● **Village**

Figure 3.3 Land use classes images from 1974 through 1996, Wat Chan watershed.

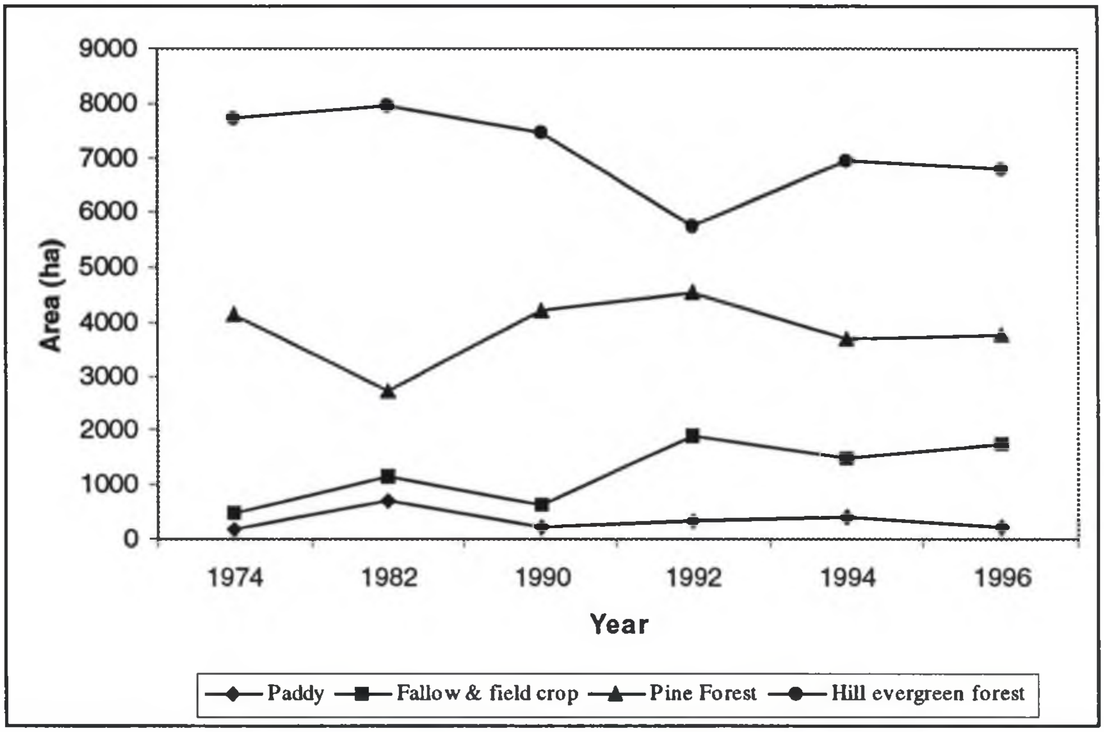


Figure 3.4 Land use change in the Wat Chan watershed

Land use change from 1974 to1982. Paddy field, field crop & fallow and hill evergreen forest have increased while the area of pine forest has dropped from 33% to 22% of the landscape (Table 3.4c). The promising change of land use during this period was that the decrease in pine forest was mainly through the transition to paddy fields mostly located near streams and to field crop & fallow lands (Figure 3.3).

Land use change from 1982 to 1992. Hill evergreen forest started declining from 63% to 46% of the landscape while area of pine forest increased by about 15%. The increase in pine forest was mainly associated with decreasing of hill evergreen forest, especially in the left side of the image with high elevation. Area of paddy field declined from 1982 to 1990 to about 4% of the landscape and maintained this amount until 1992. Area of field crop & fallow dropped from 1982 to 1990 to about 4% of the landscape and increased to about 10% from 1990 to 1992. During this period, two additional villages were established in the landscape (Figure 3.3, 1990), which might accelerate the transition of hill evergreen forest to field crops especially surrounding the villages.

Land use change from 1992 to 1996. Change of all land use classes in the landscape seems to be small from 1994 to 1996.

Change of land use not only increased or decreased the total area of each class but it also affected the size and number of patches as well. Considerable fragmentation of the landscape occurred between 1974 and 1996, the number of patches increased 87% and 96% for pine and hill evergreen forest, respectively. The number of fields increased 387% and 265% for paddy rice and field crop & fallow patches, respectively

Table 3.4 Land use class indices from 1974 to 1996
(a) Paddy field, (b) Field Crop & fallow, (c) Pine forest, (d) Hill evergreen forest

(a)

Paddy indices	**Year**					
	1974	**1982**	**1990**	**1992**	**1994**	**1996**
Class area (ha)	175	719	231	323	393	240
Percent of landscape	1.40	5.73	1.84	2.57	3.14	1.91
Numbers of patches	84	439	338	411	238	409
Mean patch size (ha)	2.09	1.64	0.68	0.79	1.65	0.59

(b)

Field Crop & Fallow indices	**Year**					
	1974	**1982**	**1990**	**1992**	**1994**	**1996**
Class area (ha)	480	1163	620	1923	1500	1745
Percent of landscape	3.83	9.28	4.95	15.3	12.0	13.9
Numbers of patches	617	2170	1428	3718	973	2249
Mean patch size (ha)	0.78	0.54	0.43	0.52	1.54	0.78

(c)

Pine Forest Indices	**Year**					
	1974	**1982**	**1990**	**1992**	**1994**	**1996**
Class area (ha)	4156	2719	4222	4554	3701	3763
Percent of landscape	33.2	21.7	33.7	36.3	29.5	30.0
Numbers of patches	2399	2755	4632	7015	1888	4480
Mean patch size (ha)	1.73	0.99	0.91	0.65	1.96	0.84

(d)

Hill evergreen indices	**Year**					
	1974	**1982**	**1990**	**1992**	**1994**	**1996**
Class area (ha)	7726	7935	7464	5739	6945	6790
Percent of landscape	61.6	63.3	59.5	45.8	55.4	54.2
Numbers of patches	1098	760	2987	6263	944	2147
Mean patch size (ha)	7.04	10.4	2.50	0.92	7.36	3.16

(Table 3.4). Trend of mean field size of paddy rice, pine and hill evergreen forest became smaller while field crop & fallow field size remained approximately the same. The need of land for agricultural activities of farmers in this landscape might affect land use by increasing isolated patches of forest and non-forest.

The tabular overview of rates and pattern of landscape in the Wat Chan watershed demonstrates the land use change from year to year in the landscape. Unfortunately, presenting the information this way does not demonstrate the spatial location of change.

Land Use Change Analysis

There are a number of different methods of estimating spatial change of land use. One method is to compare the land use image of one year with that of another year. A non-parametric test for trend is another method of characterizing the spatially dynamic change of land use when conducted on individual pixels.

Method I : Comparing the land use image of 1974 with that of 1996

Estimation of spatial change in land use by overlaying the land use images of 1974 and 1996 revealed that about 14% of the landscape was changed among land use classes during the 22-year period (Table 3.5).

Land in forest in 1974. About 10% of the forest land in the entire landscape - equivalent to an area of about 1329 ha- decreased between 1974 and 1996. Changing of forest land in this landscape revealed that about 12% and 0.7% of forest land in 1974 was converted to field crops and paddy fields respectively.

Table 3.5 Land use changes (ha) in the Wat Chan watershed, 1974 – 1996. (values in parenthesis are percentage of the1974 land use area that changed in 1996)

Land use, 1974 (ha)	Land use classes,1996 (ha)			Total in 1974
	Paddy	Field Crop and Fallow	Forest	
Paddy field	95.5 (54.5)	66.5 (38.0)	13.2 (7.53)	**175**
Field crop & Fallow	54.6 (11.4)	244 (50.9)	181 (37.7)	**480**
Forest	89.6 (0.753)	1434 (12.1)	10359 (87.2)	**11882**
Total	**240**	**1745**	**10553**	**12538**

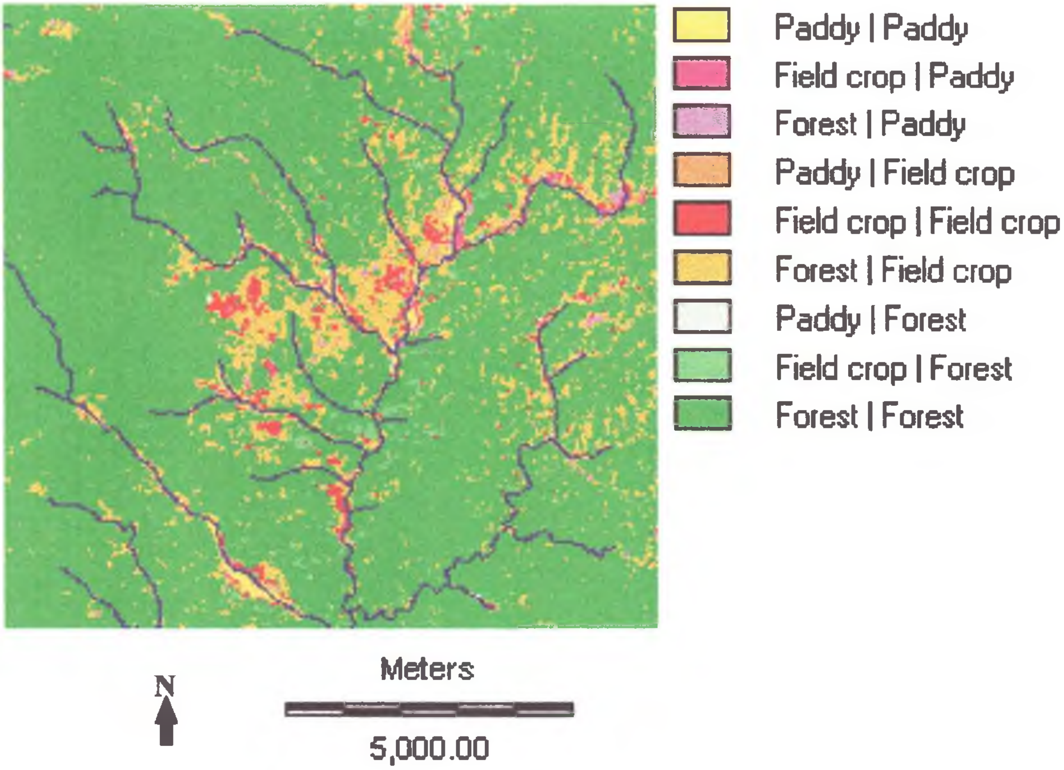


Figure 3.5 Land use change in the Wat Chan watershed, 1974 - 1996.

Land in paddy in 1974. This method revealed that about 55% of the land in paddy fields in 1974 remained the same. About 37% of the paddy land in 1974 was converted to field crop & fallow by 1996. About 8% of the paddy fields were converted to the regenerated forest by 1996.

Land in fallow & field crops in 1974. About 37% and 11% of the field crop & fallow land in 1974 was converted to forest and paddy by 1996, respectively.

Spatial change of land use in the landscape revealed that agricultural uses (paddy field, field crop & fallow) increased from 0.05% (655 ha) of the landscape in 1974 to 16% (1985 ha) by 1996. Irrigated agriculture (paddy rice area) maintained the lowest fraction of change, probably because of the large amount of water required to produce rice (usually located near the stream, Figure 3.5). Another major change was the reduction in field size of all land uses except field crop & fallow. For example, the average size of paddy fields diminished from 2.09 ha in 1974 to 0.59 ha in 1996 (Table 3.5). Low annual rainfall distribution might be the reason for reduced size of paddy field (informal interview in the 1994's survey). Farmers tended to utilize the lands along the borders of paddy fields for field crops or left them fallow. The change from forest to field crop & fallow occurred in about 25% of the total landscape. About 37% of the landscape has been abandoned for many years allowing forest regeneration.

One disadvantage of change analysis by overlaying two images from two points in time is that it shows only the net change in land use. This method was not able to extract dynamic change in land use within the 1974 to 1996 period. For example, there may have been cycling of land use. To overcome this and other limitations of the two-images method, land use images were obtained at multiple time periods. The use of overlay analysis, however, then becomes more difficult with multiple land use images. A GIS may allow one to accurately overlay images representing land use at many time periods, but a single image representing the results of the overlay of multiple images can be too complex to meaningfully interpret visually, so other techniques must be used.

Method II: A non-parametric test of land use dynamics from 1974 to 1996

A probability of land use change can be displayed as an image representing a dynamic change of land use in the landscape. Land use images in 1974, 1982, 1990, 1992, 1994 and 1996 (Figure 3.4) were used to generate a map of the probability of land use change based on the Mann-Kendall test. This image is useful when related to landscape attributes to improve the understanding of landscape structure. Six major classes of land use changes were generated by this method (Figure 3.6);

The change from agriculture to forest land (Transition to Forest, TTF). Five sub-classes of this trend representing the probability of transition to forest were estimated. The high probability value implies that the number of changes from agriculture to forest in specific locations is much higher than changes from forest to agriculture and compared to no-change during the 22-year period. So the highest probability value in this image is the land that is most likely to change from agriculture to forest land. About 12.7% of the landscape was classified as TTF and 10% had the probability value between 60 – 70% (Table 3.6).

Table 3.6 Land use dynamics classes in the Wat Chan watershed, 1974 – 1996.

Land us dynamic class	Area	
	(ha)	(%)
Transition to forest: 90-95%	1.06	0.008
Transition to forest: 80-90%	33.1	0.264
Transition to forest: 70-80%	147	1.18
Transition to forest: 60-70%	1235	9.85
Transition to forest: 50-60%	180	1.44
Transition from forest: 90-95%	304	2.42
Transition from forest: 80-90%	506	4.03
Transition from forest: 70-80%	956	7.63
Transition from forest: 60-70%	415	3.31
Transition from forest: 50-60%	642	5.12
Stable paddy	52.1	0.416
Stable cropland	46.6	0.371
Stable forest	7925	63.2
Cycled land	95.2	0.759
Total	**12538**	**100**

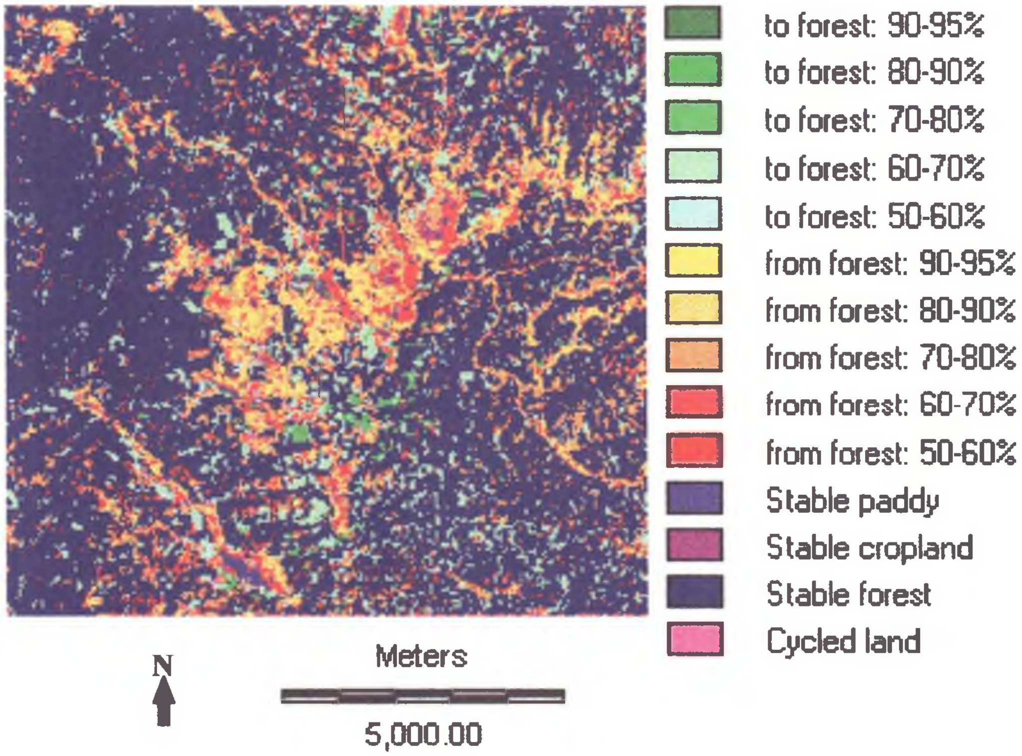


Figure 3.6 Probability of land use change in the Wat Chan watershed, 1974 – 1996.

The change from forest to agriculture land (Transition from Forest, TFF). Five sub-classes of this trend representing the probability of transition from forest were estimated. The highest probability value in this landscape is the land that is most likely to change from forest to agriculture land. About 22.5% of the landscape was classified as TFF with the probability value ranges from 50 – 95%. (Table 3.6)

Stable paddy field. This class was determined as the land permanently used for growing paddy rice since 1974 to 1996. About 0.42% (51.2 ha.) of the landscape remained as paddy fields. The amount of land in this category is low in this landscape because the amount of water and flat land limits the growing of paddy rice, which will cause difficulty in expanding paddy land.

Stable cropland & fallow land. About 0.37% of the landscape was classified as the stable cropland & fallow land. This land was used for either growing field crops or fallow land. The fact that their percentage was so low probably reflects the greate importance of rotation and fallow in the area.

Stable forest land. This land class was defined as the land that has not been used for any agricultural activities except forest land. About 63.1% of the landscape remained in forest since 1974.

Cycled land. This land was defined as the land where changes have occurred between 1974 and 1996, but the same land use was found in 1974 and 1996. About 0.76% of the landscape was located in the "cycled" class.

Comparison of land use change assessments of method I and method II

Multiple land use images in the Wat Chan watershed were used to estimate land use change from 1974 to 1996 by a non-parametric trend analysis. Dynamic changes of land use were extracted and shown as an image of probability of land use change. Comparison between the two methods is summarized in Tables 3.7, 3.8 and 3.9.

Stable land. About 85% of the landscape was classified as stable land use using method I while 64% of the landscape was so classified by method II. The difference in estimated stable land use between the two methods can be explained by the change of stable forest and stable crop land of method I to cycled land, TTF land and TFF land of method II. About 63.9, 989, and 1381 ha. of stable forest, according to method I, was classified as cycled land, TFF and TTF area respectively if calculated by method II (Table 3.8 and 3.9). About 31.3, 311, and 20.5 ha. of stable crop land, according to method I, was classified as cycled land, TFF and TTF land, respectively, if calculated by method II.

Transition lands. Both methods were able to identify lands that were in transition from forest and transition to forest. Using method II, TFF and TTF lands were classified into five sub-classes of a probability of land use change. Even though TFF land calculated by method II was greater than method I (Table 3.7), only 2.4% of the landscape was highly likely to change from forest to agriculture if calculated by method II (Table 3.6). About 12% of the landscape was converted from forest if method I was used (Table 3.7). A similar change also occurred for the land that was converted to forest.

Table 3.7 Comparison of land use change analysis by two methods.

Land use change	Method I [1/] Area		Method II [1/] Area	
	(ha)	(%)	(ha)	(%)
Transition from forest	1578	12.6	2822	22.5
Transition to forest	261	2.08	1597	12.7
Stable paddy	95.5	0.76	52.1	0.42
Stable crop land	244	1.95	46.1	0.37
Stable forest	10358	82.6	7925	63.2
Cycled land	na	-	95.2	0.76
Total	**12538**	**100**	**12538**	**100**

Table 3.8 Comparison of the permanent area(ha) estimated by method I with method II.

Method I	Method II (Transition to forest)		
	Permanent Crop land	Permanent forest	Cycled land
Stable crop land	98.7	-	31.3
Stable forest	-	7925	63.9
Total	**98.7**	**7925**	**95.2**

Table 3.9 Comparison of the changed area(ha) estimated by method I with method II.

Method I	Method II (Transition from forest)				
	90 – 95%	80 – 90%	70 – 80%	60 – 70%	50 – 60%
Stable crop land	-	-	79.7	188	42.8
Stable forest	-	-	289	203	497
Transition to For.	-	-	-	-	-
Transition from For.	304	506	588	23.6	103
Total	**304**	**506**	**956**	**415**	**642**

Method I	Method II (Transition to forest)				
	90 – 95%	80 – 90%	70 – 80%	60 – 70%	50 – 60%
Stable crop land	-	-	2.19	7.0	11.3
Stable forest	-	-	12.4	1227	142
Transition to For.	1.06	33.1	133	0.75	26.5
Transition from For.	-	-	-	-	-
Total	1.06	33.1	148	1235	180

[1/] Method I is comparison land use image of 1974 with 1996
Method II is a non-parametric test of land use change from 1974 to 1996

Using method II for detecting land use change in this landscape, a probability of land use change image can be summarized into a single image. This probability generated from 6 images representing 22 years will be useful for modeling the relationship between the land use change and landscape attributes for using in land use planning.

Relationship Between Land Use Dynamics and Landscape Attributes

Characteristics and dynamics of land in transition to forest

To understand the impact of land use change on deforestation in this landscape, topographic attributes and physical attributes were used to predict the probability of land use transition from forest and to forest. These are also the lands of most importance for intervention and policy development.

A query regarding the topographic attributes for land in transition to forest showed that these lands included all categories of aspect, plan and profile curvature. The land converted to forest was largely east-facing which comprised about 55% of the transition to forest (TTF) land (Table 3.10a). For CTI classes, about 87% of TTF land was located in land where the CTI value was less than 0.4 (Table 3.11a). Transition to forest land can be found in land with both concave and convex morphology (Table 3.12a and 3.13a). The percentage of slope was also a major factor for these lands. About 50% of the land in transition to forest was located in the area with slope higher than 20%. Farmers returned to cultivating their lands after fallowing them for a long period (Table 3.14a).

Table 3.10 Amount of land with a probability of land use change in relation to aspect

(a) Transition To Forest

Aspect	*Probability of Land use change*											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
N	0.19	17.7	5.25	15.9	14.1	9.56	172	14.0	18.2	10.1	**210**	**13.2**
NE	0.19	17.7	8.13	24.6	23.6	16.0	177	14.3	29.4	16.3	**238**	**15.0**
E	0.06	5.88	4.25	12.9	20.0	13.5	147	11.9	35.7	19.8	**207**	**13.0**
SE	0.06	5.88	4.25	12.9	26.4	17.9	154	12.4	31.7	17.6	**216**	**13.5**
S	0.38	35.3	5.25	15.9	33.3	22.5	179	14.5	27.2	15.1	**245**	**15.4**
SW	0.13	11.8	3.19	9.64	18.8	12.7	159	12.9	20.8	11.5	**202**	**12.6**
W	0.06	5.88	0.94	2.84	6.25	4.23	122	9.88	9.94	5.52	**140**	**8.72**
NW	-	-	1.81	5.48	5.31	3.60	125	10.1	7.25	4.03	**140**	**8.74**
Total	**1.06**	**100**	**33.1**	**100**	**148**	**100**	**1235**	**100**	**180**	**100**	**1597**	**100**

(b) Transition From Forest

Aspect	*Probability of Land use change*											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
N	24.0	7.88	41.0	8.11	86.9	9.09	34.6	8.33	67.8	10.6	**254**	**9.01**
NE	43.6	14.4	86.2	17.0	157	16.5	57.1	13.8	108	16.8	**452**	**16.0**
E	51.3	16.9	103	20.5	184	19.3	57.6	13.9	105	16.4	**503**	**17.8**
SE	50.0	16.5	94.7	18.7	179	18.7	55.6	13.4	109	16.9	**488**	**17.3**
S	57.4	18.9	89.3	17.7	148	15.5	69.9	16.9	123	19.1	**488**	**17.3**
SW	37.9	12.5	42.3	8.35	98.4	10.3	68.4	16.5	66.7	10.4	**314**	**11.1**
W	19.9	6.57	26.0	5.14	50.6	5.29	39.2	9.45	33.3	5.18	**169**	**5.99**
NW	19.6	6.46	22.6	4.46	50.9	5.32	32.4	7.82	29.8	4.64	**155**	**5.50**
Total	**304**	**100**	**506**	**100**	**956**	**100**	**414**	**100**	**642**	**100**	**2822**	**100**

Table 3.11 Amount of land with a probability of land use change in relation to CTI.

(a) Transition To Forest

CTI	*Probability of Land use change*											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
0 – 2	0.44	41.2	15.3	46.3	85.9	58.2	819	66.3	114	63.5	**1035**	**64.8**
2 – 4	0.25	23.5	14.4	43.7	45.7	30.9	284	23.0	42.3	23.5	**387**	**24.2**
4 – 6	0.19	17.7	2.00	6.05	8.13	5.50	72.2	5.84	11.6	6.42	**94.1**	**5.89**
6 – 8	0.06	5.88	0.44	1.32	2.56	1.74	32.7	2.65	3.94	2.19	**39.7**	**2.49**
8 – 10	-	-	0.31	0.95	1.75	1.18	17.1	1.38	2.63	1.46	**21.8**	**1.36**
10 – 12	0.13	11.8	0.19	0.57	2.13	1.44	7.44	0.60	3.31	1.84	**13.2**	**0.83**
12 – 14	-	-	0.31	0.95	1.19	0.80	2.88	0.23	1.44	0.80	**5.81**	**0.36**
14 – 16	-	-	0.06	0.19	0.31	0.21	0.38	0.03	0.50	0.28	**1.25**	**0.08**
Total	**1.06**	**100**	**33.1**	**100**	**148**	**100**	**1235**	**100**	**180**	**100**	**1597**	**100**

(b) Transition From Forest

CTI	*Probability of Land use change*											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
0 – 2	118	38.9	212	41.8	509	53.2	187	45.2	410	63.8	**1435**	**50.9**
2 – 4	117	38.7	189	37.4	285	29.8	127	30.7	155	24.1	**874**	**31.0**
4 – 6	36.7	12.1	59.7	11.8	86.7	9.07	52.0	12.5	40.4	6.29	**275**	**9.76**
6 – 8	12.6	4.14	20.7	4.09	33.8	3.54	18.0	4.34	18.2	2.83	**103**	**3.66**
8 – 10	8.00	2.63	11.1	2.19	17.4	1.82	7.75	1.87	9.00	1.40	**53.3**	**1.89**
10 – 12	7.69	2.53	8.00	1.58	14.9	1.56	9.94	2.40	6.44	1.00	**47.0**	**1.67**
12 – 14	2.56	0.84	5.13	1.01	7.31	0.76	11.0	2.65	3.00	0.47	**29.0**	**1.03**
14 – 16	0.75	0.25	0.38	0.07	1.94	0.20	1.56	0.38	0.38	0.06	**5.00**	**0.18**
Total	**304**	**100**	**506**	**100**	**956**	**100**	**415**	**100**	**642**	**100**	**2822**	**100**

Table 3.12 Amount of land with a probability of land use change in relation to plan curvature.

(a) Transition To Forest

Plan Curvature	***Probability of Land use change***											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
Convex	0.50	47.1	12.9	39.1	55.7	37.7	531	43.0	68.3	37.9	**669**	**41.9**
Concave	0.56	52.9	20.2	60.9	92.1	62.3	704	57.0	112	62.1	**928**	**58.1**
Total	**1.06**	**100**	**33.1**	**100**	**148**	**100**	**1235**	**100**	**180**	**100**	**1597**	**100**

(b) Transition From Forest

Plan Curvature	***Probability of Land use change***											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
Convex	125	40.9	200	39.5	403	42.1	171	41.1	266	41.4	**1163**	**41.2**
Concave	179	59.1	306	60.5	553	57.9	244	58.9	376	58.6	**1659**	**58.8**
Total	**304**	**100**	**506**	**100**	**956**	**100**	**415**	**100**	**642**	**100**	**2822**	**100**

Table 3.13 Amount of land with a probability of land use change in relation to profile curvature.

(a) Transition To Forest

Profile Curvature	*Probability of Land use change*											
	90 - 95 %		80 -90 %		70 - 80 %		60 - 70 %		50 - 60 %		Total	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Convex	0.38	35.3	17.7	53.5	76.3	51.6	607	49.1	89.8	49.8	**791**	**49.5**
Concave	0.69	64.7	15.4	46.5	71.4	48.4	628	50.9	90.3	50.2	**806**	**50.5**
Total	**1.06**	**100**	**33.1**	**100**	**147**	**100**	**1235**	**100**	**180**	**100**	**1597**	**100**

(b) Transition From Forest

Profile Curvature	*Probability of Land use change*											
	90 - 95 %		80 -90 %		70 - 80 %		60 - 70 %		50 - 60 %		Total	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Convex	130	42.8	224	44.4	434	45.4	172	41.5	325	50.5	**1285**	**45.5**
Concave	174	57.2	282	55.6	522	54.6	243	58.5	317	49.5	**1537**	**54.5**
Total	**304**	**100**	**506**	**100**	**956**	**100**	**415**	**100**	**642**	**100**	**2822**	**100**

Table 3.14 Amount of land with a probability of land use change in relation to slope.

(a) Transition To Forest

Slope	*Probability of Land use change*											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		Total	
(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)
0 – 3	0.13	11.8	5.31	16.1	17.8	12.0	76.1	6.16	17.2	9.55	**116**	**7.29**
3 – 8	0.50	47.1	10.1	30.4	33.6	22.8	148	12.0	29.6	16.5	**222**	**13.9**
8 – 20	0.31	29.4	11.7	35.4	51.9	35.1	335	27.1	49.0	27.2	**448**	**28.0**
20 35	0.13	11.8	4.63	14.0	28.9	19.6	353	28.6	44.6	24.8	**432**	**27.0**
> 35	-	-	1.38	4.16	15.4	10.5	323	26.2	39.6	22.0	**379**	**23.8**
Total	**1.06**	**100**	**33.1**	**100**	**148**	**100**	**1235**	**100**	**180**	**100**	**1597**	**100**

(b) Transition From Forest

Slope	*Probability of Land use change*											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		Total	
(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)	**(ha)**	(%)
0 – 3	62.5	20.6	90.9	18.0	102	10.7	70.0	16.9	54.1	8.43	**379**	**13.5**
3 – 8	84.9	28.0	144	28.4	212	22.2	112	27.0	103	16.1	**655**	**23.2**
8 – 20	99.9	32.9	176	34.7	304	31.8	121	29.2	177	27.5	**877**	**31.1**
20 35	38.0	12.5	63.6	12.6	188	19.6	48.9	11.8	154	24.1	**492**	**17.5**
> 35	18.4	6.07	32.0	6.33	151	15.8	62.8	15.1	154	23.9	**418**	**14.8**
Total	**304**	**100**	**506**	**100**	**956**	**100**	**415**	**100**	**642**	**100**	**2822**	**100**

There was little effect on probability of land use change to forest by proximity to villages. About 61% of the land in transition to forest was located within 2 km from villages (Table 3.15a). About 64% of land in transition to forest area was in the distance less than 500 m. from the road. Land with a low probability of land use change from agriculture to forest tended to be located away from roads by more than 500 m (Table 3.16a).

Characteristics and dynamics of land in transition from forest

The land converted from forest to agriculture lands was largely east-facing which comprised about 60% of the TFF land (Table 3.10b). Table 3.11b indicated that about 89% of the TFF land was characterized by a CTI of less than 4.0. Agricultural activities tended to be practiced on the concave plan and profile areas (Table 3.12b and 3.13b) probably because this morphology has a tendency to maintain maximum soil moisture (Hall et al., 1991) or to be areas of soil deposition.

There was some trend between the probability of transition from forest lands and slope classes steeper than 20%. In the low probability (50 – 60%) class of the transition from forest land, about 50% this land was located on slope steeper than 20%. While the high probability (90 – 95%) of TFF land, about 18% of this area located on slope steeper than 20% (Table 3.14b). This implied that there tended to be less conversion of steep land to agriculture, suggesting that farmers tended not to practice permanent agriculture in the steep areas. However, increasing population density and/or low crop production might be the reason that farmers were, nonetheless, still opening land with steep slopes.

Table 3.15b showed that in the high probability (90 – 95%) of TFF land, about 77% of this land was located within 2 km of villages. While the low probability (50 – 60%) of the TFF land, about 60% of this land located within a proximity to village less than 2 km. This implied that there was a lower probability of transition from forest for land located further from the villages. Farmers tended to practice agriculture within 2 km from the villages. So proximity to villages influenced conversion from forest to agriculture land. Land use change in different classes of proximity to roads has similar trend as proximity to villages. About 55% of transition from forest land was also located within 500 m. from the road (Table 3.16b). The further land was from the road, the lower the probability of land use change.

Land Use Change Modeling

Change of land use in the landscape is heavily influenced by human activities, physical attributes (road, villages, soil and climate) and topographic attributes. Historical description of change in land use is an important, and often the only, source of information from which to derive transition probabilities associated with change in land use. To predict land use change, a probability of transition from forest was regressed on probable driving variables including 1) transportation network (roads), 2) topographic attributes, 3) population density (villages) and 4) resource accessibility (forest area). Logistic regression analysis of the probability of land use change from forest to agriculture area with physical and topographic attributes is shown in equation (3.1).

Table 3.15 Amount of land with a probability of land use change in relation to proximity to villages

(a) Transition To Forest

	Probability of Land use change											
Proximity	**90 - 95 %**		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
to villages	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
< 2 km.	1.0	94.1	28.6	86.6	123	83.3	695	56.3	126	70.0	974	61.0
> 2 km.	0.062	5.89	4.4	13.4	24.7	16.7	540	43.7	54.0	30.0	623	39.0
Total	**1.06**	**100**	**33.0**	**100**	**148**	**100**	**1235**	**100**	**180**	**100**	**1597**	**100**

(b) Transition From Forest

	Probability of Land use change											
Proximity	**90 - 95 %**		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
to villages	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
< 2 km.	234	77.1	400	79.1	614	64.3	314	75.6	397	61.9	1959	69.4
> 2 km.	69.6	22.9	106	21.0	342	35.7	101	24.4	245	38.1	863	30.6
Total	**304**	**100**	**506**	**100**	**956**	**100**	**415**	**100**	**642**	**100**	**2822**	**100**

Table 3.16 Amount of land with a probability of land use change in relation to proximity to roads

(a) Transition To Forest

Proximity to roads	***Probability of Land use change***											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
< 0.5 km.	0.813	76.5	17.0	51.4	60.4	40.9	408	33.0	75.0	41.7	561	35.8
> 0.5 km.	0.25	23.5	16.0	48.6	87.3	59.1	827	67.0	105	58.3	1036	64.2
Total	**1.06**	**100**	**33.0**	**100**	**148**	**100**	**1235**	**100**	**180**	**100**	**1597**	**100**

(b) Transition From Forest

Proximity to roads	***Probability of Land use change***											
	90 - 95 %		**80 -90 %**		**70 - 80 %**		**60 - 70 %**		**50 - 60 %**		**Total**	
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
< 0.5 km.	199	65.7	358	70.8	507	53.0	255	61.4	250	39.0	1569	55.6
> 0.5 km.	105	34.3	148	29.2	449	47.0	160	38.6	392	61.0	1253	44.4
Total	**304**	**100**	**506**	**100**	**956**	**100**	**415**	**100**	**642**	**100**	**2822**	**100**

A logistic model of predicted probability of land use change from forest to agriculture area was

$$\begin{aligned} \text{logit(fcprob1)} = &- 6.77 - 0.000388 * \text{EDGE} - 0.0000532 * \text{ROAD} \\ &- 0.0000743 * \text{VILL} + 0.0357 * \text{CTI} + 0.00301 * \text{ELEVATION} \\ &+ 0.0687 * \text{PLAN} + 0.0544 * \text{PROFILE} - 0.00587 * \text{SLOPE} \quad (3.1) \end{aligned}$$

Where fcprob1 is the probability of land in transition from forest image
EDGE is distance from the forest edge image (meters)
ROAD is proximity to road network image (meters)
VILL is proximity to villages image (meters)
CTI is compound topographic index image (dimensionless)
ELEVATION is elevation image (meters)
PLAN is plan curvature image (dimensionless)
PROFILE is profile curvature image (dimensionless)
SLOPE is slope image (degrees)

This model fit of the data was highly significant. Coefficients of all variables were also highly significant as indicated by t-tests ($P = 0.01$) with a coefficient of determination (R^2) of 0.74 (Table 3.17). Elevation, proximity to village, distance to forest edge, slope and CTI were the most significant factors predicting the conversion of forested land to agricultural area.

Table 3.17 Logistic regression model of the probability of the change form forest to agricultural area.

Variables	Coefficient	t value
Intercept	-6.77	-948
Distance from forest edge (m)	-0.000388	-47.3
Proximity to roads (m)	-0.0000532	-24.4
Proximity to village (m)	-0.0000743	-47.2
CTI	0.0357	36.4
Elevation (m)	0.00301	444
Plan curvature	0.0687	16.3
Profile Curvature	0.0544	20.2
Slope (degree)	-0.00587	-43.2

F-statistic = 70863
R^2 = 0.74

Relationships between the transition from forest and landscape attributes revealed that land located near road networks, villages, and forest edges had a high possibility of transition from forest to agriculture. Steeply sloping land tended to remain occupied by the forests. The high value of plan and profile curvature indicated that the surface is usually concave that was most likely to shift to agriculture.

CONCLUSIONS

Low soil fertility, weed infection and low rainfall and uneven distribution are important factors in reducing crop yield (informal interview) in this landscape. So far, increasing the amount of agricultural land is the only solution that farmers usually practice rather than increasing production through intensification. This leads to the dynamic change of land use from forest to agriculture.

Landscape characteristics and dynamics in the Wat Chan watershed were determined from relationships between land use pattern and change (obtained from satellite images from 1974 to 1996) and topographic attributes by using spatial analysis. This analysis showed that steep rugged mountain lands with different land use types were defined in this landscape. Most of forested lands were in the steep areas.

Two methods were used to estimate land use change in this study: 1) A simple comparison the land use image of 1974 with that of 1996 and 2) A non-parametric test of land use dynamics from multiple images from 1974 to 1996. Comparison between the two methods of detecting land use change in this landscape shows different percentages of land use change. The method of non-parametric trend analysis for land use change, in combination with spatial analysis capability of GIS permits extracting a probability of change in land use image during 1974 through 1996. The probability of transition from the method II analysis helps illustrate that land use change is dynamic. About 0.76% of this landscape can be identified as cycled land. The remaining forest land, calculated according to method II, was less than that estimated by method I by about 20%. This might be misleading and lead to incorrect management unless one is aware of which method was used. It also suggests that estimates of land use change can be misleading unless the dynamic characteristics are properly considered.

The conversion of forest to non-forest land remains less than the average in Northern Thailand (Charuppat, 1994). Even though the hill tribe people tend to preserve the vulnerable lands (steep slope and low CTI) for the regenerated forest in this landscape, these lands are still not in stable forests (the low percentage in land with high probability of TTF). The amount of land in field crop & fallow and the number of patches increased drastically during the 22-year period, while patch size remained the same. It shows that farmers apparently respond to food shortages by increasing cultivated area rather than intensified production. These will cause further loss of forest area over time. Regressing the probability of land use change on physical attributes and topographic attributes indicated that short distances to villages, short distances to the forest edge, high elevation and high CTI were associated with increased land use change from forest to open lands in this landscape based on 22 years of change.

Spatial analysis of land use characteristics and dynamics in this chapter provides information on the rates and patterns of land use change in the Wat Chan watershed which are useful for understanding relationships among attributes in the landscape. Besides land use and topographic attributes of the landscape, other factors such as soil attributes are also important for sound landscape management. The information developed in this chapter will be employed in the next chapter for characterizing the distribution of soil properties in the landscape.

CHAPTER IV

Soil Characteristics and Prediction of Soil Properties

INTRODUCTION

In recent years, a major focus of attention in Thailand for resource managers has been the deforestation processes in the highland area. This attention has led to the development of sustainable land resources 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). So with accelerated land and environmental degradation in tropical forest caused by deforestation, maps of soil information have become valuable tools for land use planning and natural resources management.

Soil maps have been obtained for the entire country by the Department of Land Development, Ministry of Agriculture. These maps are also frequently updated for current agricultural land use planning and management. Unfortunately, the highland, the most vulnerable areas for deforestation and a complex landscape, the Thailand soil maps describe only a slope complex for which soil characteristics and properties are not available.

In order to understand processes of land use planning and resources management for sustaining land resources in an area that lacks soil information, conventional soil survey was employed in the specific highland of the study. However, in some cases (especially in highly complex landscapes) conventional soil survey might not map soil variability in sufficient detail for land and resource evaluation. The conventional soil survey is both costly and labor intensive. In order to obtain high-resolution maps of soil required for detailed environmental modeling applications and site specific crop management (Peterson 1991; Robert 1993), some methods (such as soil-landscape modeling) are needed for application of soil data in modern land evaluation.

Soil-landscape Relationships

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 weighted 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 based on fundamental principles that complex spatial patterns are related to basic underlying controls on the type and intensity of soil development enables soil scientists to accurately predict soil types and their associated properties using the relation between soil and landscape attributes. These soil-landscape attributes are natural terrain units resulting from the interactions of the five factors effecting 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. Soil-landscape relationships can be considered as a standard practice in free and integrated survey as well (Christain and Stewart, 1968). So soil-landscape study will 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 Wat Chan watershed, for example, has an area of about 13,000 ha. This area was considered a small to medium watershed assuming it has low spatial variation of parent material and climate (e.g. temperature and rainfall). Not considering temporal change of soil properties, the relationship between topographic attributes and soil properties should be a fundamental concept for characterizing spatial variability of soil properties in this landscape. Prediction of soil properties might be possible as well.

Topographic Attributes for Soil-landscape Study

The relationships between topographic attributes, such as elevation, slope, aspect, specific catchment area, plan curvature and profile curvature and hydrological and erosional processes occurring in landscapes have been outlined by Moore et al. (1991). This outline hypothesized that landforms derived from topographic attributes would correlate with characteristics of the soils while assuming other soil forming factors were constant.

Slope curvature. An important determinant of water movement and the resultant geomorphic and pedologic processes is the planar curvature of the slope, both plan and profile curvature. Curvature of landscape is classified as convexity and concavity of slopes. These properties strongly affect flow velocity, runoff and soil loss (Wischmeier and Smith, 1978) and directly related to the variability of soils on a hillslope. A number of studies focused on illustrating characteristics of slope configuration. For example Ruth (1975) described slope curvature using these components: 1) slope gradient, 2) slope length and 3) slope width.

In several studies of the relationship between slope curvature and the differences in fertility status and soil morphological properties has been examined, for example, Aandahl (1948) observed that the nitrogen content of loess soils in western Iowa was related to length of slope, measured from the slope shoulder. He found that the nitrogen content of all soil profiles collected near the tops of the ridges were low compared to those on the lower slopes (where length of slope is greater than the tops of the ridge).

Soil moisture is also affected by slope curvature. The soil tends to become saturated and seepage occurs in the foot slope and upper slope positions where the slope is concave. Convex shoulder positions are drier due to divergence of moisture in the hillslope. Because the movement and accumulation of water on hillslope positions differ, the resultant soils would be expected to be different. Pennock et al. (1987) found that soil moisture content in soils of the upper slope was lower than that of the foot slope. They also found shallow depth to carbonates in soil in upper slope positions.

Variation in depth of A and B horizons was reported as a result of pedological processes involved in profile development. This indicated that soil often eroded from the upper slopes and deposited on the lower slopes of the toposequence. Kirby et al. (1997) observed a very shallow A horizon in the upper slope position. The depth of the A horizon then increased down the toposequence. The differences in the amounts of total phosphorus (P) in soils at each of four positions along the toposequence could be explained by the different thickness of the A horizon. The least amount of P was found at the upper slope position, whereas the highest amount was in the foot slope position. The amount of P in soils from the mid slope and the lower slope was intermediate between these two extremes.

Aspect. Aspect (Slope direction) influences flow direction, insolation, and intensity of rain evaporation (Young, 1972). This topographic attribute is likely to be important in affecting soil properties, such as nitrogen and organic carbon distribution in the landscape, since some topographic setting offers protection from sun and wind and thus favors increased soil nitrogen and organic carbon.

Compound topographic index (CTI). CTI is an index that refers to a steady state of soil moisture. It can be calculated using a specific catchment area (upslope area per unit width of contour) and slope. This function reflects the hydrological processes in the landscape. So CTI should be a useful predictor because it combines contextual and site information via the upslope catchment area and slope, respectively. Gessler et al. (1995) found that attributes that characterize the distribution of hydrologic process (such as CTI) were significantly correlated with soil properties (such as silt percentage, organic matter content and phosphorus).

Elevation. Elevation in many respects affects microclimate (Geiger, 1966). Its effects are often associated with reduction of mineralization by the cooler temperature with estimation of 1 – 2 °C decrease per 1000 m increase in altitude. So this attribute is likely to affect organic matter content and nitrogen availability in the landscape. Heaney and Proctor (1989) measured litterfall and the turnover of surface organic matter along a transect of volcanic soils from a lowland tropical forest at 100 m elevation to an upper montane forest at 2600 m. They found that the mass of litter on the soil surface increased from 2.3 to 3.7 Mg ha^{-1} with increasing altitude.

The topographic attributes (such as elevation, slope, aspect, plan curvature, profile curvature and CTI) play an important role in relation to soil properties and are often used in landscape and, specifically in soil studies. They influence soil properties such as moisture, thickness of soil horizons, density, pH, organic matter, content of nitrogen, calcium, and phosphorus. The need for quantitative knowledge in obtaining topographic attributes becomes even more acute as we enter the era of computers and information systems. GIS capabilities for surface analysis provide a computationally efficient method of estimating both primary topographic attributes, such as elevation, slope, aspect, plan and profile curvature from digital elevation models and also secondary topographic attributes, such as CTI (Jenson et al.1988; Moore et al.1993).

Land Use Attribute for Soil-landscape Study

Vegetation (land use types) is one of the important factors in soil formation (Jenny, 1941). Including land use factor with topographic attributes, it might be able to improve soil property predictions. Changing land use should, consequently, affect soil properties. So this possibility led to the investigation of mapping soil properties of the landscape. Several studies have reported that forested soils contain a significant portion of organic carbon (Zinke et al. 1984; Eswaran et al. 1993). Mann (1986) found that changing land use from forests to crops caused a loss of organic carbon in the soils. With availability of remote sensing technology, land use patterns in the landscape scale can be obtained for soil-landscape study such as that discussed in chapter 3.

In the Wat Chan watershed, Northern Thailand, an understanding of how soil characteristics vary with landscape attributes may provide a basis from which to develop broad scale policies in natural resource management. This chapter uses a soil-landscape analysis approach to quantify relationships between landscape attributes generated from remotely sensed data and GIS technology and measured soil properties. The objectives of this study were 1) Characterize soil properties in the region, 2) Investigate relationships between soil properties and landscape attributes, and 3) Apply the soil-landscape modeling for predicting soil properties in the Wat Chan watershed. The results are then used to identify and prioritize sub-watershed areas for land use planning and watershed management.

MATERIALS AND METHODS

Stratification of Sample Locations

The Wat Chan watershed was selected for studying soil characteristics and distributions at the landscape scale. Site conditions of this landscape were described in Chapter 3. Many of the hydrological, geomorphologic and biological processes active in the landscape are sensitive to topographic position (Moore et al. 1991). Therefore, the spatial distribution of topographic attributes may be useful as an indirect measure of the spatial variability of these processes that influence soils and soil properties. Odeh et al (1994) found that slope, plan curvature, profile curvature accounted for much of the soil variation in their study. Consequently, elevation, slope, aspect, plan curvature, profile curvature and compound topographic index (CTI) images generated in chapter 3 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 a Gaussian distribution exists for the topographic attributes. Log transformations were applied to each image to create normal distributions of the data. An iterative self-organizing unsupervised classifier, based on a concept similar to the ISODATA routine of Ball and Hall (1965) 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 (ESRI, Inc. 1995). Landform classes were then overlaid with the1996's land use image (obtained from Chapter 3) to generate a land units image. Land units that were expected to influence the soil properties in the Wat Chan watershed were used as a basic image for stratifying sample sites. 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 a depth of 0 – 20 cm, and subsoil at the depth from 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 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 et al. 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 should have 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 measured soil properties. 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 analyzes were performed on transformed values, where necessary.

Recent studies using linear models revealed the validity 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 successes could be extended to the traditional model of soil variation that assumed spatial correlation between soil properties and topographic attributes. So stepwise model selection was used to choose the best model of each soil property in terms of 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

Landform Characteristics in the Landscape

There is no single optimal sampling design for quantifying soil map unit composition that serves all requirements. In the soil resource inventories, soil scientists often rely on their knowledge of soil-topography-hydrology-vegetation relationships to infer soil types from landforms. This knowledge allows them to make assumptions about soil attributes and to identify areas for field verification. Stratifying samples according to landform distribution in the landscape should be suitable in this landscape.

Six landform classes (Figure 4.1) were identified in this landscape based on topographic attributes including elevation, aspect, slope, plan and profile curvature and CTI. Elevation, slope and CTI were clearly differentiated among landform classes. Landform class #6 had the highest mean, mode, and median values of elevation and slope while the lowest of those values occurred in landform class #1 (Table 4.1). In contrast, the highest value of CTI value occurred in landform class #1 while the lowest

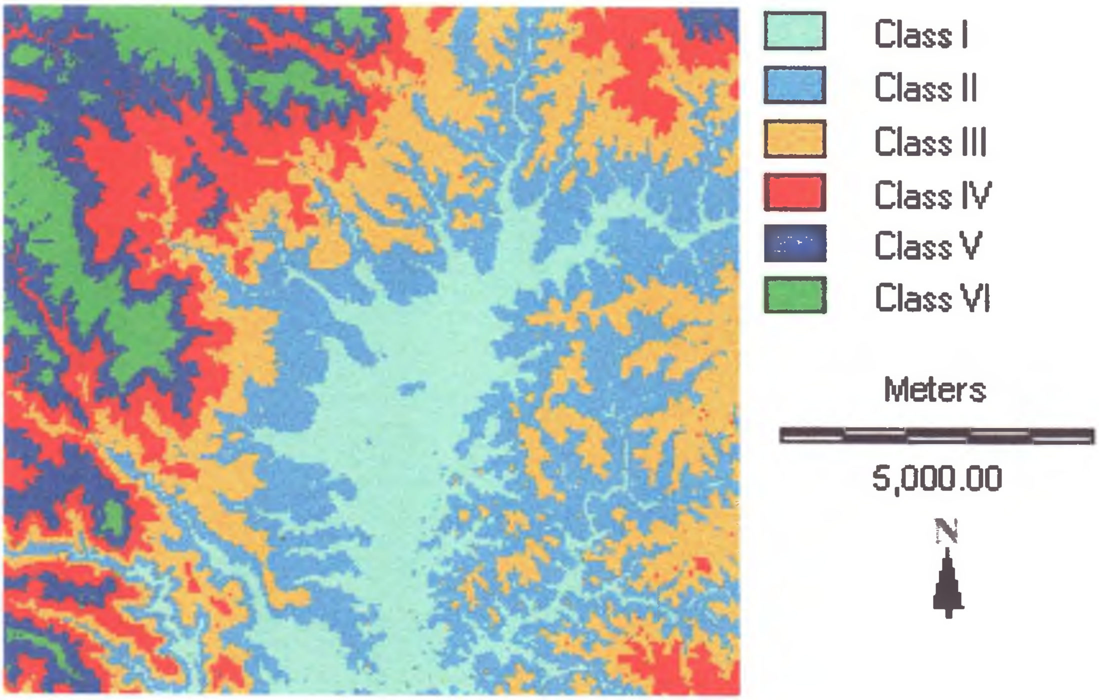


Figure 4.1 Landform Classes in the Wat Chan Watershed

Table 4.1 Topographic characteristics of landform classes

Topographic attributes	Landform class	Mean	Min	Max	SD	Mode	Median
Elevation (m)	1	970	912	1018	15.9	980	974
	2	1010	944	1058	12.2	1020	1010
	3	1052	971	1089	15.4	1040	1047
	4	1116	1010	1194	20.5	1100	1116
	5	1191	1149	1295	24.6	1160	1188
	6	1286	931	1432	47.5	1240	1279
Aspect (degree)	1	172	-1	359	96.1	180	175
	2	173	-1	359	99.3	225	173
	3	168	-1	359	98.1	45	167
	4	163	-1	359	96.5	43	160
	5	165	-1	359	97.9	79	164
	6	170	0	359	99.3	70	172
Slope (degree)	1	14.7	0	103	12.6	2	11
	2	21.8	0	150	15.2	6	19
	3	24.1	0	161	17.2	6	21
	4	33.1	0	149	18.7	30	32
	5	35.6	0	120	17.7	38	35
	6	43.6	0	157	20.4	43	43
Plan Curvature	1	-0.012	-3	3	0.186	0	0
	2	-0.011	-4	4	0.328	0	0
	3	0.025	-3	4	0.332	0	0
	4	-0.038	-7	5	0.517	0	0
	5	0.001	-3	3	0.37	0	0
	6	0.089	-4	7	0.635	0	0
Profile Curvature	1	0.118	-4	6	0.483	0	0
	2	0.069	-3	6	0.531	0	0
	3	-0.062	-5	5	0.599	0	0
	4	0.039	-6	9	0.821	0	0
	5	-0.027	-4	4	0.638	0	0
	6	-0.214	-9	6	0.986	0	0
CTI	1	3.93	0	16	3.09	2	3
	2	2.50	0	13	1.92	1	2
	3	2.08	0	12	1.62	1	2
	4	1.99	0	12	1.96	1	1
	5	1.66	0	9	1.39	1	1
	6	1.10	0	6	0.973	1	1

value was in class #6. Landform classes #2, #3, #4 and #5 had values of elevation, slope and CTI in the range between these two extremes. This can imply that landform class #1 in this study area was characterized by the highest moisture accumulation with a low slope gradient and elevation. Landform class #6 was characterized by low moisture accumulation with a high slope gradient and elevation. This supports the concept that slope affects the overall rate of water movement downslope that causes low moisture accumulation in very steep slope areas.

In this method of landform classification, aspect did not play an important role probably because values of aspect did not show any difference among landforms. Landform classes #3, #5 and #6 were mainly characterized by concave plan curvature that should enhance topographic convergence of flow while landform class #1, #2, and #4 were mainly categorized with topographic divergence (convexity). The profile curvature, which affects water flow and sediment transport processes, in landform class #1, #2, and #4 was mainly concave, which decelerates flow.

Performing landform classification using these topographic attributes helped simplify the spatial distribution of zones of surface saturation, soil water content, runoff and catenary soil development. However, spatial variability of land use was recognized in this landscape (presented in Chapter 3). So the results of overlaying the landform map with the 1996's land use map (Figure 4.2) was used to identifying soil sample locations.

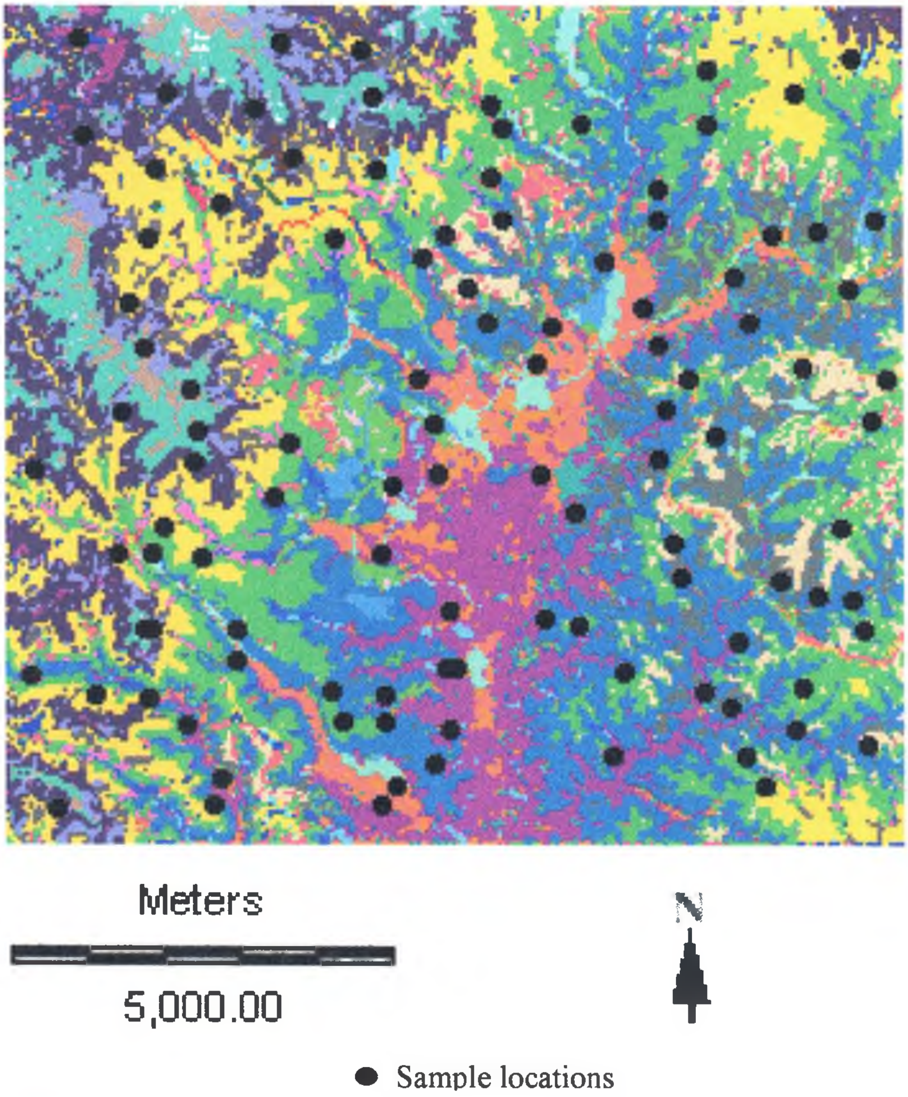


Figure 4.2 Land units and distribution of sample locations in the Wat Chan watershed

Landscape Attributes of the 107 Sample Sites

A correlation matrix of landscape attributes, calculated from the 107 sample locations, revealed that there were some highly significant correlations among topographic attributes. The most notable relationships were between degree of slope and parameters such as elevation and CTI (R = 0.48 and -0.60 respectively, Table 4.2). This indicated that high elevation areas were likely to be a steeply sloping and low moisture accumulation area. It was mostly occupied by forest and had high annual rainfall. There also was a highly significant negative correlation between plan and profile curvature (R = -0.45). This relationship would indicate that this landscape was mostly considered to be a medium runoff and throughflow area. In most case, significant correlations occurred between attributes (P = 0.05) except aspect that showed no correlation with other attributes.

A comparison between the statistical distribution of landscape attributes in the whole landscape and that of the sampling locations revealed a similar distribution of elevation, slope, aspect, CTI and annual rainfall information (Table 4.3). The plan and profile curvature distribution of sampled locations was only slightly narrower than that of the entire landscape. Consequently it was assumed that measured soil properties represented the variability of non-sampled locations in the landscape. Based on this assumption, soil properties from 107 sampling locations were used to study soil-landscape relationships.

Table 4.2 Correlation matrix of landscape attributes.

	Elevation	**Slope**	**Aspect**	**Plan**	**Profile**	**CTI**	**Land Use**	**Rain**
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

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

Table 4.3 Statistical data of landscape attributes in the Wat Chan watershed, (a) the whole watershed , (b) the 107 sample sites

(a)

Attributes	**Min**	**Max**	**Mean**	**SD**
Elevation (m)	912	1432	1064	88.2
Slope (degree)	1.00	58.0	13.7	9.29
Aspect (degree)	0	360	170	98.2
Plan curvature	-7.82	-7.23	0.02	0.88
Profile curvature	-9.39	9.81	0.02	1.03
CTI	-0.47	16.0	2.88	2.21
Rainfall (mm)	1068	1167	1135	20.1

(b)

Attributes	**Min**	**Max**	**Mean**	**SD**
Elevation (m)	949	1333	1049	82.6
Slope (degree)	1.00	47.0	13.6	9.60
Aspect (degree)	2.86	354	155	96.4
Plan curvature	-3.19	0.76	-0.17	0.50
Profile curvature	-1.51	5.44	0.27	0.82
CTI	0.51	13.9	3.69	2.74
Rainfall (mm)	1083	1166	1135	19.1

Soil Property Distributions

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). The variation for topsoil properties was also higher than that in subsoil except the variation in soil Mg that was greater in the subsoil layer (Tables 4.4 and 4.5).

Physical properties

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 content of the topsoil were higher than in the subsoil while there was an increase in clay content with depth in this landscape. Clay content of the topsoil ranges from 11.1 to 54.2 % while the subsoil ranges from 18.6 to 60.9 %.

Changes in soil bulk density within and among soil profiles is a useful criterion for evaluating root depth and water-storage capacity in the root zone. 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 4.6). 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 4.4 Properties of topsoil (0 – 20 cm) in the Wat Chan watershed, 107 samples.

Soil Properties	Min	1st Qu.	Mean	Median	3rd Qu.	Max	Std Dev.
Sand (%)	35.0	42.6	53.3	55.2	61.2	77.4	11.3
Silt (%)	6.70	12.3	17.3	14.3	21.7	32.6	6.34
Clay (%)	11.1	24.7	29.4	28.5	34.3	54.2	7.60
pH (KCl)	4.07	4.50	4.66	4.62	4.77	5.78	0.282
pH (Water)	4.73	5.14	5.31	5.30	5.44	6.15	0.254
Total N (%)	0.041	0.065	0.107	0.082	0.132	0.328	0.057
P (mg kg^{-1})	0.771	3.53	10.7	5.99	12.0	53.5	10.9
K (mg kg^{-1})	29.13	97.3	132	121	149	349	63.9
Ca ($cmol_c\,kg^{-1}$)	0.272	0.806	1.35	1.05	1.52	7.01	1.03
Mg ($cmol_c\,kg^{-1}$)	0.181	0.379	0.409	0.429	0.459	0.498	0.071
Na (mg kg^{-1})	15.5	25.5	28.5	27.6	30.9	62.3	6.23
Sum of cations ($cmol_c\,kg^{-1}$)	0.741	1.66	2.22	1.95	2.51	8.32	1.16
OM (%)	0.772	2.08	3.30	2.70	4.26	8.15	1.59
EC (dS m^{-1})	2.85	4.99	7.50	6.53	8.47	24.3	3.83
Bulk Density (g/cm^3)	0.851	1.18	1.35	1.35	1.53	1.75	0.210
Water Holding Capacity (%)	3.50	7.74	8.86	8.57	9.63	19.1	2.13

Table 4.5 Properties of subsoil (20 – 40 cm) in the Wat Chan watershed, 107 samples.

Soil Properties	Min	1st Qu.	Mean	Median	3rd Qu.	Max	Std Dev.
Sand (%)	33.1	36.2	43.1	42.8	47.1	68.1	7.85
Silt (%)	0.210	10.8	13.5	12.5	14.7	29.7	4.95
Clay (%)	18.6	39.7	43.4	42.9	47.8	60.9	7.28
pH (KCl)	3.93	4.39	4.48	4.45	4.53	5.43	0.202
pH (Water)	4.73	5.14	5.23	5.21	5.32	5.99	0.198
Total N (%)	0.021	0.040	0.060	0.050	0.070	0.179	0.028
P (mg kg^{-1})	0.359	1.23	3.05	1.94	2.78	25.4	3.62
K (mg kg^{-1})	31.8	72.8	104	102	129	279	45.5
Ca (cmol$_c$ kg^{-1})	0.158	0.450	0.746	0.618	0.842	4.43	0.622
Mg (cmol$_c$ kg^{-1})	0.095	0.353	0.385	0.404	0.442	0.500	0.081
Na (mg kg^{-1})	21.4	26.9	29.6	29.9	32.3	50.9	4.31
Sum of cations (cmol$_c$ kg^{-1})	0.526	1.15	1.53	1.40	1.73	5.31	0.710
OM (%)	0.331	1.00	1.43	1.22	1.74	4.05	0.622
EC (dS m^{-1})	2.00	2.87	4.01	3.87	4.40	16.3	1.94
Bulk Density (g/cm^3)	0.755	1.23	1.37	1.41	1.50	1.76	0.173
Water Holding Capacity (%)	3.96	6.60	7.37	7.39	8.03	12.6	1.47

Table 4.6 Correlation matrix of selected topsoil properties.

	Sand (%)	**Silt (%)**	**Clay (%)**	**OM (%)**	**BD (g/cm^3)**	**WHD (%)**
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	
WHD (%)	0.38	-0.34	-0.27	-0.39	0.44	1.00

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

Table 4.7 Correlation matrix of selected subsoil properties.

	Sand (%)	**Silt (%)**	**Clay (%)**	**OM (%)**	**BD (g/cm^3)**	**WHD (%)**
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	
WHD (%)	0.20	-0.29	-0.02	-0.14	0.08	1.00

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

Chemical properties

Reaction of soils in this landscape was mostly slightly acid 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 indicates 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 5.0 which only four subsoil samples obtained less than 5.0 that they are needed to measure exchangeable Al.

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 has shown that most topsoil nutrients had higher values than those of the subsoil. The variation of the topsoil nutrients was also higher than that the subsoil in this landscape except for Mg, because topsoil is subject to manipulation and management.

Landscape Attributes and Soil Property Relationships

The relationship between landscape attributes and properties of the topsoil and subsoil showed that significant correlations occurred between several soil properties and landscape attributes (Tables 4.8 and 4.9). The landscape attributes most highly correlated with topsoil and subsoil properties were elevation, slope, land use and annual

Table 4.8 Correlation matrix between landscape attributes and topsoil properties.

Soil Properties	Elevation	Slope	Aspect	Plan	Profile	CTI	Land use	Rain
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

Table 4.9 Correlation matrix between landscape attributes and subsoil properties.

Soil Properties	Elevation	Slope	Aspect	Plan	Profile	CTI	Land use	Rain
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

rainfall. These topographic attributes heavily influence water movement through and over the landscape, which probably influences 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 identified in this analysis as well. This correlation suggests that soil hydrology and erodibility as mechanisms of runoff processes on hillslopes.

Physical soil properties

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 a higher percent sand at the low elevation, less slope and lower amounts of 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 might be explained with the hydrological and erosional process.

In this landscape, which is steep, rugged, mountain land in the Wat Chan watershed, 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 4.3) and consequently higher elevations experience stronger leaching conditions. With respect to physical soil properties, the texture and structure play a dominant role. Soils with high content of very fine sand (such as 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 encouragement 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 found 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 might have been 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 low slopes 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.

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 occurred in the high elevation, steep slope and higher amounts of annual rainfall, then soil bulk density was likely to low in this landscape characteristic which was supported by correlation between soil texture and landscape attributes in this landscape.

Chemical soil properties

Topsoil properties. Soil organic matter and N content were both positively correlated with elevation, slope and annual rainfall. This indicated that the input of organic matter was probably greater and the decomposition rate slower in the cooler and wetter high elevations that also had higher rainfall. This would account for the larger values of 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 closely associated 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 also correlation to organic matter and N content. This can be explained because cation exchange capacity of organic matter is higher than that of low activity clays. Thus sum of cations was highest in areas at higher elevations and annual rainfall areas, 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) that resulted in low P in the topsoil.

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

Subsoil properties. 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 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 (Appendix 4.1). Degree of slope and CTI were log transformed before analysis. Tables 4.10 and 4.11 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.

Table 4.10 Predicted soil properties of topsoil (0 – 20 cm) using landscape attributes in the Wat Chan watershed. (values in parenthesis are standard errors)

Soil Properties	Intercept	Elevation (m)	Log(Slope) (degree)	Aspect	Log(CTI)	Plan Curvature	Profile Curvature	Land Cover	Rainfall (mm/year)	R^2
Sand (%)	440 (50.5)	-0.0595 ** (0.0108)			-1.86 (1.265)		-1.67 (1.0140)		-0.284 ** (0.0444)	0.46
Silt (%)	-155 (25.2)	0.0463 ** (0.0054)					1.15 * (0.541)	-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)					-0.088 (0.060)	-0.0543 (0.0372)	-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)					-0.0260 (0.0132)			-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)				-0.637 (0.380)			-0.0220 * (0.0103)	0.17

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

Table 4.11 Predicted soil properties of subsoil (20-40 cm) using landscape attributes in the Wat Chan watershed. (values in parenthesis are standard errors)

Soil Properties	Intercept	Elevation (m)	Log(Slope) (degree)	Aspect	Log(CTI)	Plan Curvature	Profile Curvature	Land Cover	Rainfall (mm/year)	R^2
Sand (%)	223 (37.6)	-0.0418 ** (0.0079)					-1.22 (0.777)		-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)					-0.0284 (0.0155)		-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)	0.0002 (0.000)					-0.0047 ** (0.0007)	0.44
Water Holding Capacity (%)	-1.10 (7.95)	-0.0063 ** (0.0017)				-0.389 (0.265)			0.0132 (0.0072)	0.15

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

The correlation among landscape attributes indicated that independent statistical tests could not be carried out on single attributes.

Topsoil properties. The regression equations presented in Table 4.10 which includes sand, silt, nitrogen (N), organic matter (OM), extractable P (P), and bulk density (BD), explained from 40% to 55% of the variability of measured topsoil properties. 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 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 was uniform moisture conditions, the average total OM and N content tended to increase. Buckman (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.

Elevation and rainfall were the main landscape attributes for predicting soil bulk density in this landscape.

Subsoil properties. Sand, silt, nitrogen content (N), organic matter content (OM) and bulk density (BD), explained from 33% to 47% of the variability of measured subsoil properties (Table 4.11), and thus were considered for predicting subsoil properties in this landscape.

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. So percent sand, percent silt, N, OM and BD variables were selected to predict the spatial distribution of soil properties in this landscape (Appendix 4.2) which will be selected to identify and prioritize sub-watershed areas in the next chapter.

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 in this chapter 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 organic matter content in this landscape. More attention should be focussed on stratifying samples. 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, 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 improve the prediction of soil chemical properties.

CHAPTER V

Watershed Characterization and Prioritization for Sustaining Watershed Resource Management

INTRODUCTION

Landscape attributes, such as land use types, topographic attributes and soil characteristics, play important roles in determining the landscape structure and function that are useful for land use planning and resources management at the watershed scale (watershed decision support system). Interactions among these landscape attributes can influence erosion potential and the quality of forest ecosystems in mountainous areas (Lamberson et al. 1992; Morse et al. 1985; and Saunders et al. 1991). Increasing soil erosion and decreasing quality of forest ecosystems associated with late-successional forests have mostly occurred in the highly degraded highland watersheds (Swanson et al. 1982), especially in tropical forests. This will lead to increased surface runoff (Costales, 1979 and Tangtham et al. 1972) and the incidence of shallow landslides (Bartaya, 1989), which induce the movement of soil nutrients and water from upland watersheds resulting in a decline of soil fertility. So issues of greatest concern in watershed studies include the related problems of deforestation (for agriculture purposes) and soil erosion processes.

The Wat Chan watershed has undergone dynamic changes of the landscape during the last two decades. Variability of land use types in this watershed ranged from ecologically significant primary forest cover to a small parcel agricultural production (see Chapter 3). Topography varied from flat to steeply sloping lands. Spatial soil information indicated that values ranged from very low to very high for both physical and chemical soil properties (see Chapter 4). Due to the variation in these landscape attributes, the sensitivity of watershed and sub-watersheds within it also varies from place to place. Such variation will lead to the spatial variability in the landscape that causes difficulty in defining and solving problems for site specific management. Useful biophysical indicators which may be derived from the spatial information include those which are related to risk in environmental degradation of the watershed. When available information permits to estimate soil loss and enrichment ratio of sediments, it is recommended to use them as an indicator for loss in soil productivity of the sub-watersheds. To improve land use planning and resource management in this watershed, characterization and prioritization of sub-watersheds based on an index of the watershed degradation is needed. An index of the different degree of watershed degradation then can be selected for improved management such as precision-farming and other approaches.

Characterizing Sub-watersheds with a Degradation Index

A watershed is considered to be a basic ecological, geomorphologic, and politically functional unit of study (Hufschmidt, 1986; Armitage, 1995). An understanding of the ecosystems and socio-economic processes can come about only by understanding geomorphology and hydrology of an area. This leads to the development of the watershed analysis concept (a synthesis of information that focuses on issues important to a particular watershed) which is one of the important methodologies that attempts to provide a more complete understanding and balance of economic and ecological priorities at the watershed scale. However, identifying the degraded watersheds should be the first concern for selecting the study area at the watershed scale. A degradation index can be based on existing data, access and the ability for the agencies to cooperatively complete the analyses.

Watershed characterization involves determining the physical and biological characteristics of a watershed surface for water quality and predicting the magnitude of stream flows. Surface water runoff (usually the most critical assessment for degraded watersheds) is a function of many interrelated factors including; 1) climate, mainly rainfall, 2) soils and their inherent resistance to dispersion, infiltration, and percolation, 3) land use cover, and 4) physiography of sub-watershed areas (such as slope, relief and stream networks). Some methods have been used to characterize the watershed with respect to runoff from the watershed. Cook's method (US-SCS, 1953), for example, has been used for watershed characterization by considering four watershed attributes including; 1) the relief, 2) the soil infiltration, 3) the vegetative cover, and 4) the surface storage. The total of four numbers representing these properties is the watershed characteristic and will lie between extreme values of 100 (if the highest number has been chosen for each of the four attributes) and 25 (if the lowest value has been chosen in each case). This method was modified for African conditions and found to have effect on runoff rates (Hudson, 1995). So identifying characteristics of each sub-watershed of the landscape provides useful information to prioritize the degradation and determine which sub-watersheds require the most attention in the landscape.

Watershed Attributes as Criteria for Watershed Characterization

Characteristics of sub-watersheds that were related to surface water runoff could be determined as the related watershed attributes including; contributing drainage area (CDA), average basin slope (ABS), basin relief (BR), total stream length (TSL) and stream density (STD), proportional area of disturbance (PD), proportional area with slope greater than 12 degrees (PS), proportional area of watershed class I and II (PWC), average soil organic matter content (AOM) and soil texture index (STI) within the sub-watershed.

Contributing drainage area. This is defined as the total area that contributes to surface-water runoff at the basin outlet. This can be determined by calculating the planimetric surface area and the true surface area of the sub-watershed. It is one of the important attributes that affects soil erosion potential in a watershed. Studies by Garbrecht (1991) and Bloschl et al. (1995) have examined and estimated the effect of the size of drainage area on simulated runoff and found that the spatial runoff accumulation increased with increasing sub-watershed size. Using this variable Wolock (1995) found that the percentage of overland flow in the total stream flow was most variable for sub-watershed areas. This variability increased as sub-watershed size increased from 1 to 5 km^2 and then changed little for sub-watersheds larger than 5 km^2.

This was because values of flow path characteristics increased as sub-watershed size increased from 1 to 5 km^2.

Slope and relief. The slope and relief characteristics of a sub-watershed can be expressed in a variety of ways, but probably the simplest is the basin relief, defined as the difference in elevation between the highest and lowest points in the watershed. This value can be used to indicate areas possessing various types of terrain which are varied in scale from a few meters in height and length to several kilometers long and more than a kilometer high such as micro relief, meso relief, hilly terrain and mountainous terrain. Within a region of roughly uniform climate and geology, both slope and relief parameters are useful indices of sediment production and flood peaks (Schumm et al., 1961). Slope is the maximum rate of change in elevation for each location. A steep slope results in greater energy of stream flow that causes a greater potential for erosion. Such areas are susceptible to damage. Almost all geomorphic processes on hillslopes are concerned with the action of water, and therefore with the way in which runoff is produced.

Stream length and density. A stream network is a main drainage system of sediment transportation from upslopes. A high stream density will permit the movement of sediment more rapidly than a low density of streams. So stream density in the watershed should be considered for determining watershed prioritization.

Proportional area of disturbance. It is defined as a ratio of total open land within sub-watershed to the contributing drainage area. The amount of surface water runoff and sediment transportation in a watershed is directly influenced by land use and vegetation of the area. Undoubtedly, the most important effect of vegetation is to reduce the movement of water over the surface. Putjaroon et al. 1987 found that surface water runoff from abandoned fields was twice that from the forest land in Thailand. So these characteristics are useful criteria for prioritizing the degraded sub-watersheds in the Wat Chan watershed.

Proportional area of watershed class I and II. This criterion is defined as a ratio of the total area of watershed class I and II within a sub-watershed to a contributing drainage area. Watershed class I and II, according to the watershed classification system in Thailand, has been reserved as forest and water source protection area. This classification is considered useful for prioritizing degraded watersheds.

Average soil organic matter. Recent studies tend to confirm the importance of water stable soil aggregates in reducing water erosion. Organic matter is an important factor that increases aggregation of soil particles and the stability of the particles. So organic matter content in the watershed can be important for characterizing degraded sub-watersheds.

Soil texture index. Many studies have confirmed that sand and silt tend to increase erodibility, while clay decreases it (Hudson, 1995). Barnett and Rogers (1966) suggested a soil texture index for evaluating soil erosion in the landscape based on soil texture. This index can be calculated as follows;

$$STI = \frac{\%sand + \%silt}{\%clay} \quad \text{------------------------} \quad (5.1)$$

This index is a possible criterion for judging the relative susceptibility of soil to erosion (Bouyoucos, 1935) and can be considered as a watershed attribute that influences soil erosion. Table 5.1 shows the relationship of soil texture index corresponding with selected soil texture classes.

Table 5.1 Soil texture classes and a corresponding soil texture index.

Soil texture class	Clay content (percent)	Soil texture index
Clay	47.1	1.12
Silty Clay	59.5	0.679
Davidson Clay Loam	23.8	3.02
Fine Sandy Loam	25.3	2.86
Silty Clay Loam	34.0	1.85
Silt Loam	35.3	1.72
Loam	16.4	4.55

Source: Bouyoucos, 1935.

The watershed attributes discussed above influence surface-water runoff, which leads to an understanding of the effect of watershed characteristics on potential for erosion. In the past, quantification of these attributes was a tedious and time-consuming process, which might lead to an inaccurate watershed characterization. The possibilities and applications of watershed characterization are exponentially greater at present due to the increasing power of GIS. Eash (1994) has quantified characteristics of drainage basins using computerized techniques for the purpose of reducing time and improving the precision. The effectiveness of GIS in characterizing the sub-watersheds has led to studies of watershed ranking. Civco et al. (1995) reduced the 45 preliminary watersheds to 19 watersheds with 53 watershed characteristics in meeting the objective of developing an equation to predict low-flow events in highly forested, humid, montane regions in Puerto Rico. With emerging GIS capability of spatial analysis, watershed characterization and prioritization can be improved.

Multiple Criteria Decision Making for Prioritizing the Degraded Watershed

In watershed studies, soil loss by water is of interest primarily in terms of on-site effects of erosion. An important tool for estimating longtime average annual soil losses from sheet and rill erosion has been the Universal Soil Loss Equation (USLE). This empirical model has been used most widely for predicting soil erosion at the field experiment scale. However, in situations such as complex watersheds of mountainous land this model is seldom applied to study soil erosion. In order to understand watershed characteristics affecting surface-water runoff on the landscape scale, multi-criteria analysis for determining structure and function of the sub-watersheds on erosion potential might be more reliable for watershed decision support in this study than empirical models.

Multiple criteria decision making (MCDM) methods are procedures and mathematical algorithms for aiding decision making when multiple criteria must be considered. Researchers from different disciplines including management science, economics, marketing research have developed methods for their own particular use. To meet a specific objective, several criteria are frequently evaluated. Briefly, the application of MCDM can be described in five steps (Howard, 1991): 1) define the objectives, 2) choose the criteria used to measure the performance, 3) transform the criteria scales into units that are commensurate, 4) assign weights to the criteria that reflect their relative values to the decision makers, 5) apply a mathematical algorithm for ranking the objectives.

Landscape attributes, such as land use, topographic attributes and soil information, obtained from Chapters 3 and 4 were used as criteria for the purpose of classifying degraded sub-watersheds in the Wat Chan watershed. In order to fulfil this objective, this chapter uses a multiple criteria decision making approach to index the degraded sub-watershed in the Wat Chan watershed Northern Thailand. Such evaluations can help resource planners and managers make a decision in choosing the problematic sub-watershed for land and resources improvement.

MATERIALS AND METHODS

The Wat Chan watershed was selected for a study of sub-watershed characteristics and prioritization at the landscape scale. Site conditions of this landscape were described in Chapter 3. Land use patterns obtained from Chapter 3 were used to calculate proportional area of deforested land as a sub-watershed attribute. Spatial variability of soil information in the study area has shown in Chapter 4. Selected soil properties such as soil organic matter content, percent sand and silt content were extrapolated throughout the landscape and used as sub-watershed attributes as well.

Delineating Sub-watershed for Characterization

A Digital Elevation Model (DEM) image constructed from an elevation map (1:50,000 scale) in Chapter 3 was used to generate sub-watershed boundaries in this landscape by conditioning procedures for automatic delineation of sub-watersheds reported by Jenson and Domingue (1988). Their procedures were compared with the manually delineated watersheds and found that it was 97 percent in spatial agreement. For this study, watershed delineation, based on the above procedures, was accomplished using the standard ARC GRID watershed tool (ESRI, Inc. 1995) and a digital elevation map (DEM). The major processing steps and ARC commands used for stream network and sub-watershed delineation are shown in Figure 5.1.

Creating a stream network data set from a sink-free DEM. Prior to using GRID tools to build a stream network image, an elevation map was processed into a single seamless digital elevation model image by using the TOPOGRID command in the Arc/Info software. The seamless digital elevation image was then filled by the FILL command in the GRID tool to insure that no areas of the surface acted as sinks that might hinder flow routing. Then a "flow direction image" was generated from sink-free DEM by using the FLOWDIRECTION command in the GRID tool. The flow direction for a cell in a flow direction image is the direction of water flow out of the cell. It is encoded to correspond to the orientation of one of the eight cells that surround the cell. Then the flow accumulation image where each cell of the image was assigned a value equal to the number of cells that flow to it was created by the FLOWACCUMULATION command in the GRID tool. Finally, a flow accumulation

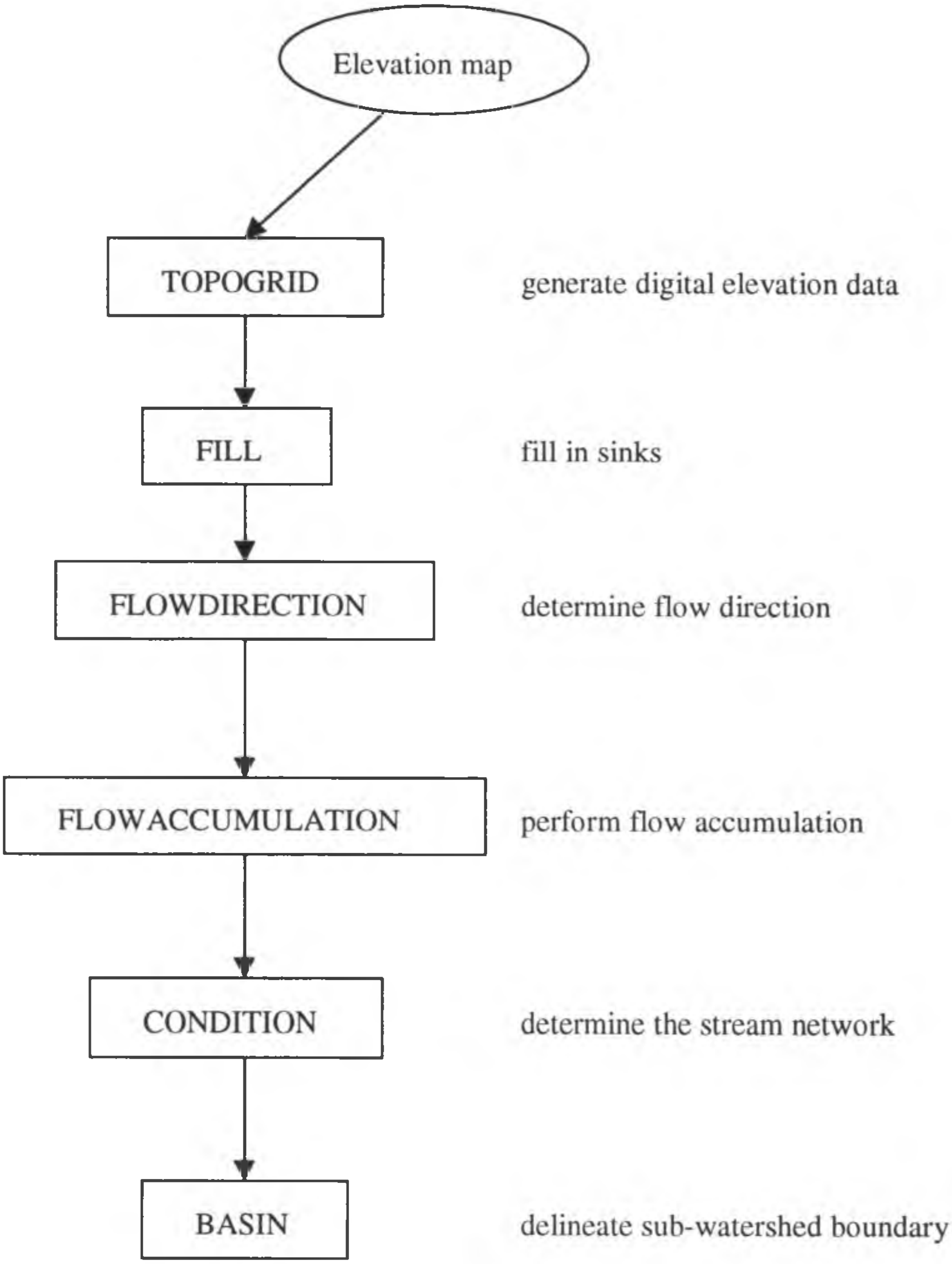


Figure 5.1 The major processing steps for sub-watershed delineation and ARC commands used

image was used to produce a stream network image by applying a threshold value of 100 to the flow into the generated streamline. In this step, the GRID algebraic expression was used to build isolating cells collecting flow from a relatively large number of surrounding cells (100 cells).

Delineating different sizes of sub-watersheds. The "flow direction image", generated by Arc/Info, was used to delineate the sub-watershed boundaries by identifying ridge lines between sub-watersheds based on the number of cells that accumulate flow to each section of the stream. The BASIN command in the GRID tool was used to accomplish this procedure.

Each sub-watershed in the Wat Chan watershed generated from the ARC GRID watershed tools was considered in characterizing the watershed.

Data Compilation and Analysis

Sub-watershed characterization

The spatial analysis capability of GIS was used to quantify sub-watershed attributes based on land use types, topographic attributes and soil information. The following attributes were considered in characterizing and prioritizing degraded sub-watersheds in the Wat Chan landscape; 1) contributing drainage area (surface area, ha), 2) average basin slope (degree), 3) basin relief (m), 4) stream density ($m.ha^{-1}$), 5) proportional area of disturbance; 6) proportional area with slope greater than 12 degrees, 7) proportional area of watershed class I and II; 8) average soil texture index, and 9) average soil organic matter content (Table 5.2).

Table 5.2 Selected sub-watershed attributes for multi-criteria analysis

	Attribute	**Description**
#1, CDA	Contributing drainage area	Size of each sub-watershed (ha).
#2, ABS	Average basin slope	Mean of slope value within sub-watershed (degree).
#3, BR	Basin relief	The sea-level elevation difference between the highest and the lowest elevation within sub-watershed (m).
#4, STD	Stream density	Ratio of total stream length within sub-watershed to contributing drainage area (m/ha).
#5, PD	Proportional area of disturbance	Ratio of total open land within sub-watershed to contributing drainage area.
#6, PS	Proportional area with slope greater than 12 degrees	Ratio of total area with slope greater than 12 degrees within sub-watershed to contributing drainage area.
#7, PWC	Proportional area of watershed class I and II	Ratio of total area of watershed class I and II within sub-watershed to contributing drainage area.
#8, STI	Average soil texture index	Mean of soil texture index within sub-watershed.
#9, AOM	Average soil organic matter content	Mean of soil organic matter content within sub-watershed (%).

Sub-watershed attributes #1 to #4 and #6 were obtained from a DEM image as explained in the section of sub-watershed delineation of this Chapter and Chapter 4. Attribute #5 was obtained from the 1996's land use map from Chapter 3. A watershed class map (1: 50,000 scale) obtained from the Department of Forestry, Thailand, was stored in the computer in digital format using ARC/Info GIS software. This map was then used to obtain sub-watershed attribute #7. Characteristics #8 and #9 were obtained from extrapolated soil properties based on the soil-landscape model described in Chapter 4.

Sub-Watershed prioritization

Descriptive statistical analysis was performed for all sub-watershed attributes in the landscape. Each attribute within a sub-watershed was then used as a basic criteria for multiple criteria decision support analysis. A weighted linear combination method (Equation 5.2) of multi-criteria aggregation (Voogd, 1983) was employed for evaluating the degraded sub-watersheds. With a weighted linear combination, sub-watershed attributes were combined by applying a weight to each attribute followed by a summation of the results to yield an index of watershed degradation.

$$D = \sum W_i X_i \qquad \text{--------------------------- (5.2)}$$

Where D is the index of watershed degradation
W_i is the criteria weight of attribute i
X_i is the criteria score of attribute i

Weighting of attributes was determined based on the importance of their effect on surface water runoff and potential of erosion. It is necessary that the criteria weights must sum to one in the procedure of multi-criteria analysis using a weighted linear combination. So a pairwise comparison developed by Saaty (1977) in the context of the decision making process known as the Analytical Hierarchy Process (AHP) was used to calculate criteria weights for each attribute. Weights can be derived by taking the principal eigenvector of a square reciprocal matrix of pairwise comparisons between the criteria and can be calculated with the WEIGHT command in IDRISI software.

Due to the different scales of sub-watershed attributes, it is necessary to standardize those attributes before the weighted linear combination is performed. Linear scaling normalization proposed by Voogd (1983) was used to standardize each attribute as follows:

$$X_i = (f_i - f_{min})/(f_{max} - f_{min})$$

where X_i is the transformed attribute value for the i^{th} criterion
f_i is the attribute value in the original units for the i^{th} criterion
f_{min} is the minimum values for attribute i
f_{max} is the maximum values for attribute i

The criteria score after normalization ranged from 0 to 1. The worst outcome (the highest potential soil erosion) is indicated by criterion values of $X_i = 1$, while the best outcome (the lowest potential of soil erosion) is indicated by $X_i = 0$.

RESULTS AND DISCUSSION

Sub-watershed Characteristics

Forty-nine sub-watersheds were automatically delineated along the topographic divide in the Wat Chan watershed (Figure 5.2) by using raster based GIS (GRID

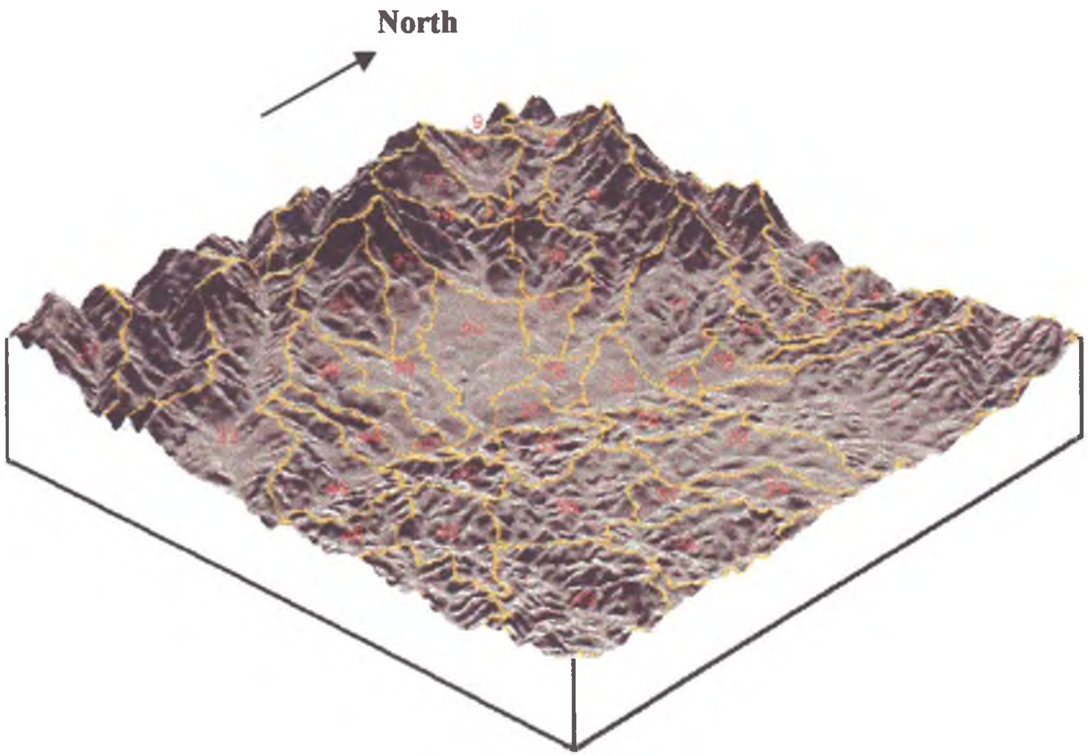


Figure 5.2 Sub-watershed boundary in the Wat Chan watershed.

module) of the ARC/INFO software. Due to the spatial variability of landscape attributes, different watershed attributes were estimated within the sub-watersheds (Appendix 5.1) based on definition and description of the nine selected sub-watershed attributes shown in Table 5.2. There was a high degree of variation in these attributes (Table 5.3), which can lead to the characterization and prioritization of degraded sub-watersheds.

Contributing drainage area. Two methods for calculating contributing drainage area (sub-watershed area) were performed; 1) The planimetric surface area and 2) The true surface area. The planimetric surface area of sub-watershed ranged from 38.5 to 1158 ha with the average of 250 ha (Table 5.3). While the true surface area of the sub-watershed varied from 43.7 to 1318 ha. Contributing drainage area calculated by true surface area method was higher than that calculated using the planimetric surface area about 2.43 – 26.7%. The true surface area (Table 5.3) depended upon the variation of topography such as slope and relief within a sub-watershed. The "true" surface area is more accurate than planimetric surface area for a soil erosion study and is important for watershed studies, especially in complex landscapes. A large sub-watershed is likely to be more sensitive than a small sub-watershed if inappropriately managed. This is because a large sub-watershed contributes a large amount of sediment to the lower slope area that can affect the quality of the watershed area. An estimate of the true surface area of the sub-watershed revealed that thirty-nine sub-watersheds (about 80% of total number of sub-watersheds) have a contributing drainage area less than 400 ha (Plate I), which is considered a small sub-watershed. About 20% of the sub-watersheds

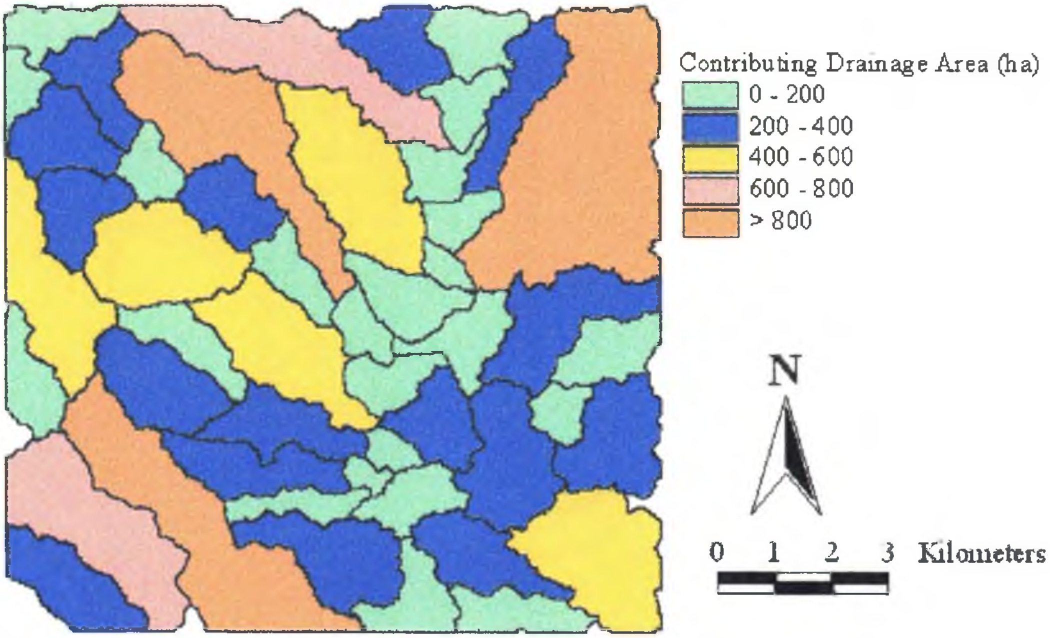
Table 5.3 Statistical data of sub-watershed attributes in the Wat Chan watershed

Characteristic[1/]	Minimum	Average	Maximum	SD
Area (ha)	38.5	250	1158	204
CDA (ha)	43.7	294	1318	244
Difference between Area and CDA (%)	2.43	13.5	26.7	5.48
PD	0.00972	0.234	0.659	0.158
PS	0.0387	0.497	0.880	0.225
PWC	0.0001	0.350	1	0.350
ABS	7.631	24.2	42.1	8.86
BR	48	202	448	121
STI	1.94	2.55	3.55	0.425
AOM	1.37	2.81	5.36	1.09
TSL	-	1883	7110	1571
STD	0	6.95	16.8	3.90

[1/] CDA = Contributing drainage area (ha)
ABS = Average basin slope (degree)
BR = Basin relief (m)
TSL = Total stream length (m)
STD = Stream density (m/ha)
PD = Proportional area of disturbance
PS = Proportional area with slope > 12 degrees
PWC = Proportional area of watershed class I and II
STI = Average soil texture index
AOM = Average soil organic matter (%)

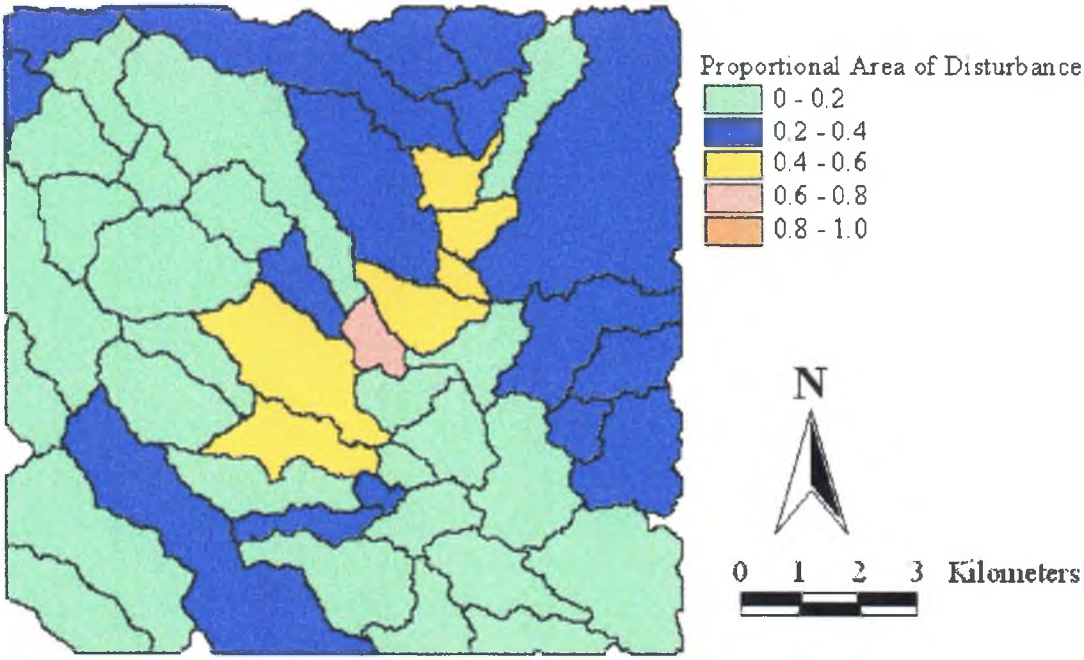
were considered as medium sub-watersheds.

Proportion area of disturbance. The estimation of proportional area of disturbance within sub-watersheds of this landscape revealed that the proportion of agricultural land ranged from 0.010 to 0.659. Twenty-five sub-watersheds (about 51% of the total number of sub-watersheds) were less than 20% occupied by agricultural land (Plate II.), while there was no sub-watershed fully occupied by agricultural lands in this landscape. Seven sub-watersheds were characterized as the watersheds that were occupied by more than 40% agricultural use. These sub-watersheds have a high possibility of degradation.



Contributing drainage area (ha)	Number of sub-watersheds	% of total sub-watersheds
0 – 200	23	46.9
200 – 400	16	32.7
400 – 600	5	10.2
600 – 800	4	8.16
> 800	1	2.04

Plate I. Contributing drainage area (ha) characteristics of sub-watersheds



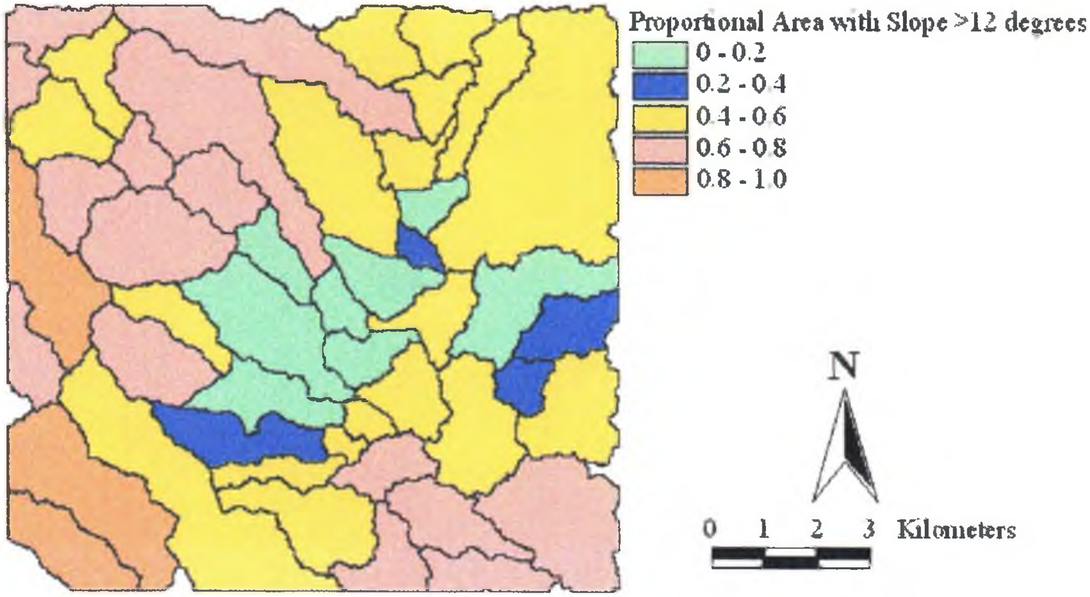
Proportional area of disturbance	Number of sub-watersheds	% of total sub-watersheds
0 – 0.2	25	51.1
0.2 – 0.4	7	14.3
0.4 – 0.6	6	12.2
0.6 – 0.8	1	2.04
0.8 – 1.0	-	-

Plate II. Proportional area of disturbance characteristics of sub-watersheds.

Proportional area with slope greater than 12 degrees. The estimation of proportional area with slopes greater than 12 drgrees within a sub-watershed revealed that eighteen sub-watersheds (about 36% of the total number of sub-watersheds) were classified as highly degraded watersheds (more than 60% of total area within the sub-watershed has a slope greater than 12 degrees, Plate III). While eight sub-watersheds were considered as not degraded sub-watersheds based on low proportional area with slope greater than 12 degrees.

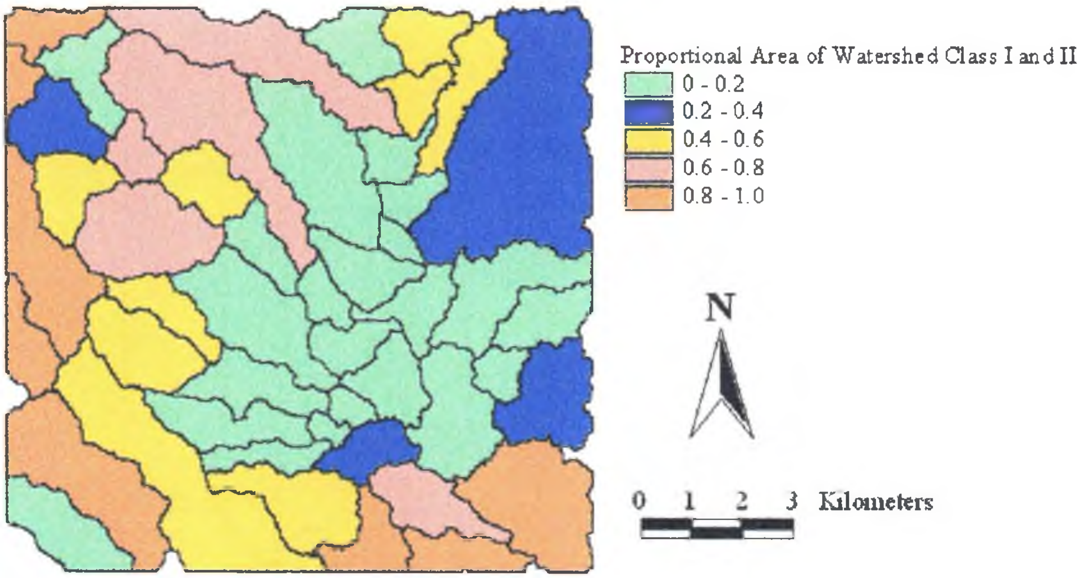
Proportional area of watershed class I and II. The estimation of proportional area of watershed class I and II within a sub-watershed showed that eight sub-watersheds (about 16% of the total number of sub-watersheds) were fully determined as watershed class I and II (Plate IV). These are sub-watersheds in which we would recommend banning agricultural activities by the government in order to prevent negative environmental impacts. Forest and water need to be conserved in these sub-watersheds. So they were considered as highly degraded sub-watersheds if any agricultural activities would be proposed. Twenty-two sub-watersheds have less than 20% of the area covered with watershed class I and II. These sub-watersheds might be considered as less degraded sub-watersheds based on government policy and available for selected agricultural activities.

Average basin slope. Average slope within a sub-watershed ranged from 7.63 to 42.1 degrees (Table 5.3). There was only one sub-watershed with an estimated average basin slope of less than 8 degrees (Plate V). Almost all sub-watersheds were characterized by steep slopes that are, in general, difficult to access, have relatively low



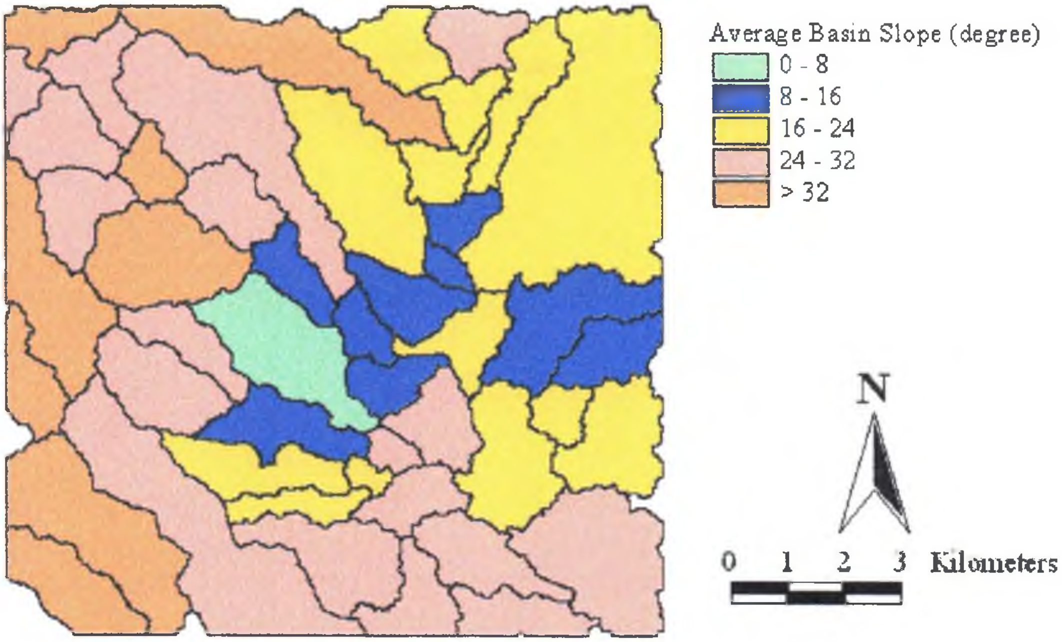
Proportional area that slope greater than 12 degrees	Number of sub-watersheds	% of total sub-watersheds
0 – 0.2	8	16.3
0.2 – 0.4	4	8.16
0.4 – 0.6	19	38.8
0.6 – 0.8	15	30.6
0.8 – 1.0	3	6.12

Plate III. Proportional area that slope greater than 12 degrees characteristics of sub-watersheds.



Proportional area of watershed class I and II	**Number of sub-watersheds**	**% of total sub-watersheds**
0 – 0.2	22	44.9
0.2 – 0.4	5	10.2
0.4 – 0.6	9	18.4
0.6 – 0.8	5	10.2
0.8 – 1.0	8	16.3

Plate IV. Proportional area of watershed class I and II characteristics of sub-watersheds.



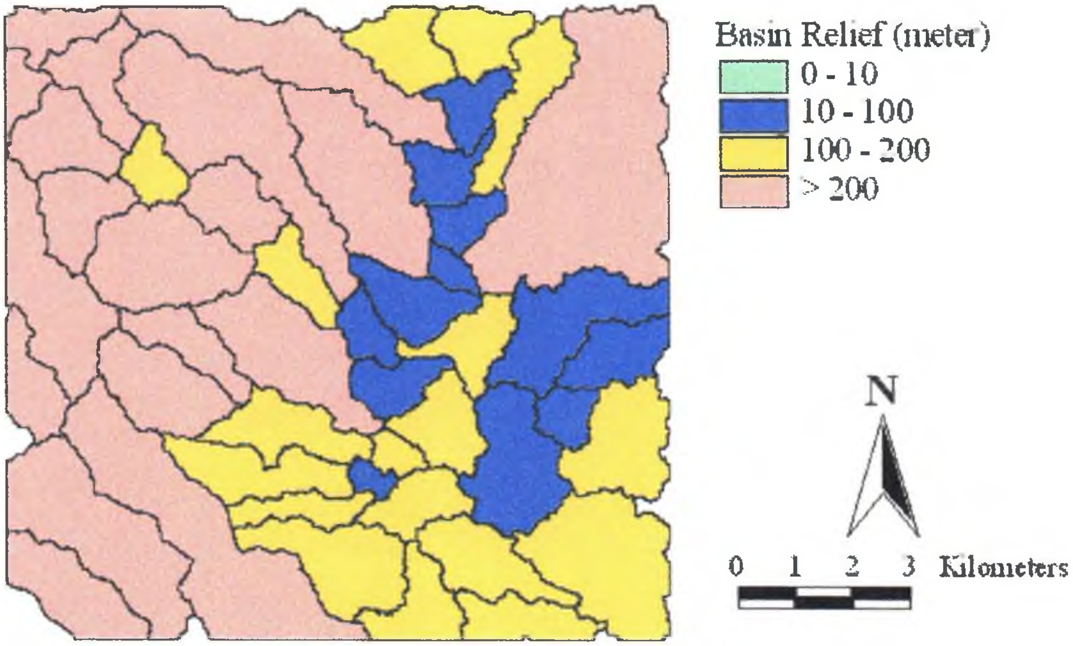
Average basin slope (degree)	Number of sub-watersheds	% of total sub-watersheds
0 – 8	1	2.04
8 – 16	9	18.4
16 – 24	13	26.5
24 – 32	18	36.8
> 32	8	16.3

Plate V. Average basin slope (degree) characteristics of sub-watersheds.

suitability for agriculture, and are costly for the construction of buildings and other facilities. Sub-watersheds with this characteristic will become very degraded if the suitable practices are ignored.

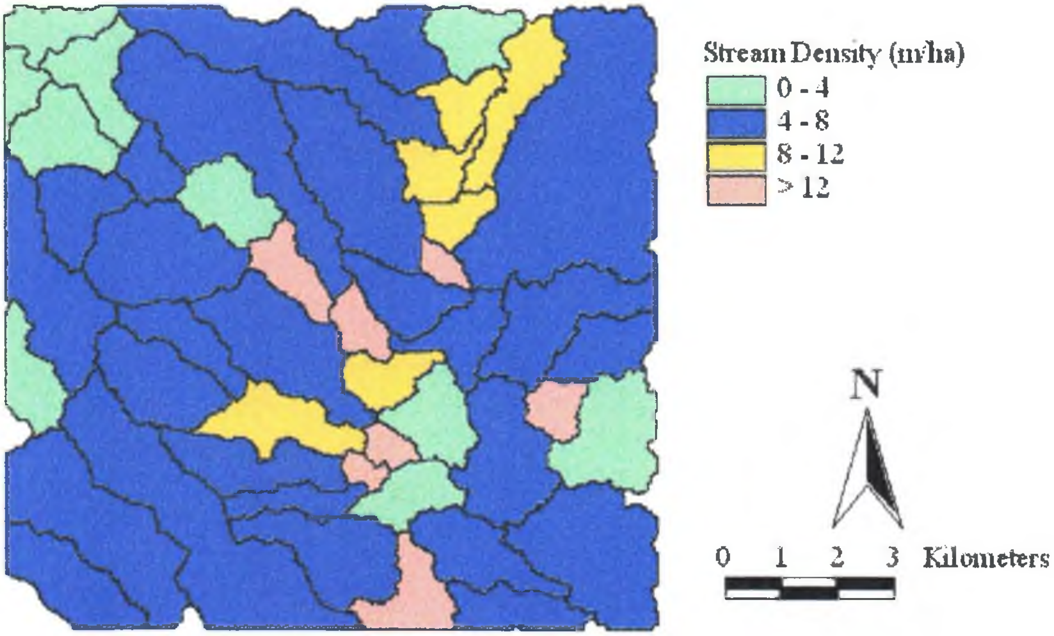
Basin relief. This attribute is measured as the sea-level elevation difference between the highest contour elevation and the lowest interpolated elevation at the basin outlet within a sub-watershed. Basin relief within the sub-watersheds showed that the relief of the sub-watershed in this landscape ranged from 48 to 448 m (Table 5.3). Thirty-seven out of forty-nine watersheds (about 75%) have basin relief higher than 100 m, which are considered as macro relief watersheds (Plate VI). Twelve sub-watersheds were considered as meso relief watersheds (10 – 100 m. of basin relief). There were no micro relief sub-watersheds defined in this landscape. With a macro relief sub-watershed, a large amount of sediment is likely to be transported into the lower slope area, which will likely cause extensive degradation in those sub-watersheds.

Total stream length and stream density. Total stream length within the sub-watershed in this landscape ranged from < 25 to 7110 m (Table 5.3). The estimation of stream density within sub-watersheds in this landscape found that stream density ranged from 0 to 16.8 m/ha. Thirty-six sub-watersheds (about 73% of the total number of sub-watersheds) have stream density less than 8 m/ha (Plate VII) while only one sub-watershed has stream density more than 12 m/ha. Sub-watersheds with high stream density are associated with high flood peak and sediment production. This implied that surface runoff is likely to be the main cause of sediment transportation because low stream density was estimated for almost all of the sub-watersheds.



Average basin relief (m)	Number of sub-watersheds	% of total sub-watersheds
0 – 10	0	0
10 – 100	12	24.5
100 – 200	18	36.7
> 200	19	38.8

Plate VI. Basin relief (m) characteristics of sub-watersheds.



Stream density (m/ha)	Number of sub-watersheds	% of total sub-watersheds
0 – 4	10	20.4
4 – 8	26	53.1
8 – 12	12	24.5
> 12	1	2.04

Plate VII. Stream density (m/ha) characteristics of sub-watersheds.

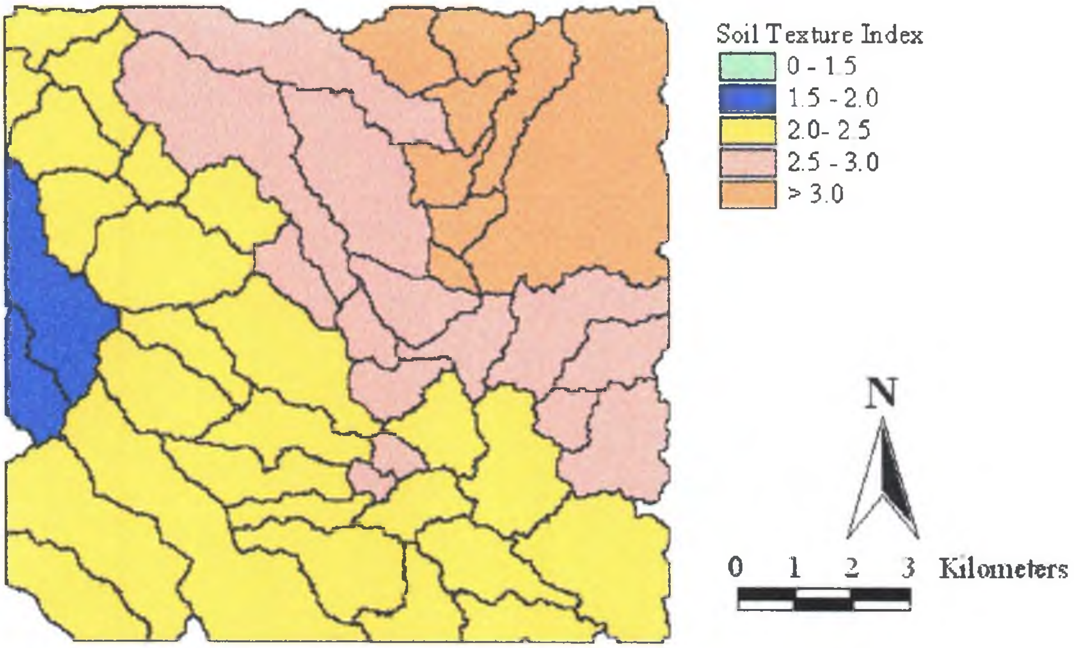
***Soil texture index*.** The examination of general data presented in Table 5.3 revealed that the soil texture index in the different sub-watersheds ranged from 1.94 to 3.55. Forty-seven sub-watersheds (about 96% of the total number of sub-watersheds) were characterized by average soil texture indices greater than 2.0 (Plate VIII). While two sub-watersheds had soil texture indices less than 2.0. Soil texture index presumably indicates the general susceptibility of soil to erosion (Bouyoucos, 1935). The smallest value was considered to be less erosive while the largest value was considered to be very erosive. Almost all of sub-watersheds in this landscape were characterized by high values of the soil texture index.

***Soil organic matter content*.** The estimation of soil organic content in the different sub-watersheds revealed that average soil organic content ranged from 1.37 to 5.36% (Table 5.3). Thirty-two sub-watersheds (about 65% of the total) had average soil organic matter contents of less than 3.0% (Plate IX). These sub-watersheds were likely to be more susceptible to soil erosion than sub-watersheds with high a values.

Criteria Weighting of Sub-watershed Attributes

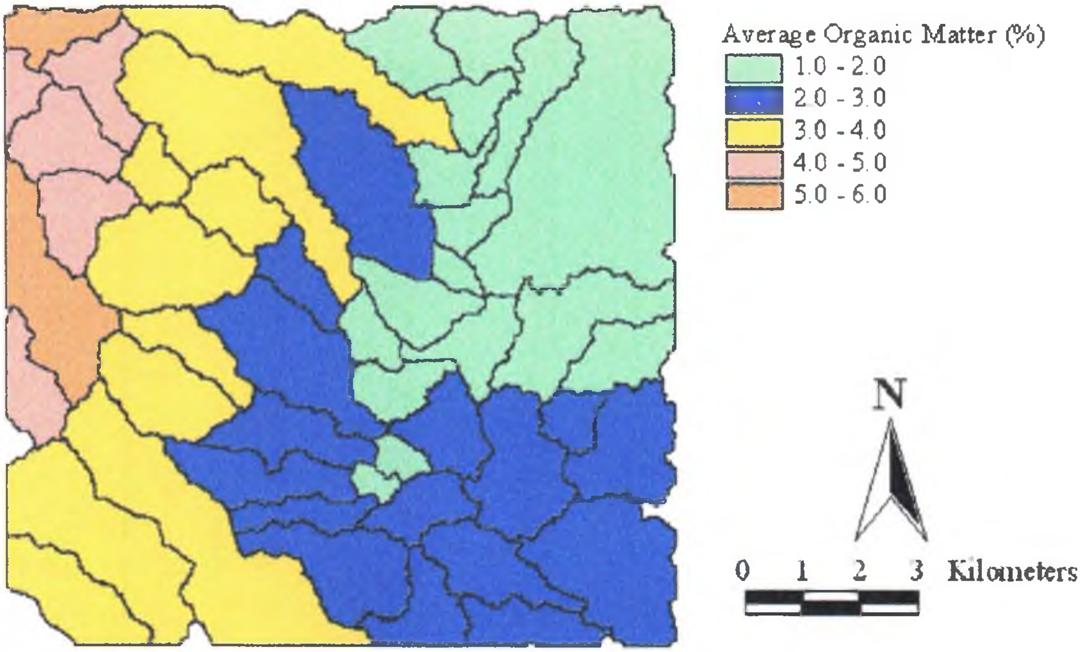
The above sub-watershed attributes influence erosion potential to different degrees. To characterize sub-watersheds based on susceptibility to erosion, four groups of watershed attributes were categorized with the different scale of the importance in order to compare among watershed attributes.

With the process of deforestation, more of the land surface becomes impermeable. Rain falling over the area no longer infiltrates as easily or as quickly, so



Average soil texture index	Number of sub-watersheds	% of total sub-watersheds
0 – 1.5	0	0
1.5 – 2.0	2	4.08
2.0 – 2.5	25	51.0
2.5 – 3.0	14	28.6
> 3.0	8	16.3

Plate VIII. Average soil texture index characteristics of sub-watersheds.



Average soil organic matter (%)	Number of sub-watersheds	% of total sub-watersheds
1.0 – 2.0	16	32.7
2.0 – 3.0	16	32.7
3.0 – 4.0	10	20.4
4.0 – 5.0	5	10.2
5.0 – 6.0	2	4.08

Plate IX. Average organic matter characteristics of sub-watersheds.

much more is “excess” flow or runoff, over the land surface. The different land uses alter the land in different ways. In terms of the movement of water in the watershed, land use often changes the permeability of land surface, thus affecting surface drainage systems. The most dramatic example is the high proportion of deforested area to total watershed area (Turner et al., 1993 and Heathcote, 1998). So group #1 attributes should comprise of a proportional area of disturbance, a proportional area of watershed class I and class II , and a proportional area with slope greater than 12 degrees. This group was considered as the most important watershed attributes.

Detailed topographic maps are an excellent source of information about degree, shape, and length of slope which are important in controlling runoff and erosion. It can give a general indication of historical and modern forces affecting water flow and, thus the distribution of surface water (Heathcote, 1998). So group #2 attributes should comprise of average basin slope and basin relief. This group was considered as the important watershed attributes.

Characteristics of watershed are important in calculating runoff rate and positively related to the stream flow which affect the amount of sediment transportation. So group #3 attributes should comprise of contributing drainage area and stream density. This group was considered as the moderately important watershed attributes.

Soil information should be the least consideration for ranking the degraded watershed because it can alter by land use and topography within a watershed. So group #4 attributes comprise soil texture index and soil organic matter content. This group was considered as the least important watershed attributes.

Results of the pairwise comparison matrix between sub-watershed attributes shown in Table 5.5 was generated based on the score of the importance assigned in Table 5.4. Rating are provided on a 7-points continuous scale. For example proportional area of disturbance (PD, sub-watershed attribute group #1) was very strongly more important than average organic matter (AOM, sub-watershed attribute group #2) in determining erosion potential, a score 7 was assigned on this scale. If the inverse were the case, a score 1/7 was assigned in this scale.

Sub-watershed attributes group #1 were considered very strongly important in increasing erosion potential if compared with sub-watershed attributes for group #4. While attributes group #1 were strongly important if compared with sub-watershed attributes group #3. A moderate importance would be assigned if sub-watershed attributes group #1 were compared with sub-watershed attributes group #2.

Sub-watershed attributes group #2 was strongly important if compared with sub-watershed attributes group # 4, but it was moderately important if compared with sub-watershed attributes group #3.

Sub-watershed attributes group #3 were moderately important if compared with sub-watershed attributes group #4.

Weight of each sub-watershed attribute (Table 5.6) was calculated from the pairwise comparison matrix of nine selected watershed attributes (Table 5.5). The result of consistency for assigning scores in pairwise comparison matrix based on the above procedures was accepted (consistency ratio = 0.02). This implied that the scoring system described above was consistent for weighting the criteria for indexing watershed

Table 5.4 Score assigned for generating the pairwise comparison matrix.

1/7	1/5	1/3	1	3	5	7
Very strongly	Strongly	moderately	equally	Moderately	strongly	Very strongly

less important

more important

Table 5.5 Pairwise comparison matrix between attributes
(rating of the row factor relative to the column factor)

	CDA	**PD**	**PS**	**PWC**	**ABS**	**BR**	**STI**	**AOM**	**STD**
CDA	1								
PD	5	1							
PS	5	1	1						
PWC	5	1	1	1					
ABS	3	1/3	1/3	1/3	1				
BR	3	1/3	1/3	1/3	1	1			
STI	1/3	1/7	1/7	1/7	1/5	1/5	1		
AOM	1/3	1/7	1/7	1/7	1/5	1/5	1	1	
STD	1	1/5	1/5	1/5	1/3	1/3	3	3	1

Table 5.6 Weight of attributes relating to degradation idex.

Factor	**Weight**
CDA	0.0462
PD	0.221
PS	0.221
PWC	0.221
ABS	0.100
BR	0.100
STI	0.0228
AOM	0.0228
STD	0.0462

Consistency ratio = 0.02
Consistency is acceptable

degradation. These weighted values and normalized watershed attributes (Appendix 5.2) were used to generate a sub-watershed index.

Degradation Index of Sub-watershed in the Wat Chan Watershed

Five groups of sub-watersheds in the Wat Chan watershed were obtained based on nine selected watershed attributes (Figure 5.3). There were no sub-watersheds that were classified as extremely degraded in this landscape. Five sub-watersheds were classified as highly degraded, while only two sub-watersheds were classified as extremely low or not degraded (Table 5.7). Most of the sub-watersheds were classified as low and moderately degraded (about 85% of the total number of sub-watersheds).

Proportional area with slopes greater than 12 degrees (PS), proportional area of watershed class I and II (PWC), average basin slope (ABS) and sub-watershed relief (BR) were the watershed attributes found most important in differentiating between extremely low degradation and extremely high degradation (Table 5.8). Relatively high values of these attributes within a sub-watershed usually resulted in a classification as highly degraded sub-watershed. This study showed that only one high attribute was not likely to indicate that the sub-watershed was degraded. Some attributes such as proportional area of deforested land was expected to strongly influence the index but it appeared not to play an important role in this landscape. This might be because the land use pattern of the Wat Chan landscape was mostly occupied with forest (see Chapter 3). For example, sub-watershed #25, which was classified as a less degraded sub-watershed even though about 66.0% of this sub-watershed was deforested (Table 5.9). This might

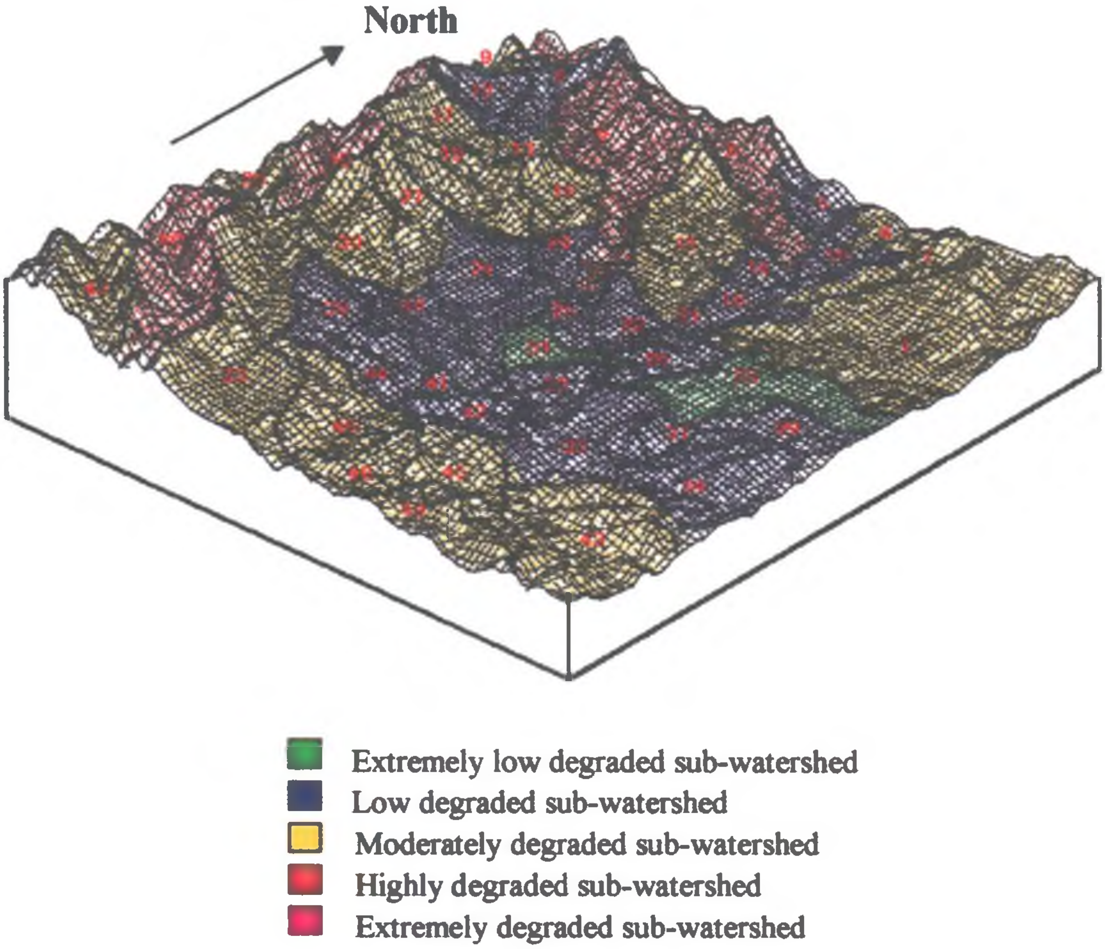


Figure 5.3 Degradation index of sub-watershed in the Wat Chan watershed.

Table 5.7 Sub-watershed classes based on degraded index.

Sub-watershed class	Number of sub-watersheds	% of total sub-watersheds
Extremely low degradation	2	0.041
Low degradation	22	44.9
Moderate degradation	20	40.8
High degradation	5	10.2
Extremely high degradation	-	-

Table 5.8 Comparison of highly degraded sub-watershed with extremely low degraded sub-watersheds.

Attribute	Highly degraded (Min. – Max.)	Very low degradation (Min. – Max.)
CDA	157 – 839	141 – 398
PD	0.030 – 0.289	0.152 – 0.249
PS	0.669 – 0.848	0.133 – 0.184
PWC	0.653 – 1.00	0.001 – 0.009
ABS	31.7 – 42.1	11.2 – 13.1
BR	294 – 448	70 – 86
AOM	3.33 – 5.36	1.75 – 1.85
STD	6.23 – 7.72	4.06 – 9.56
STI	1.97 – 2.77	2.53 – 2.95

Table 5.9 Attributes of sub-watershed #25, which was classified as low degraded sub-watershed.

Attribute	Value
CDA	95.8
PD	0.659
PS	0.089
PWC	0.001
ABS	9.93
BR	48.0
AOM	1.98
STI	2.78
STD	16.8

occur because topographic attributes (such as average basin slope and basin relief) least influenced surface water runoff in this sub-watershed.

Based on this sub-watershed classification, a number of recommendations for land use planing and resource management follow; 1) In less degraded sub-watersheds agricultural activities could be practiced if land is quite scarce due to population pressure. 2) The five sub-watersheds that were classified as highly degraded should be maintained in forest conservation no matter how great the population pressure. 3) The twenty sub-watersheds that were classified as moderately degraded should be studied in more detail regarding on-site effects of deforestation to determine the appropriate management in spatial and temporal aspects. However, some field validation of this classification should be performed before implementing the recommendations.

CONCLUSION

Because a number of factors (such as slope gradient, land use, soil information) are influencing erosion potential and the quality of forest ecosystem in the watershed, using only one factor to determine watershed degradation is not appropriate for the best land use planning and resource management. However, indexing sub-watersheds based on many factors needs a method that allows analysts to define the degree of importance of each factor when compared to another factor. This will lead to interdisciplinary discussion (including farmers) in order to obtain the proper weights. Multiple criteria analysis based on a weighted linear combination method, is one of the methods that allows assigning weights to the criteria. This method was used to characterize sub-watersheds based on the index of degradation. This index then was used to prioritize sub-watershed in the Wat Chan watershed for remedial action.

The index of degradation was estimated with multi-criteria analysis in the Wat Chan watershed and was simplified as a value ranging from 0 to 1 for extremely low to extremely high degradation. Proportional area with slopes greater than 12 degrees, proportional area of watershed class I and II, average basin slope and basin relief which seem to be less subject to change by management were main watershed attributes that played the most important roles in determining the index of degradation. So these attributes might be suitable for indexing the environmental degradation. Unexpectedly proportional area of amount of deforested land did not strongly influence the overall ranking extremely low or extremely high degradation. However these attributes should be verified before implementation.

Characterizing the sub-watershed for determining the index of degradation will help develop guidelines for land use planning and resource management. For example an extremely high degraded sub-watershed should be conserved for forest and water resources. The sub-watersheds with intermediate values need further study on land use and soil characteristic which are more manageable than topography in the landscape for development of appropriate management, while those watersheds with low value can be wisely managed.

CHAPTER VI

Summary

Characteristics and dynamics of landscape attributes in the Wat Chan watershed have been explored spatially and temporally in order to understand the structure of the landscape and to formulate broad scale policies in natural resource management. Spatial database queries and summaries and a non-parametric Mann-Kendall trend analysis were used to determine patterns and changes of land use from 1974 to 1996. A raster or cell-based geographic information system (GIS) was used to estimate the necessary data. Knowledge obtained from spatial relationships between land use characteristics and landscape attributes (physical factors and topographic attributes) has led to the development of a logistic model that forecasts land use change in this landscape.

Characteristics of land use showed that most areas in the landscape were occupied by hill evergreen forest, dry dipterocarp and pine forest. Rates and patterns of land use change between forest and agricultural land from 1974 to 1996 varied non-linearly. This probably was influenced by the importance of crop rotation and fallow, which might result from the small-scale subsistence farming practice such as shifting cultivation due to population pressure and low crop productivity. Dynamic change of land use, estimated by non-parametric analysis of six land use images indicated that degree of crop rotation within 22-year period was expressed as a probability of land use change. This method showed that farmers seldom repeatedly cultivate the same land except paddy fields that require specific field conditions such as leveled land where water control is easier. Stable forest land was also distinguishable from regenerated forest with this method.

There were relationships between land use change and topographic attributes. The estimation of a probability of land use change based on the logistic model showed that elevation, proximity to villages, distance to forest edge, slope and CTI were the most significant factors that influence farmer decisions in clearing new land for agriculture.

Characteristics of soil information, which are important for landscape study, were also studied in this landscape by relating measured soil properties with landscape attributes. A stepwise model was estimated to predict soil properties throughout the landscape based on fundamental principles related to basic underlying controls on the type and intensity of soil development.

Elevation, slope, land use and annual rainfall were the attributes most important in predicting topsoil properties in this landscape, especially physical properties such as soil texture and bulk density. CTI and profile curvature showed some influence on the variation of the topsoil chemical properties such as N and organic matter content. Surface soil pH, Na, Mg and Ca were not correlated with topographic attributes in this landscape nor were subsoil samples.

Based on landscape attributes (such as land use types, topographic attributes and soil information) of this landscape, a spatially-explicit, quantitative sub-watershed degradation index was developed as a guideline for land resource management. Such an index related to the potential of surface water runoff in each sub-watershed of the Wat Chan watershed, Chiang Mai Province, Northern Thailand. Selected watershed attributes such as land use pattern, topographic attributes (slope and relief), and soil information (e.g. soil texture and organic matter content) were generated based upon the surface water runoff potential. Multiple criteria decision analysis was applied to characterize sub-watersheds in order to prioritize them for management.

Nine sub-watershed attributes were selected as criteria for the degradation index which were; proportional area of disturbance, proportional area with slope greater than 20%, proportional area of watershed class I and II, average basin slope, basin relief, contributing drainage area, stream density, average soil texture index, and average soil organic matter content.

Five classes of sub-watersheds were grouped based on the index of watershed degradation. Proportional area with slopes greater than 20%, proportional area of watershed class I and II, average basin slope and basin relief were the main watershed attributes that played the most important role in determining the index of degradation. This index will be useful for land use planning and decision making for resource management such as using the less degraded sub-watersheds for agricultural activities if land is quite scarce due to high population pressure. The highly degraded sub-watersheds should be maintained in forest conservation.

Spatial and temporal analysis of landscape attributes can be important in understanding landscape structure, especially with the complex landscapes. These techniques can lead to an understanding that is useful for land resource management and especially in complex landscapes.

Appendix A

Appendix 4.1 Stepwise linear regression between soil properties and landscape attributes

Y = Sand (topsoil)

```
Coefficients:
                Value Std. Error  t value  Pr(>|t|)
(Intercept)  440.2421   50.4883    8.7197    0.0000
        dem   -0.0595    0.0108   -5.4804    0.0000
   log(cti)   -1.8599    1.2651   -1.4701    0.1446
    profile   -1.6742    1.0140   -1.6511    0.1018
       rain   -0.2838    0.0444   -6.3850    0.0000

Residual standard error: 8.403 on 102 degrees of freedom
Multiple R-Squared: 0.4631
F-statistic: 22 on 4 and 102 degrees of freedom, the p-value is 4.111e-013
```

Y = Sand (subsoil)

```
Coefficients:
                Value Std. Error  t value  Pr(>|t|)
(Intercept)  223.1449   37.5984    5.9350    0.0000
        dem   -0.0418    0.0079   -5.2959    0.0000
    profile   -1.2249    0.7770   -1.5764    0.1180
       rain   -0.1196    0.0339   -3.5288    0.0006

Residual standard error: 6.503 on 103 degrees of freedom
Multiple R-Squared: 0.3331
F-statistic: 17.15 on 3 and 103 degrees of freedom, the p-value is 4.177e-009
```

Y = Silt (topsoil)

```
Coefficients:
                Value Std. Error  t value  Pr(>|t|)
(Intercept) -155.1473   25.2345   -6.1482    0.0000
        dem    0.0463    0.0054    8.5099    0.0000
    profile    1.1458    0.5409    2.1180    0.0366
        use   -1.4076    0.5029   -2.7988    0.0061
       rain    0.1160    0.0227    5.1162    0.0000

Residual standard error: 4.346 on 102 degrees of freedom
Multiple R-Squared: 0.5477
F-statistic: 30.88 on 4 and 102 degrees of freedom, the p-value is 1.11e-016
```

Y = Silt (subsoil)

```
Coefficients:
                Value Std. Error  t value  Pr(>|t|)
(Intercept) -109.3624   23.5648   -4.6409    0.0000
        dem    0.0314    0.0051    6.1373    0.0000
 log(slope)    0.9709    0.6319    1.5363    0.1276
   log(cti)    1.6691    0.7491    2.2281    0.0281
        use   -0.7315    0.4563   -1.6033    0.1120
       rain    0.0794    0.0207    3.8417    0.0002

Residual standard error: 3.88 on 101 degrees of freedom
Multiple R-Squared: 0.4144
F-statistic: 14.3 on 5 and 101 degrees of freedom, the p-value is 1.426e-010
```

Y = Clay (topsoil)

```
Coefficients:
                Value Std. Error   t value  Pr(>|t|)
(Intercept) -162.3855   40.1676    -4.0427    0.0001
        use    1.1214    0.7523     1.4907    0.1391
       rain    0.1633    0.0352     4.6357    0.0000

Residual standard error: 6.919 on 104 degrees of freedom
Multiple R-Squared: 0.1868
F-statistic: 11.95 on 2 and 104 degrees of freedom, the p-value is 0.00002136
```

Y = Clay (subsoil)

```
Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept) 28.7343  8.9311     3.2173  0.0017
        dem  0.0140  0.0085     1.6447  0.1030

Residual standard error: 7.219 on 105 degrees of freedom
Multiple R-Squared: 0.02511
F-statistic: 2.705 on 1 and 105 degrees of freedom, the p-value is 0.103
```

Y = pH (water) (topsoil)

```
Coefficients:
               Value Std. Error  t value Pr(>|t|)
(Intercept)   5.0681   0.1773    28.5889   0.0000
       plan  -0.0875   0.0594    -1.4736   0.1436
    profile  -0.0543   0.0372    -1.4597   0.1474
        use  -0.0706   0.0307    -2.2970   0.0236

Residual standard error: 0.2737 on 103 degrees of freedom
Multiple R-Squared: 0.08371
F-statistic: 3.136 on 3 and 103 degrees of freedom, the p-value is 0.02867
```

Y = pH (water) (subsoil)

```
Coefficients:
               Value Std. Error  t value Pr(>|t|)
(Intercept)   4.3968   0.2496    17.6187   0.0000
        dem   0.0005   0.0002     1.9875   0.0495
        use  -0.0700   0.0214    -3.2753   0.0014

Residual standard error: 0.1926 on 104 degrees of freedom
Multiple R-Squared: 0.1077
F-statistic: 6.276 on 2 and 104 degrees of freedom, the p-value is 0.002672
```

Y = pH (KCl) (topsoil)

```
Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  8.6803  1.4373     6.0395  0.0000
       rain -0.0030  0.0013    -2.3452  0.0209

Residual standard error: 0.2487 on 105 degrees of freedom
Multiple R-Squared: 0.04977
F-statistic: 5.5 on 1 and 105 degrees of freedom, the p-value is 0.0209
```

Y = pH (KCl) (subsoil)

```
Coefficients:
                Value Std. Error t value Pr(>|t|)
(Intercept)  9.7157  1.0533     9.2245  0.0000
        dem  0.0003  0.0002     1.5532  0.1234
       rain -0.0043  0.0009    -4.4869  0.0000

Residual standard error: 0.1823 on 104 degrees of freedom
Multiple R-Squared: 0.1646
F-statistic: 10.25 on 2 and 104 degrees of freedom, the p-value is 0.00008684
```

Y = soil bulk density (topsoil)

```
Coefficients:
                Value Std. Error t value Pr(>|t|)
(Intercept)  8.0890  0.9403     8.6025  0.0000
        dem -0.0009  0.0002    -4.5363  0.0000
       rain -0.0051  0.0008    -6.0322  0.0000

Residual standard error: 0.1627 on 104 degrees of freedom
Multiple R-Squared: 0.4096
F-statistic: 36.07 on 2 and 104 degrees of freedom, the p-value is 1.261e-012
```

Y = soil bulk density (subsoil)

```
Coefficients:
                Value Std. Error t value Pr(>|t|)
(Intercept)  7.3251  0.7931     9.2363  0.0000
        dem -0.0007  0.0002    -4.0639  0.0001
     aspect  0.0002  0.0001     1.6775  0.0965
 log(slope)  0.0277  0.0162     1.7175  0.0889
       rain -0.0047  0.0007    -6.6403  0.0000

Residual standard error: 0.1326 on 102 degrees of freedom
Multiple R-Squared: 0.4356
F-statistic: 19.68 on 4 and 102 degrees of freedom, the p-value is 4.964e-012
```

Y = water holding capacity (topsoil)

```
Coefficients:
                  Value Std. Error  t value Pr(>|t|)
(Intercept)  41.4785  11.3833      3.6438   0.0004
        dem  -0.0074   0.0024     -3.1216   0.0023
       plan  -0.6370   0.3796     -1.6784   0.0963
       rain  -0.0220   0.0103     -2.1408   0.0346

Residual standard error: 1.969 on 103 degrees of freedom
Multiple R-Squared: 0.1681
F-statistic: 6.937 on 3 and 103 degrees of freedom, the p-value is 0.0002677
```

Y = Water holding capacity (subsoil)

```
Coefficients:
                Value Std. Error t value Pr(>|t|)
(Intercept) -1.1022  7.9419    -0.1388  0.8899
        dem -0.0063  0.0017    -3.7953  0.0002
       plan -0.3890  0.2648    -1.4690  0.1449
       rain  0.0132  0.0072     1.8435  0.0681

Residual standard error: 1.374 on 103 degrees of freedom
Multiple R-Squared: 0.1485
F-statistic: 5.987 on 3 and 103 degrees of freedom, the p-value is 0.0008395
```

Y = Nitrogen (topsoil)

```
Coefficients:
                Value Std. Error t value Pr(>|t|)
(Intercept) -1.4335  0.2458    -5.8321  0.0000
        dem  0.0004  0.0001     6.9699  0.0000
 log(slope)  0.0150  0.0066     2.2821  0.0246
   log(cti)  0.0176  0.0078     2.2508  0.0266
        use -0.0135  0.0048    -2.8443  0.0054
       rain  0.0010  0.0002     4.8007  0.0000

Residual standard error: 0.04047 on 101 degrees of freedom
Multiple R-Squared: 0.515
F-statistic: 21.45 on 5 and 101 degrees of freedom, the p-value is 1.432e-014
```

Y = Nitrogen (subsoil)

```
Coefficients:
                Value Std. Error t value Pr(>|t|)
(Intercept) -0.7001  0.1289    -5.4293  0.0000
        dem  0.0001  0.0000     4.9908  0.0000
     aspect  0.0000  0.0000    -1.6806  0.0960
 log(slope)  0.0063  0.0034     1.8469  0.0677
   log(cti)  0.0069  0.0041     1.7074  0.0908
        use -0.0087  0.0025    -3.4983  0.0007
       rain  0.0006  0.0001     5.0789  0.0000

Residual standard error: 0.02102 on 100 degrees of freedom
Multiple R-Squared: 0.4653
F-statistic: 14.5 on 6 and 100 degrees of freedom, the p-value is 7.626e-012
```

Y = Phosphorus (topsoil)

```
Coefficients:
                  Value Std. Error   t value  Pr(>|t|)
(Intercept)  424.3628   48.9710     8.6656    0.0000
       rain   -0.3644    0.0431    -8.4486    0.0000

Residual standard error: 8.474 on 105 degrees of freedom
Multiple R-Squared: 0.4047
F-statistic: 71.38 on 1 and 105 degrees of freedom, the p-value is 1.799e-013
```

Y = Phosphorus (subsoil)

```
Coefficients:
                  Value Std. Error   t value  Pr(>|t|)
(Intercept)  109.0255   18.2764     5.9654    0.0000
       rain   -0.0933    0.0161    -5.7993    0.0000

Residual standard error: 3.163 on 105 degrees of freedom
Multiple R-Squared: 0.2426
F-statistic: 33.63 on 1 and 105 degrees of freedom, the p-value is 7.091e-008
```

Y = Potassium (topsoil)

```
Coefficients:
                  Value Std. Error   t value  Pr(>|t|)
(Intercept) -786.4340  351.6469    -2.2364    0.0275
        dem    0.2622    0.0763     3.4379    0.0009
 log(slope)   20.7492    9.4301     2.2003    0.0301
   log(cti)   25.2289   11.1786     2.2569    0.0262
        use  -16.3697    6.8084    -2.4043    0.0180
       rain    0.5854    0.3085     1.8976    0.0606

Residual standard error: 57.89 on 101 degrees of freedom
Multiple R-Squared: 0.2184
F-statistic: 5.644 on 5 and 101 degrees of freedom, the p-value is 0.0001248
```

Y = Potassium (subsoil)

```
Coefficients:
                Value Std. Error   t value  Pr(>|t|)
(Intercept)  639.4273  252.7156    2.5302    0.0129
        dem    0.1488    0.0535    2.7794    0.0065
        use   -8.2653    4.8344   -1.7097    0.0903
       rain   -0.5667    0.2270   -2.4971    0.0141

Residual standard error: 43.52 on 103 degrees of freedom
Multiple R-Squared: 0.1113
F-statistic: 4.299 on 3 and 103 degrees of freedom, the p-value is 0.006703
```

Y = Calcium (topsoil)

```
Coefficients:
               Value Std. Error  t value Pr(>|t|)
(Intercept) -10.4319   5.5751    -1.8711   0.0642
        dem   0.0032   0.0012     2.6769   0.0087
 log(slope)   0.4206   0.1495     2.8131   0.0059
   log(cti)   0.4096   0.1772     2.3114   0.0228
        use  -0.4572   0.1079    -4.2352   0.0001
       rain   0.0085   0.0049     1.7337   0.0860

Residual standard error: 0.9179 on 101 degrees of freedom
Multiple R-Squared: 0.2491
F-statistic: 6.7 on 5 and 101 degrees of freedom, the p-value is 0.00001982
```

Y = calcium (subsoil)

```
Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  1.6100  0.4266     3.7741  0.0003
 log(slope)  0.2130  0.0938     2.2692  0.0253
   log(cti)  0.1757  0.1109     1.5848  0.1161
        use -0.2664  0.0682    -3.9032  0.0002

Residual standard error: 0.5859 on 103 degrees of freedom
Multiple R-Squared: 0.1376
F-statistic: 5.476 on 3 and 103 degrees of freedom, the p-value is 0.001565
```

Y = Magnesium (topsoil)

```
Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  1.4082  0.3949     3.5661  0.0005
       plan -0.0260  0.0132    -1.9733  0.0511
       rain -0.0009  0.0003    -2.5414  0.0125

Residual standard error: 0.06832 on 104 degrees of freedom
Multiple R-Squared: 0.08838
F-statistic: 5.041 on 2 and 104 degrees of freedom, the p-value is 0.008134
```

Y = Magnesium (subsoil)

```
Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  0.4663  0.0506     9.2079  0.0000
       plan -0.0284  0.0155    -1.8385  0.0688
        use -0.0149  0.0087    -1.7125  0.0898

Residual standard error: 0.07934 on 104 degrees of freedom
Multiple R-Squared: 0.05018
F-statistic: 2.747 on 2 and 104 degrees of freedom, the p-value is 0.06877
```

Y = Sodium (topsoil)

```
Coefficients:
                Value Std. Error  t value Pr(>|t|)
(Intercept)  16.8718   7.6686     2.2001   0.0300
        dem   0.0151   0.0078     1.9474   0.0542
 log(slope)  -1.8600   0.7202    -2.5825   0.0112

Residual standard error: 6.073 on 104 degrees of freedom
Multiple R-Squared: 0.06897
F-statistic: 3.852 on 2 and 104 degrees of freedom, the p-value is 0.02433
```

Y = Sodium (subsoil)

```
Coefficients:
                Value Std. Error  t value Pr(>|t|)
(Intercept)  52.7005  24.0593     2.1904   0.0307
        dem   0.0150   0.0050     2.9826   0.0036
       rain  -0.0342   0.0217    -1.5739   0.1185

Residual standard error: 4.163 on 104 degrees of freedom
Multiple R-Squared: 0.08614
F-statistic: 4.901 on 2 and 104 degrees of freedom, the p-value is 0.009242
```

Y = Soil organic matter (topsoil)

```
Coefficients:
                Value Std. Error  t value Pr(>|t|)
(Intercept) -44.3871   6.8247    -6.5039   0.0000
        dem   0.0102   0.0015     6.9068   0.0000
 log(slope)   0.3694   0.1830     2.0182   0.0462
   log(cti)   0.4730   0.2170     2.1804   0.0315
        use  -0.2645   0.1321    -2.0019   0.0480
       rain   0.0327   0.0060     5.4640   0.0000

Residual standard error: 1.124 on 101 degrees of freedom
Multiple R-Squared: 0.5266
F-statistic: 22.47 on 5 and 101 degrees of freedom, the p-value is 4.33e-015
```

Y = Soil organic matter (subsoil)

```
Coefficients:
                Value Std. Error  t value Pr(>|t|)
(Intercept) -17.2286   2.8996    -5.9417   0.0000
        dem   0.0025   0.0006     4.1472   0.0001
        use  -0.0859   0.0555    -1.5488   0.1245
       rain   0.0145   0.0026     5.5755   0.0000

Residual standard error: 0.4994 on 103 degrees of freedom
Multiple R-Squared: 0.3745
F-statistic: 20.55 on 3 and 103 degrees of freedom, the p-value is 1.626e-010
```

Y = Electric conductivity (topsoil)

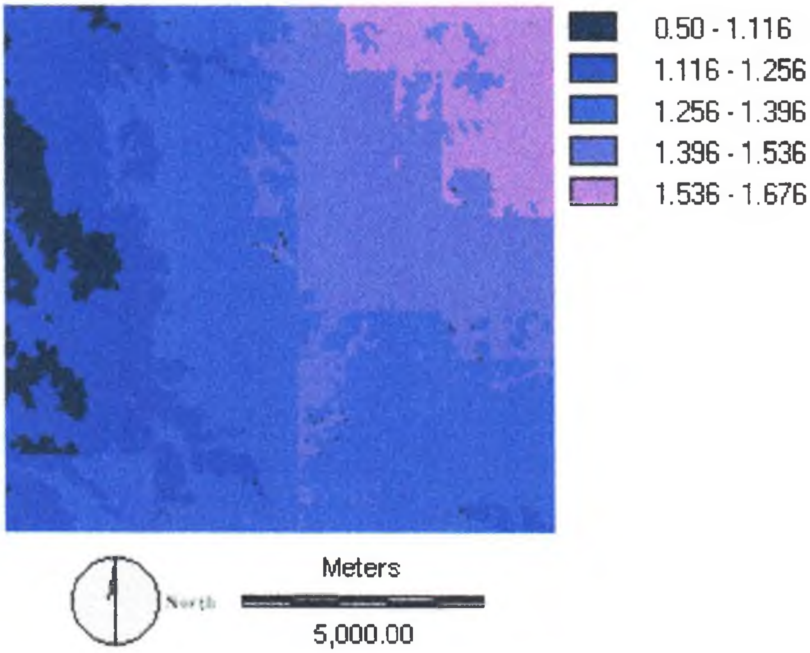
```
Coefficients:
                 Value Std. Error   t value  Pr(>|t|)
(Intercept)  -27.2427   20.4527    -1.3320    0.1858
        dem    0.0125    0.0044     2.8465    0.0053
 log(slope)    0.6978    0.4291     1.6264    0.1070
        use   -1.6254    0.3952    -4.1131    0.0001
       rain    0.0259    0.0181     1.4265    0.1568

Residual standard error: 34.06 on 102 degrees of freedom
Multiple R-Squared: 0.237
F-statistic: 7.919 on 4 and 102 degrees of freedom, the p-value is 0.00001338
```

Y = Electric conductivity (subsoil)

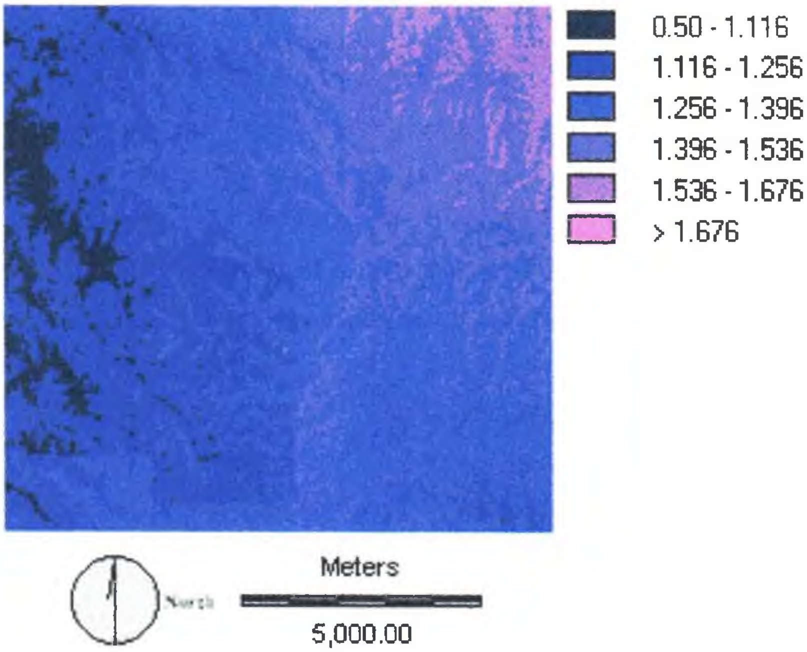
```
Coefficients:
                Value Std. Error  t value Pr(>|t|)
(Intercept)    4.0596   2.2952     1.7687   0.0799
        dem    0.0050   0.0022     2.2752   0.0250
 log(slope)    0.3933   0.2101     1.8725   0.0640
        use   -1.0660   0.1966    -5.4216   0.0000

Residual standard error: 17.01 on 103 degrees of freedom
Multiple R-Squared: 0.2489
F-statistic: 11.38 on 3 and 103 degrees of freedom, the p-value is 1.663e-006
```

Appendix B

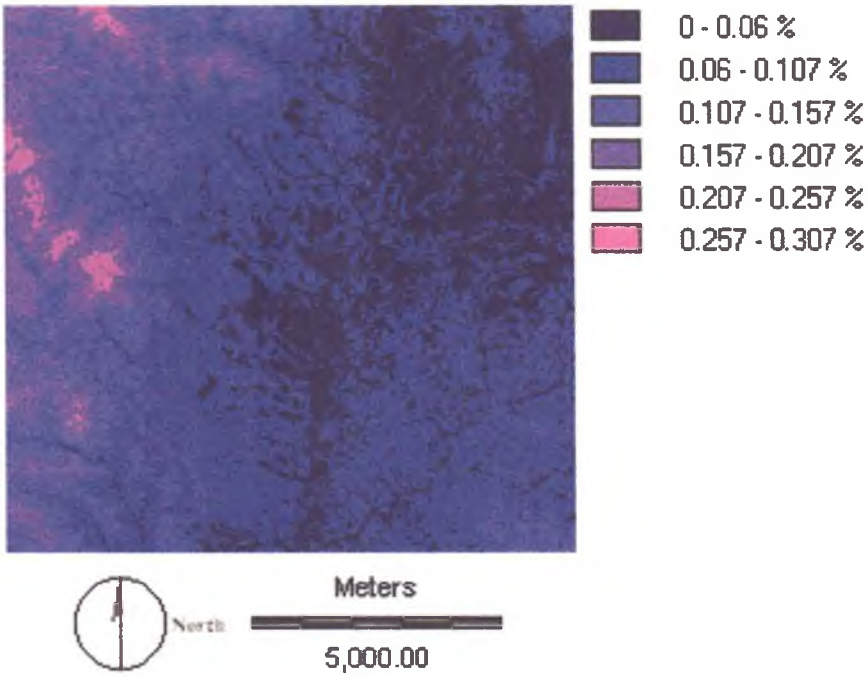
Appendix 4.2 Maps of selected soil properties in the Wat Chan watershed



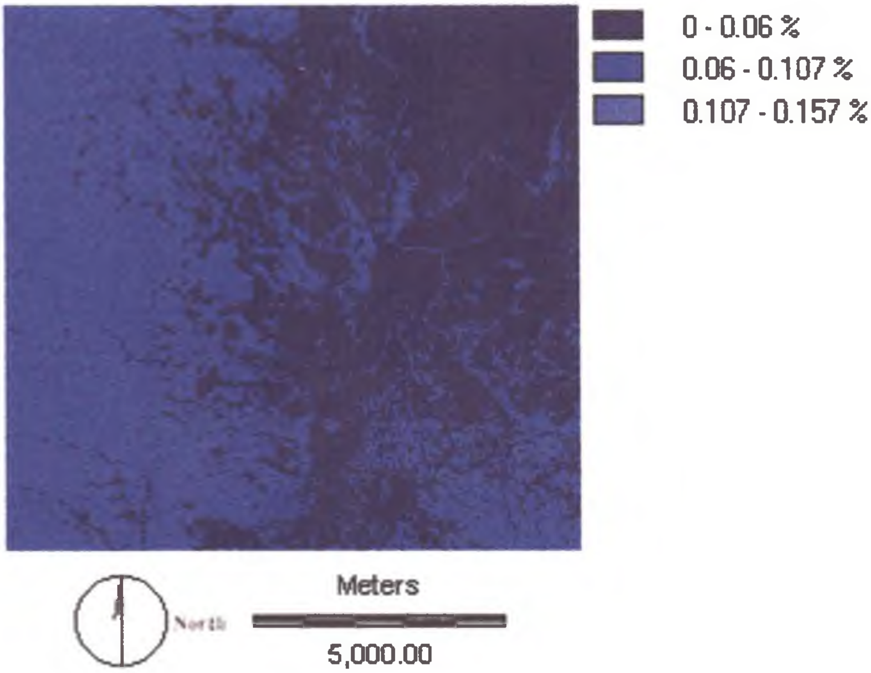
Predicted soil bulk density (g/cm^3) at the topsoil level



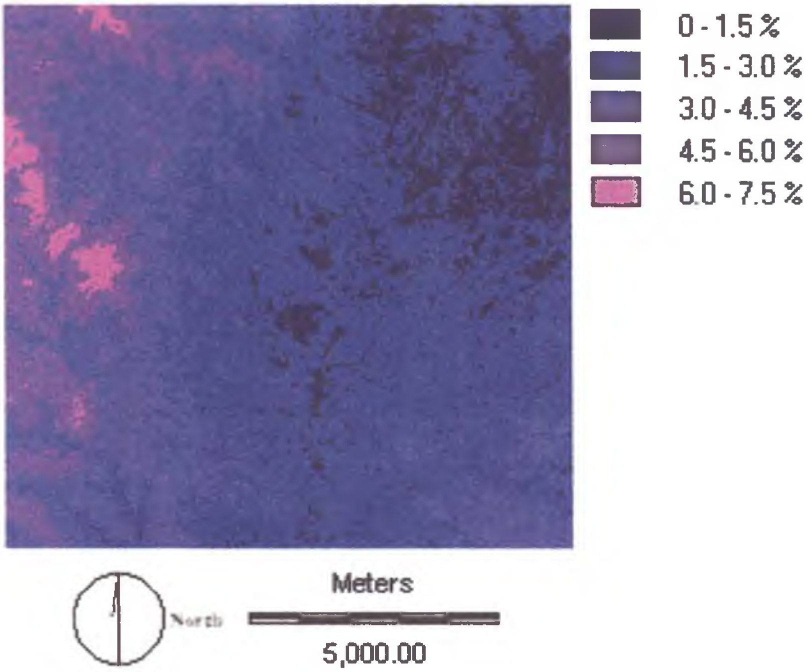
Predicted soil bulk density (g/cm^3) at the subsoil level



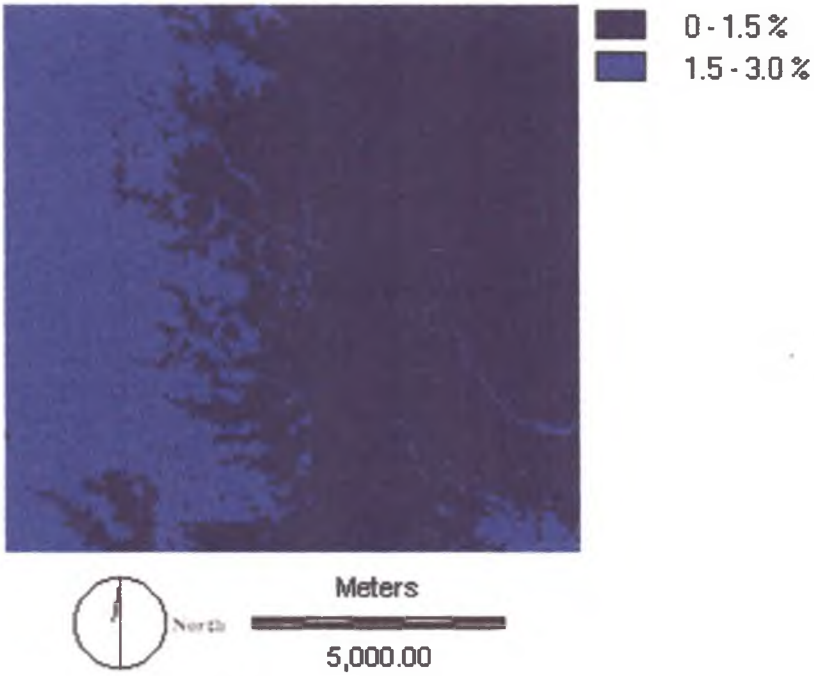
Predicted nitrogen content (%) at the topsoil level



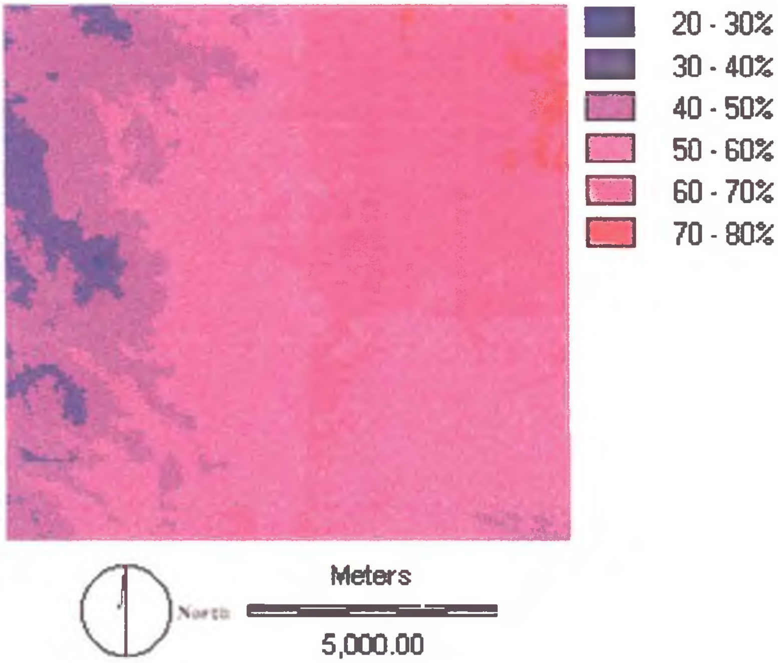
Predicted nitrogen content (%) at the subsoil level



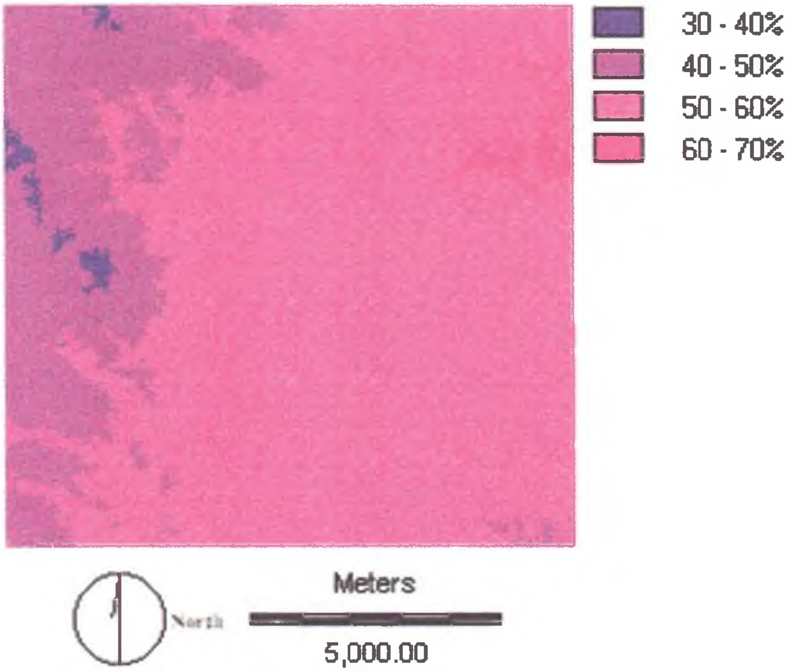
Predicted soil organic matter content (%) at the topsoil level



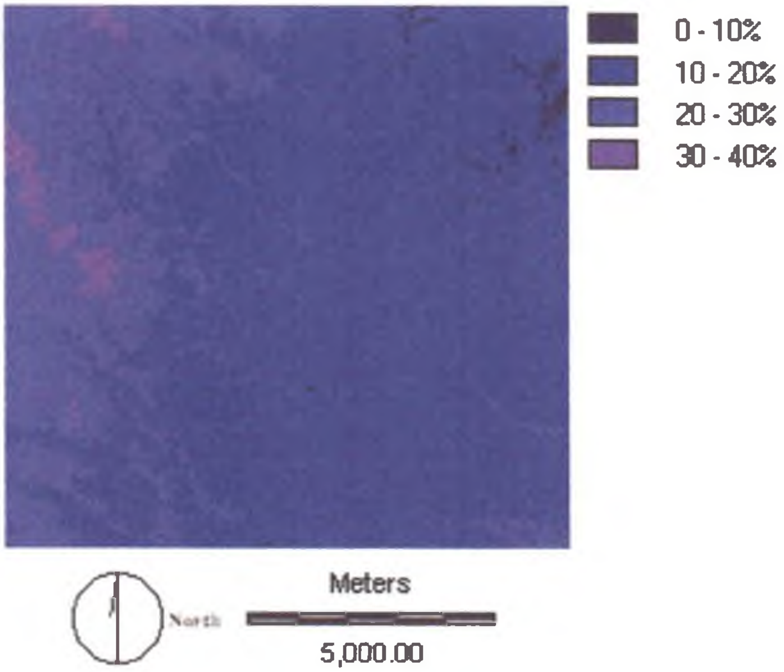
Predicted soil organic matter content (%) at the subsoil level



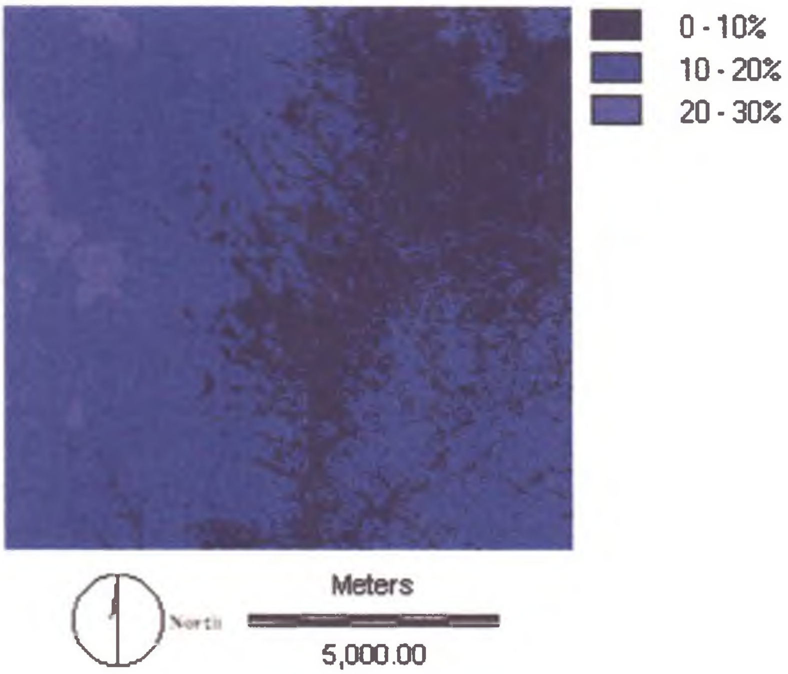
Predicted percent sand at the topsoil level



Predicted percent sand at the subsoil level



Predicted percent silt at the topsoil level



Predicted percent silt at the subsoil level

Appendix C

Appendix 5.1 Watershed attributes within sub-watershed of the Wat Chan watershed

ID	Area (ha)	CDA	PD	PS	PWC	ABS	BR	STI	AOM	STD
1	1158	1318	0.307	0.415	0.306	20.2	242	3.55	1.45	5.29
2	493	641	0.208	0.737	0.653	34.8	448	2.77	3.33	7.72
3	129	157	0.289	0.739	1.000	35.1	294	2.24	5.04	0.62
4	151	175	0.209	0.575	0.562	26.3	156	3.51	1.36	1.37
5	185	203	0.343	0.442	0.0581	20.2	169	3.33	1.83	4.74
6	181	248	0.162	0.550	0.188	26.5	364	2.27	4.5	3.68
7	211	249	0.186	0.544	0.519	23.9	179	3.40	1.56	8.01
8	650	840	0.185	0.668	0.678	31.6	435	2.51	3.55	6.73
9	72.3	86.4	0.248	0.677	0.953	29.6	207	2.16	4.98	0.00
10	116	137	0.211	0.444	0.476	20.8	87	3.23	1.41	10.2
11	488	548	0.318	0.438	0.124	21.8	328	2.84	2.33	4.95
12	211	249	0.0268	0.549	0.352	25.6	336	2.10	4.51	3.77
13	105	118	0.143	0.703	0.640	32.7	163	2.30	3.83	7.98
14	116	149	0.470	0.495	0.0224	21.9	95	3.13	1.85	8.50
15	382	481	0.0297	0.848	0.807	42.1	388	1.97	5.36	6.23
16	183	210	0.114	0.636	0.514	28.9	222	2.42	3.02	3.25
17	192	220	0.0097	0.706	0.450	31.6	324	2.06	4.61	4.02
18	91.2	93.7	0.525	0.0424	0.0001	8.96	72	3.29	1.60	11.3
19	397	445	0.181	0.685	0.659	33.6	439	2.23	3.95	6.61
20	130	136	0.388	0.133	0.0079	11.9	119	2.61	2.32	14.3
21	47.6	48.8	0.591	0.232	0.0001	13.6	88	3.11	1.91	15.7
22	180	185	0.577	0.0932	0.0001	8.87	97	2.94	1.77	7.71
23	335	398	0.249	0.133	0.0009	11.1	70	2.95	1.84	4.06
24	407	478	0.541	0.0387	0.0063	7.63	204	2.49	2.30	6.00
25	91.8	95.8	0.659	0.0898	0.0001	9.92	48	2.78	1.97	16.8
26	162	191	0.175	0.405	0.0001	19.6	103	2.72	1.99	5.64
27	160	182	0.153	0.486	0.497	26.1	448	2.16	3.77	4.71
28	151	182	0.0313	0.793	0.989	36.6	250	1.94	4.72	3.45
29	172	189	0.302	0.255	0.0001	15.1	92	2.88	1.98	4.20
30	276	304	0.0805	0.653	0.527	28.8	384	2.10	3.84	5.49
31	128	142	0.152	0.183	0.0001	13.1	86	2.53	1.74	9.56
32	182	201	0.0594	0.546	0.0001	24.1	131	2.47	2.23	2.93
33	742	911	0.292	0.579	0.522	26.9	373	2.19	3.33	7.80
34	292	328	0.277	0.475	0.289	22.4	106	2.65	2.42	3.73
35	325	382	0.128	0.459	0.202	21.3	93	2.49	2.42	7.34
36	218	265	0.441	0.144	0.0001	10.8	132	2.36	2.40	9.98
37	87.3	94.4	0.309	0.338	0.0001	17.4	78	2.70	2.29	12.5
38	56.1	61.9	0.154	0.572	0.0001	26.	113	2.57	1.94	12.8
39	236	274	0.176	0.352	0.0001	18.5	171	2.17	2.73	7.27
40	516	631	0.202	0.838	1.0000	42.0	345	2.10	3.91	6.09

Appendix 5.1 Watershed attributes within sub-watershed of the Wat Chan watershed (cont.)

ID	Area (ha)	CDA	PD	PS	PWC	ABS	BR	STI	AOM	STD
41	38.5	43.7	0.309	0.452	0.0001	21.4	75	2.56	1.92	15.5
42	147	170	0.0760	0.675	0.323	29.3	138	2.41	2.36	3.90
43	466	529	0.0974	0.665	0.876	30.4	175	2.35	2.93	4.80
44	111	144	0.272	0.472	0.0001	22.5	118	2.21	2.60	4.18
45	226	266	0.0410	0.638	0.711	28.2	150	2.32	2.64	6.99
46	308	358	0.165	0.564	0.528	25.3	128	2.27	2.42	6.15
47	244	279	0.108	0.880	0.0001	41.6	310	2.17	3.84	6.43
48	158	196	0.157	0.628	0.895	28.4	149	2.40	2.27	13.4
49	149	173	0.160	0.679	0.820	29.5	179	2.33	2.82	5.67

Appendix D

Appendix 5.2 Normalization of watershed attributes within sub-watershed of the Wat Chan watershed.

ID	Area	CDA	PD	PS	PWC	ABS	BR	STI	AOM	STD
1	1.000	1.0000	0.458	0.448	0.306	0.364	0.485	1.000	0.977	0.314
2	0.406	0.468	0.305	0.830	0.653	0.787	1.000	0.514	0.508	0.459
3	0.0806	0.0893	0.430	0.832	1.000	0.797	0.615	0.186	0.0793	0.0370
4	0.101	0.103	0.307	0.637	0.562	0.543	0.270	0.976	1.000	0.0815
5	0.131	0.124	0.512	0.480	0.0580	0.366	0.302	0.863	0.883	0.281
6	0.127	0.160	0.235	0.607	0.188	0.548	0.790	0.207	0.215	0.219
7	0.154	0.161	0.271	0.600	0.519	0.472	0.327	0.908	0.948	0.476
8	0.546	0.624	0.270	0.748	0.678	0.696	0.967	0.356	0.453	0.400
9	0.0301	0.0335	0.367	0.759	0.953	0.638	0.397	0.139	0.0951	0.000
10	0.0689	0.0734	0.310	0.482	0.475	0.381	0.0975	0.800	0.987	0.612
11	0.401	0.395	0.475	0.475	0.124	0.411	0.700	0.559	0.758	0.294
12	0.154	0.161	0.0263	0.606	0.352	0.521	0.720	0.101	0.210	0.224
13	0.0597	0.0583	0.205	0.789	0.640	0.727	0.287	0.224	0.381	0.474
14	0.0689	0.0829	0.709	0.542	0.0223	0.415	0.117	0.741	0.876	0.505
15	0.306	0.343	0.0308	0.962	0.807	1.000	0.850	0.0205	0.000	0.370
16	0.128	0.130	0.160	0.711	0.513	0.616	0.435	0.302	0.584	0.193
17	0.137	0.138	0.0000	0.793	0.450	0.696	0.690	0.0732	0.187	0.239
18	0.0470	0.0392	0.794	0.0044	0.000	0.0387	0.0600	0.842	0.940	0.676
19	0.320	0.315	0.263	0.769	0.659	0.754	0.977	0.181	0.350	0.393
20	0.0814	0.0724	0.583	0.112	0.0078	0.126	0.177	0.418	0.760	0.854
21	0.0081	0.0040	0.895	0.230	0.000	0.174	0.100	0.729	0.861	0.937
22	0.125	0.111	0.873	0.0648	0.000	0.0360	0.122	0.624	0.898	0.458
23	0.265	0.278	0.368	0.112	0.0008	0.102	0.055	0.630	0.878	0.241
24	0.329	0.341	0.817	0.0000	0.0062	0.000	0.390	0.342	0.764	0.356
25	0.0476	0.0409	1.000	0.0608	0.000	0.0665	0.000	0.525	0.846	1.000
26	0.110	0.115	0.254	0.435	0.000	0.349	0.137	0.487	0.843	0.335
27	0.108	0.108	0.221	0.532	0.497	0.535	1.000	0.141	0.395	0.280
28	0.100	0.108	0.0333	0.896	0.989	0.841	0.505	0.000	0.160	0.205
29	0.119	0.114	0.450	0.257	0.000	0.216	0.110	0.584	0.844	0.249
30	0.213	0.204	0.109	0.730	0.527	0.614	0.840	0.101	0.379	0.326
31	0.0796	0.0769	0.219	0.172	0.000	0.159	0.095	0.366	0.904	0.568
32	0.128	0.123	0.0766	0.603	0.000	0.477	0.207	0.328	0.783	0.174
33	0.628	0.680	0.435	0.643	0.522	0.561	0.812	0.155	0.507	0.464
34	0.226	0.222	0.411	0.519	0.289	0.429	0.145	0.445	0.734	0.221
35	0.256	0.265	0.182	0.499	0.202	0.396	0.112	0.341	0.736	0.436
36	0.160	0.173	0.664	0.125	0.000	0.0936	0.210	0.263	0.741	0.593
37	0.0436	0.0398	0.460	0.356	0.000	0.284	0.075	0.473	0.767	0.744
38	0.0157	0.0143	0.221	0.634	0.000	0.536	0.162	0.389	0.854	0.763
39	0.176	0.180	0.255	0.372	0.000	0.316	0.307	0.142	0.658	0.432
40	0.426	0.461	0.295	0.951	1.000	0.996	0.742	0.101	0.362	0.362

Appendix 5.2 Normalization of watershed attributes within sub-watershed of the Wat Chan watershed (Cont.)

ID	Area (ha)	CDA	PD	PS	PWC	ABS	BR	STI	AOM	STD
41	0.0000	0.0000	0.461	0.491	0.000	0.401	0.0675	0.387	0.861	0.926
42	0.0972	0.0989	0.102	0.756	0.323	0.630	0.225	0.291	0.749	0.232
43	0.382	0.380	0.135	0.744	0.876	0.662	0.317	0.255	0.606	0.285
44	0.0648	0.0787	0.404	0.515	0.000	0.431	0.175	0.169	0.688	0.248
45	0.167	0.174	0.0482	0.712	0.711	0.598	0.255	0.236	0.679	0.415
46	0.240	0.246	0.239	0.625	0.528	0.513	0.200	0.206	0.734	0.366
47	0.183	0.184	0.152	1.000	0.000	0.984	0.655	0.145	0.379	0.382
48	0.106	0.119	0.226	0.701	0.895	0.602	0.252	0.287	0.772	0.799
49	0.0990	0.101	0.231	0.762	0.820	0.636	0.327	0.243	0.635	0.337

REFERENCES

Aandahl, A. R. 1948. The characteristic of slope positions and their influence on the total nitrogen content of a few virgin soils of western Iowa. Soil Science Society of American Proceedings, 13:449–454.

Adams, J.M., H. Faure, L. Taure-Denard, J.M. McGlade and H.I. Woodward. 1990. Increase in terrestrial carbon storage from the Last Glacial Maximum to the present. Nature, 348:711–714.

Aguilar, R. and R.D. Heil. 1988. Soil organic carbon, nitrogen, and phosphorus quantities in Northern Great Plains Rangeland. Soil Science Society of American Journal, 52:1076-1081.

Alberts, E.E., W.C. Moldenhauer, and G.R. Foster. 1980. Soil aggregates and primary particles transported in rill and interrill flow. Soil Science Society American of Proceedings, 44:590–595.

Anderson, D.W., S. Saggar, J.R. Bettany, and J.W.B. Stewart. 1981. Particle-size fractions and their use in studies of soil organic matter: I. The nature and distribution of forms of carbon, nitrogen and sulfur. Soil Science Society of American Journal, 45:767–772.

Anderson, M.G., and T.P. Burt. 1978. The role of topography in controlling throughflow generation. Earth Surface Process, 3:331-344.

Arrouays, D., and P. Pelissier. 1994. Changes in carbon storage in temperate humic loamy soils after forest clearing and continuous corn cropping in France. Plant and Soil, 160:215–223.

Ball, G.H., and D.J. Hall.. 1965. A Novel Methods of Data Analysis and Pattern Classification. Menlo Park, CA : Stanford Research Institue.

Barnett, A.P., and J.S. Rogers. 1966. Soil physical properties related to runoff and erosion from artificial rainfall. Transactions of the American Society of Agricultural Engineers, 9:123–125.

Bartaya, S.K., and K.S. Valdiya. 1989. Landslides and erosion in the catchment of the Gaila river, Kumaun Lesser Himalaya, India. Journal of Mountain Research and Development, 9:405–419.

Beckett, P.H.T., and R. Webster. 1971. Soil variability : A review. Soil Fertility, 34:1–15.

Blaikie, P., and H.C. Brookfield. 1987. Land Degradation and Society. London, Methuen.

Blaszczynski, J.S. 1997. Landform characteration with geographic information systems. Photogrammetric Engineering & Remote Sensing, 63:183-191.

Bloschl, G., R.B. Grayson, and M. Sivapalan. 1995. On the representative elementary area (REA) concept and its utility for distributed rainfall-runoff modeling. Hydrological Processes, 9:313–346.

Bouma, J. 1989. Using soil survey data for quantitative land evaluation. Advances in Soil Science, 9:177–213.

Bouma, J., and H.A.V.Lanen. 1987. Transfer functions and threshold values: from soil characteristics to land qualities. In K.J. Beek et al. (eds.), ITC Publ. No.6, Enschede, 106-110.

Bouyoucos, G.J. 1935. The clay ration as a criterion of susceptibility of soil to erosion. Journal of the American Society of Agronomy, 27:738-741.

Bray, R.H., and L.T. Kurtz. 1945. Determination of total, organic and available forms of phosphorus in soils. Soil Science, 57:39–45.

Bregt, A.K., A.B. McBrantney, and M.C.S. Wopereis. 1991. Construction of isolinear maps of soil attributes with empirical confidence limits. Soil Science Society, American Journal, 55:14-19.

Buckman, H.O., and N.C. Brady. 1969. The Nature and Properties of Soils. Seventh Edition. The Macmillan Company, New York, pp: 653.

Burrough, P.A. 1986. Principle of Geographical Information Systems for Land Resources Assessment. Clarendon Press, Oxford. London, pp 194.

Burrough, P.A. 1993. Soil variability : A late 20th century view. Soil and Fertilizer, 56:531–562.

Butler, B.E. 1980. Soil Classification for Soil Survey. Clarendon Press, Oxford.

Carter, B.J., and E.D. Ciolkosz. 1991. Slope gradient and aspect effects on soils developed from sandstone in Pennsylvania. Geoderma, 49:199–213.

Charuppat, T. 1994. Forest cover assessment in Thailand. Asian-Pacific Remote Sensing Journal, 6:53–58.

Christensen, N.L., Jr. 1991. Variable fire regimes on complex landscape: Ecological consequences, policy implications, and management strategies. *In* Fire and the Environment: Ecological and Cultural Perspectives. pp. ix-xiv. Edited by S.C. Nodvin and T.A. Waldrop. USDA Forest Service, Southeastern Forest Experimental Station, Gen. Tech. Rept. SE-69.

Civco, D.L., A.R. Garcia, and G.S. Warner. 1995. Key steps to effective watershed characterization. GIS world, November 62–66.

Cohen, W.B., T.A. Spies and M. Fiorella. 1995. Estimating the age and structurres of forest in a multi-ownership landscape of Western Oregon, USA. International Journal of Remote Sensing, 16:721–746.

Coleman, D.C., C.P.P. Reid, and C.V. Cole. 1983. Biological strategies of nutrient cycling in soil systems. Advances in Ecological Research, 13:1-55.

Cook, S.E., R.J. Corner, G. Grealish, P.E. Gessler, and C.J. Chartres. 1996. A rule-based system to map soil properties. Soil Science Society, American Journal, 60:1893-1900.

Costales, E.F. 1979. Infiltration rates of soil as influenced by some landuse type in Banguet pine watershed. Sylvatrop. Philippines for Res. J. 4:255–260.

De Bruin, S., and A. Stein. 1998. Soil-landscape modelling using fuzzy c-means clustering of attribute data derived from a Digital Elevation Model (DEM). Geoderma, 83:17-33.

De Gruijter, J.J., and B.A. Marsman. 1985. Transect sampling for reliable information on mapping units. *In* D.R. Nielson et al. (eds.), Soil Spatial Variability. Proc. Workshop ISSS and SSSA, Las Vegas, Nov. 30-Dec. 1, 1984. PUDOC, Wageningen, 150-163.

Dent, D., and A. Young. 1983. Soil Survey and Land Evaluation. George Allen and Unwin, London.

Eash, D.A. 1994. A geographic information system procedure to quantify drainage-basin characteristics. Water Resource Bulletin, 30:1–8.

Eastman, J.R. 1997. Idrisi for Windows User's Guide Version 2.0. Clark University, Worcester, Massachusetts.

Eckholm, E. P. 1976. Losing Ground, Environmental Stress and World Food Prospects. Norton & Co., New York 223 pp.

Ehrlich, P.R., and E.O. Wilson. 1991. Biodiversity studies; science and policy. Science, 253:75 –762.

Environmental System Research Institute. 1995. Arc/Info Version 7.04 Users Guide. ESRI, Inc, Redlands, CA, USA.

Eswaran, H.E., V.D. Berg, and P. Reich. 1993. Organic carbon in soils of the world. Soil Science Society American Journal, 57:192–194.

Forman, R.T.T., and M. Gordon. 1986. Landscape Ecology. John Wiley & Sons, New York, pp. 619.

Fox, J., J. Krummel, S. Yanasarn, M. Ekasingh, and N. Podger. 1995. Land use and landscape dynamics in Northern Thailand: Assessing change in three upland watersheds. Ambio, 24:328–334.

Franklin, J.F., and R.T.T. Forman, 1987. Creating landscape patterns by forest cutting: Ecological consequences and principles. Landscape Ecology, 1:5–18.

Friedman, S.K., and E.H. Zube. 1992. Assessing landscape dynamics in a protected area. Environmental Management, 16:363-370.

Garbrecht, J. 1991. Effects of spatial accumulation of runoff on watershed response. Journal of Environmental Quality, 20:31–35.

Gee, G.W., and J.W. Bauder. 1982. Particle-size analysis. *In* Methods of Soil Analysis : Part 1, Physical and Mineralogical Methods, 2nd edn (eds. Klute, A) pp. 383 – 409. American Society of Agronomy, Medison, WI.

Geiger, R. 1966. The Climate Near the Ground. Translated by Scripta Technica from the 4th German ed. 2nd print. Harvard University Press, Cambridge, pp. 611.

Gessler, P.E., I.D. Moore, N.J. McKenzie, and P.J. Ryan. 1995. Soil-landscape modelling and spatial prediction of soil attributes. International Journal of Geographic Information Systems, 9:421–432.

Glesser, P.E., I.D. Moore, N.J. McKenzie, and P.J. Ryan. 1996. Soil-landscape modeling in Southeastern Australia. *In* M.F. Goodchild et al. (eds.) GIS and Environmental modeling : Progress and Research Issues, 53-63.

Giambelluca, T.W., and A.D. Ziegler. 1995. Climatological and hydrological implications of land cover change in Highland Southeast Asia. *In* Montane Mainland Southeast Asia in Transition, November 12-16, 1995, Chiang Mai University, Thailand. 181 – 205.

Gilbert, R.O. 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold, New York, pp 320.

Hall, G.F., and C.G. Olson. 1991. Predicting variability of soils from landscape models. *In* Spatial Variabilities of Soils and Landforms. Soil Science Society of American, Special Publication Number 28, 9-24.

Hamlett, J.M., D.A. Miller, R.L. Day, G.W. Peterson, G.M. Baumer, and J. Russo. 1992. Statewide GIS-based ranking of watersheds for agricultural pollution prevention. Journal of Soil and Water Conservation, 47:399-404.

Heaney, A., and J. Proctor. 1989. Chemical elements in litter in forests on Volcan Barve, Costa Rica. *In* Proctor J. (ed.) Mineral Nutrients in Tropical Forest and Savana Ecosystems. Blackwell Sci., Oxford, England, pp. 255–271.

Heathcote, I.W. 1998. Integrated Watershed Management: Principles and Practice. John Wiley & Sons, Inc., New York, pp 414.

Hollander, M., and D.A. Wolfe. 1973. Nonparametric Statistical Methods. Wiley, New York, pp 503.

Howard, A.F. 1991. A critical look at multiple criteria decision making techniques with reference to forestry applications. Canadian Journal of Forest Research, 21:1649–1659.

Hudson, N. 1995. Soil Conservation. Iowa State University Press, Iowa, pp.391.

Hufschmidt, H.M. 1986. A conceptual framework for watershed management. *In* K.A. Easter, et al. (eds). Water Resource Management : An Integrated Framework with Studies from Asia and Pacific. Westview Press, Boulder, Colorado, pp.17–31.

Huggett, R.J. 1975. Soil landscape system: a model of soil genesis. Geoderma, 13:1–12.

Jenny, H. 1941. Factors of Soil Formation. McGraw-Hill Book Co., New York.

Jenson, S.K., and J.O. Domingue. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing, 54:1593–1600.

Kemper, W., and E. Koch. 1966. Aggregate stability of soil from Western United States and Canada. USDA Tech. Bull. No.1355. Washington: US Dept. of Agriculture.

Kirby, C.A., L.J. Smythe, J.W. Cox, and D.J. Chittleborough. 1997. Phosphorus movement down a toposequence from a landscape with texture contrast soils. Australian Journal of Soil Research, 35:399–417.

Klute, A. 1965. Water capacity. In Methods of Soil Analysis: Part 1, Physical and Mineralogical Properties. Including Statistics of Measurement and Sampling (eds. Black, C.A.) pp. 273–285. American Society of Agronomy, Medison, WI.

Knight, D.H. 1987. Parasites, lighting, and the vegetation mosaic in wilderness landscapes. In Landscape Heterogeneity and Disturbance. pp. 59–83. Edited by M.G. Turner. Springer-Verlag, New York.

Lamberson, R.H., R. McKelvey, B.R. Noon, and C. Voss. 1992. A dynamic analysis of northern spotted owl viability in a fragmented forest landscape. Conservation Biology, 6:1–8.

Lammers, R.B., and L.E. Band. 1990. Automated object description of drainage basin. Compt. Geosci. 16:787-810.

Landon, J.R. 1990. Booker Tropical Soil Manual. A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. John Wiley, Toronto.

Landon, J.R. 1984. Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Longman, New York.

Lo, C.P., and R.L. Shipman. 1990. A GIS approach to land-use change dynamics detection. Photogrammetric Engineering & Remote Sensing, 56:1483–1491.

Loague, K., and G.A. Gander. 1990. R-5 revisited, 1: spatial variability of infiltration on a small rangeland catchment. Water Resources Research, 26:957–972.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Science, 142:279–288.

Manrique, L.A., C.A. Jones, and P.T. Dyke. 1991. Predicting soil water retention characteristics from soil physical and chemical properties. Commun. Soil Sci. Plant Anal., 22:1847–1860.

Mathsoft. 1997. S-PLUS 4 : Guide to Statistics. Data Analysis Products Division, Mathsoft, Inc. Seattle, Washington.

McCullagh, P., and J.A. Nelder. 1983. Generalized Linear Models. Chapman and Hall, London.

McKenzie, N.J., and M.P. Austin. 1993. A quantitative Australian approach to medium and small scale surveys based on soil stratigraphy and environmental correlation. Geoderma, 57:329-355.

McKenzie, N.J., K.R.J. Smettem, and A.J. Ringrose-Voase. 1991. Evaluation of methods for inferring air and water properties of soils from field morphology. Australian Journal of Soil Research, 29:587–602.

McLean, E.O. 1982. Soil pH and lime requirement. In Methods of Soil Analysis : Part 2, Chemical and Microbiological Properties, 2nd edn (eds. A.L. Page et al.) pp. 199–224. American Society of Agronomy, Medison, WI.

Methi, E., B. Shinawatra, T. Onpraphai, P. Promburom, and C. Sangchyoswat. 1995. Role of spatial information in assessing resources of highland communities in Northern Thailand. *In* Montane Mainland Southeast Asia in Transition. Chiang Mai University, 402–425.

Meyer, L. 1981. How rain intensity affects interrill erosion. Trans Am. Soc. Agric. Engrs, 24:1472–1475.

Miller, D.H. 1978. The factor of scale: ecosystem, environmental mosaic and region. In K.A. Hammond (ed.), Sourcebook of the Environment. Chicago, University of Chicago Press, 63-88.

Milne, G. 1953. Some suggested units for classification and mapping, particularly for East African Soils. Soil Research (Berl.) 4:183-198.

Montgomery, D.R., G.E. Grant, and K. Sullivan. 1995. Watershed analysis as a framework for implementing ecosystem management. Water Resource Bulletin, 31:369–386.

Moore, I.D., P.E.Gessler, G.A. Nielsen, and G.A. Peterson. 1993. Soil attribute prediction using terrain analysis. Soil Science Society American Journal, 57:443–452.

Moore, I.D., R.B. Grayson, and A.R. Ladson. 1991. Digital terrain modelling: A reviw of hydrological, geomorphological and biological applications. Hydrological process, 5:3–30.

Morse, D.R., J.H. Lawton, and M.M. Dodson. 1985. Fractal dimension of vegetation and the distribution of arthropod body lengths. Nature, 314:731–733.

Naveh, Z., and A. Lieberman. 1994. Landscape Ecology: Theory and Application. Springer-Verlag, New York, pp. 360.

Neill, C., M.C. Piccolo, P.A. Steudler, J.M. Melillo, B.J. Feigl and C.C. Cerri. 1995. Nitrogen dynamics in soils of forests and active pastures in the Western Brazilian Amazon basin. Soil Biology and Biochemistry, 27:1167–1175.

Nelson, D.W., and L.E. Sommers. 1982. Total organic carbon and organic matter. . In Methods of Soil Analysis : Part 2, Chemical and Microbiological Properties, 2nd edn (eds. A.L. Page et al.) pp. 529–579. American Society of Agronomy, Medison, WI.

Odeh, I.O.H., A.B. McBratney, and D.J. Chittleborough. 1994. Spatial prediction of soil properties from landform attributes derived from a digital elevation model. Geoderma, 63:197–214.

Patron, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Science Society of American Journal, 51:1173–1179.

Pennock, D.J., B.J. zebarth, and E. deJong. 1987. Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. Geoderma, 40:297-315.

Pennock, D.J., D.W. Anderson, and E. deJong. 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. Geoderma, 64:1–19.

Peterson, G.A., D.G. Westfall, L. Sherrod, E. Mcgee, and R. Kolberg. 1991. Crop and soil management in druland agroecosystems. Technical Bulletin. LTB88-6. Colorado State University, Fort Collins.

Pfaff, A.S. 1996. What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data. Discussion Paper Series No. 9596-27. Columbia University, pp 44.

Pimetal, D., and J.R. Krummel. 1987. Biomass energy and soil erosion : Assessment of resources cost. Biomass, 14:15–38.

Pulliam, H.R. 1988. Sources, sinks, and population regulation. American Nature, 132:652–661.

Putjaroon, W, and K. Pongboon. 1987. Amount of runoff and soil losses from various land-use sampling plots in Sakolnakorn Province, Thailand. *In* R.H. Swanson et al. (eds). Forest Hydrology and Watershed Management. pp. 231–238.

Raghubanshi, A.S. 1992. Effect of topography on selected soil properties and nitrogen mineralization in a dry tropical forest. Soil Biology & Biochemistry, 24:145-150.

Rainforest Action Network. 1993. Southeast Asia Rainforest : A Resource Guide & Directory, pp. 100.

Richter, D.D., L.I. Babbar, M.A. Huston, and M. Jaeger. 1990. Effects of annual tillage on organic carbon in a fine texture Udalf: the important of roots dynamics to soil carbon storage. Soil Science, 149:78–83.

Ripple, W.J., G.A. Bradshaw and T.A. Spies. 1991. Measuring forest landscape patterns in the Cascade Range of Oregon, USA. Biological Conservation, 57:73–88.

Robert, P. 1993. Characterization of soil conditions at the field level for soil specific management. Geoderma, 60:57–72.

Ruth, R.V., and P.H. Walker. 1968. Hillslope models and soil formation. I. Open systems. Transactions of IX International Soil Science Congress, 4:551-560.

Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures. J. Math Psychology, 15:234–281.

Salati, E., and C.A. Nobre. 1991. Possible climate impacts of tropical deforestation. Climate change, 19:177–196.

Saunders, D., R.J. Hobbs, and C.R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology, 5:18–32.

Schlagel, J.D., and C.M. Newton. 1996. A GIS-based statistical method to analyze spatial change. Photogrammetric Engineering & Remote Sensing, 62:839–844.

Schmidt, M.G., H.E. Schreier, and P.B. Shah. 1995. A GIS evaluation of land use dynamics and forest soil fertility in a watershed in Nepal. International Journal of Geographical Information Systems, 9:317-327.

Schumm, S.A., and R.F. Hadley. 1961. Progress in the application of landform analysis in studies of semi-arid erosion, U.S. Geological Survey Circular 437.

Sinai, G., D. Zaslavsky, and P. Golany. 1981. The effect of soil surface curvature on moisture and yield- Beer Sheba Observations. Soil Science, 132:367-375.

Sinha, S.K., and M.S. Swaminathan. 1991. Deforestation, climate change and sustainable nutrition security: a case study of India. Climate Change, 19:201–209.

Skidmore, A.K. F. Watford, P. Luckananurug, and P.J.Ryan. 1996. An operational GIS expert system for mapping forest soils. Photogrammetric Engineering & Remote Sensing, 62:501-511.

Skole, D., and C. Tucker. 1993. Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988. Science, 26:1905–1910.

Soil Survey Staff. 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. U.S.Dep. Agric. Handbook 435, U.S Dep. Agric., Washington D.C.

Spies, T.A., W.C. Ripple, and G.A. Bradshaw. 1994. Dynamics and pattern of managed coniferous forest landscape in Oregon. Ecological Application, 4:555-568.

Swanson, F.J., and J.F. Franklin. 1992. New forestry principles from ecosystem analysis of Pacific Northwest forests. Ecological Application, 2:262–274.

Swanson, F.J., S.V. Gregory, J.R. Sedell, and A.G. Cambell. 1982. Land-water interactions: the riparian zone. *In* R.L. Edmonds (ed.), Analysis of Coniferous Forest Ecosystems in the Western United States. U.S./I.B.P. Synthesis Series 14. Hutchison Ross, Stroudsburg, P.A. pp. 267–291.

Syers, J.K. 1995. Evaluation of sustainable land management. In Montane Mainland Southeast Asia in Transition, Chiang Mai University, p 366–381.

Tangtaham, et al. 1972. Research note, Kog-Ma Watershed Research Station. Kasetsart University, Bangkok, Thailand.

Thomas, G.W. 1982. Exchangeable cations. *In* Methods of Soil Analysis : Part 2, Chemical and Microbiological Properties, 2nd edn (eds. A.L. Page et al.) p. 159-165. American Society of Agronomy, Medison, WI.

Trangmar, B.B. 1984. Spatial variability of soil properties in Sitiung, West Sumatra, Indonesia. Ph.D. dissertation, University of Hawaii, Hawaii.

Turner, M.G., and R.H. Gardner. 1991. Quantitative Methods in Landscape Ecology. Springer-Valger, New York.

Turner, M.G., W.H. Romone, R.H. Gardner, R.V. O'Neil and T.K. Kratz. 1993. A revised concept of landscape equilibrium: Disturbance and stability on scaled landscape. Landscape Ecology, 8:213-227.

United States Department of Agriculture. 1967. Soil survey laboratory methods and procedures for collecting soil samples. Soil Survey Investigations Report No.1, Soil Conservation Service-USDA, Washington D.C.

United States Soil Conservation Service. 1953. Engineering Handbook for Farm Planners; Upper Mississippi Valley Region III.

Vink, A. P. A. 1983. Landscape Ecology and Land Use. Translated by Davidson, D.A. University of Strathclyde, Longman, London and New York, 264 pp.

Voogd, H. 1983. Multicriteria Evaluation for Urban and Regional Planning. Pion, Ltd., London.

Walker, P.H., G.F. Hall, and R. Protz. 1968. Relation between landform parameters and soil properties. Soil Sci. Soc. Amer. Proc., 32:101–104.

Wallin, D.O., F.J. Swanson and B. Marks. 1994. Landscape pattern response to changes in pattern generation rules: Land-use legacies in forestry. Ecological Application, 43:569–580.

Webb, T.H., and S.J. Burgham. 1997. Soil-landscape relationships of downlands soils formed from loess, eastern South Island, New Zealand. Australian Journal of Soil Research, 35:827-842.

Webster, R. 1985. Quantitative spatial analysis of soil in the field. Adv. Soil Sci., 3:1-70.

Webster, R., and B.E. Butler. 1976. Soil survey and classification studies at Ginninderra. Australia Journal of Soil Research, 14:1-24.

Webster, R., and M.A. Oliver. 1990. Statistical Methods in Soil and Land Resource Survey. Oxford University Press, Oxford.

Whitington, G. 1994. P Leaching through a Texture Contrast Soil under High and Low Irrigation Rates. BSc (Hons) Thesis, Flinders University of South Australia.

Wilding, L.P., and L.R. Drees. 1983. Spatial variability and pedology. In L.P. Wilding et al. (eds.), Pedogenesis and Soil Taxonomy. I. Concepts and Interactions. Elsevier, New York, 83-116.

Wischmeier, W.H., C. Johnson, and B. Cross. 1971. A soil erosibility nomograph for farmland and construction sites. J. Soil Water Conservation, 26:189–193.

Wischmeier, W.H., D.D. Smith. 1978. Predicting rainfall erosion losses, A guide to conservation planning. Agr. Handbook No. 537. USDA, Washington, pp. 58.

Wolock, D.M. 1995. Effects of subbasin size on topographic characteristics and simulated flow paths in Sleepers River wtershed, Vermont. Water Resources Research, 31:1989–1997.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche and D.B. Boktin. 1978. The biota and the world carbon budget. Science, 199:141–146.

Young, A. 1972. Slopes. Oliver and Boyd, Edinburgh, pp. 288.

Zampella, R.A., and R.G. Lathrop. 1997. Landscape changes in Atlantic white cedar (Chamaecyparis thyoides) wetlands of the New Jersey Pinelands. Landscape Ecology, 12:397–408.

Zervenbergen, L.W., and C.R. Thorne. 1987. Quantitative analysis of land surface topography. Earth Surface Processes Landforms, 12:47–56.

Zheng, D., D.O. Wallin, and Z. Hao. 1997. Rates and patterns of landscape change between 1972 and 1988 in the Changbai Mountain area of China and North Korea. Landscape Ecology, 12:241-254.

Zinke, P.J., A.G. Stangenberger, W.M. Post, W.R. Emmanuel, and J.S. Olsen. 1984. Worldwide organic soil carbon and nitrogen data. Pub. No.2212. Oak Ridge National Lab., Environmental Sciences Div. Oak Ridge, TN.