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**SOIL MICROSTRUCTURE AND SOIL ERODIBILITY
AT IBSRAM SLOPING LANDS MANAGEMENT SITES
IN SOUTH-EAST ASIA**

by

Mark Douglas Sunohara, B.A. Hons.

A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of
Masters of Arts

Department of Geography

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Ottawa, Ontario
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Thesis Supervisor

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Chair, Department of Geography

CARLETON UNIVERSITY
Date: December, 1998

Abstract

Associations among soil microstructural type and behaviour, soil erodibility, and soil erosion were investigated at seven research sites of the International Board for Soil Research and Management (IBSRAM) Asialand Sloping Lands Network in Southeast Asia (Chiang Mai and Chiang Rai, Thailand; Vientiane, Laos; Hoa Son, Vietnam; Los Baños and Mabini, Philippines; and Kuala Dal, Malaysia). Soil microstructure was investigated on thin sections prepared from undisturbed samples and microstructural behaviour and other soil properties were determined on bulk samples taken from the surface immediately adjacent to undisturbed samples. The sites were grouped into three clusters according to their microstructural behaviours: stable microaggregates composed of stable domains; unstable microaggregates composed of stable domains; and unstable microaggregates composed of unstable domains. Erosion and rainfall data indicate that structural stability affects the susceptibility to detachment by raindrop impact and that microaggregate or domain size influence the susceptibility to transport by runoff. The nature of the influence of microstructure on the severity of soil loss was not always the same at the various sites. The Chiang Mai and Vietnam sites have unstable microaggregates which disperse into stable domains with low transportability and experience the least soil loss per unit rainfall. At the Laos site a stable soil structure with low detachability and transportability experienced moderate soil loss per unit rainfall under high erosivity conditions. The unstable soil structures at the Los Baños and Mabini sites are easily dispersed and transported causing moderate soil loss per unit rainfall. At the Chiang Rai site stable microaggregates, which are easily detached and transported, experienced very high soil loss per unit rainfall.

Preface

"Nurture your mind with great thoughts, for you will never go any higher than you think." Benjamin Disraeli

"Write what you know about." Mark Twain

I would like to express my sincere gratitude to my advisors, Ken Torrance and Mike Fox, for their invaluable support and friendship throughout this project. My appreciation is extended to all those at IBSRAM and the Asialand network cooperands for their generous hospitality and assistance during my stay in Bangkok and visits to the research sites.

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1. INTRODUCTION

1.1 BACKGROUND

The sustainability of agriculture on sloping lands in the humid tropics is dependent upon, among other factors, controlling the amount of soil loss by the physical process of soil erosion, which requires understanding the factors which influence this process. In Southeast Asia, population pressure and the demand for agricultural products have forced resource-poor farmers to encroach upon marginal lands, including steeply sloping lands, for agricultural purposes (Thapa and Weber, 1991; Blaikie and Brookfield, 1987). By leaving the soil surface exposed to climatic elements, many agricultural practices have accelerated the rate of soil erosion by increasing the soil's exposure to rainfall erosivity. These practices may also be affecting the soil's erodibility. Although farmers are becoming aware of soil erosion and its effects, the adoption of soil conservation technologies by local farmers has been limited (Sajjapongse and Syers, 1995).

Soil conservation technologies aim to decrease soil loss by addressing the aspects of climatic erosivity and soil erodibility which accentuate soil erosion. The basic physical process of soil erosion involving the detachment and transport of soil material and the factors which affect the process are broadly understood, and consequently, soil conservation practices have been developed which are effective in reducing soil losses. Regardless, the interactions among variables involved in the soil erodibility factor have yet to be fully understood. The effectiveness of land management strategies which are

introduced to increase sustainability may be improved by examining the interaction and the involvement of soil erodibility variables not yet well investigated.

At the International Board for Soil Research and Management (IBSRAM) Asialand Sloping Lands Network research site at Chiang Rai, Thailand, Dr. J. K. Torrance observed the eroded material to be dominated by apparently stable microaggregates less than 2 mm in size (Torrance, personal communication, 1997). While it is generally accepted that stable soil structures increase a soil's resistance to erosion, Collins (1995) suggests that the structural stability of microaggregates at the Chiang Rai site and their ease of detachment and transport may be responsible, at least in part, for the high erodibility at this site. This contradiction of conventional wisdom on structural stability and erosion may be applicable to soils at other sites.

1.2 SCOPE AND OBJECTIVES

To explore the possible role of soil microstructure in soil erodibility, a range of soils was chosen for this analysis. From June to July, 1997, soil samples were collected from seven land management research sites of the IBSRAM Asialand Sloping Lands Network in the Southeast Asian countries of Thailand, Malaysia, the Philippines, Vietnam, and Laos.

The aim of the IBSRAM Asialand Sloping Lands Network is to achieve a sustainable form of agriculture through the application of soil and crop management techniques. Situated on sloping lands in humid to sub-humid tropical areas, the research sites experience highly erosive rainfall events during their wet seasons. All sites have highly weathered soils, reflective of their humid tropical environments. Inherent soil properties lend to the intrinsic erodibility of these soils, compounding the severity of soil erosion caused by climatic erosivity. The similarities in climatic and

topographic conditions between sites facilitates the exploration of relationships between microstructural characteristics and soil erodibility.

The most common forms of soil erosion on these sloping plots are inter-rill and rill erosion, involving both the destructive forces of raindrop impact and the shear stress and carrying capacity of the overland flow of water. The soil loss experienced at these sites is considered to be related to the rainfall erosivity and soil erodibility.

The main goal of this study is to explore the role of microstructure in soil erodibility and erosion. With this in mind, the following research objectives were set.

1. Examine and characterize the structural and microstructural properties of the soils from IBSRAM research sites;
2. Investigate the soil properties which might influence aggregate and microaggregate stability at each site;
3. Explore possible associations between soil microstructure and its behaviour, other soil properties, and soil erodibility.

1.3 ORGANIZATION OF THESIS

This thesis is organized as follows. Chapter 2 provides a background review of the soil erosion process and soil erodibility. Chapter 3 identifies site locations and describes the field and laboratory methods used in this analysis. In Chapter 4, experimental results are included in the site descriptions and the results of the soil characterization are presented. Also discussed in Chapter 4 is a site-by-site comparison of structural stability and the role of microstructure in potential soil erodibility. Chapter 5 provides an analytical comparison of sites based on clustering of soil loss results. Chapter 6 summarizes the conclusions of this thesis, discusses limitations encountered during the research, and provides recommendations for further research.

2. SOIL EROSION

Soil erosion is a multi-step process of detachment and transportation of soil material by various erosive agents (Hudson, 1995; Lal, 1990; Meyer and Wischmeier, 1969). The process which leads to soil loss requires the interaction of multiple factors such as: climatic conditions, inherent soil properties, topography, vegetation, and land use. The interactions of these factors determine the magnitude of soil loss.

Figure 2-1 presents a schematic illustration of the soil erosion process in which the overlapping of the four main factors of soil erosion - climatic erosivity, landform, vegetation, and soil erodibility - reflects their interaction. Macro- and microstructure properties influential in soil erodibility and the soil properties which have been known to influence aggregate stability are also shown in Figure 2-1.

Figure 2-1: Factors in the Soil Erosion Process

The Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1958), conceptualized the interactions among these soil erosion factors in the equation,

$$A = RKLSCP$$

where: A is soil loss, R is climatic erosivity, K is soil erodibility, L is slope length, S is slope gradient, C is cropping method, and P is conservation practice (Hudson, 1995). Although inaccurate in predicting soil loss outside its empirical data set, the USLE provides a framework for understanding the basic erosion process and the influential factors (Loch and Pocknee, 1995; Romkens et al., 1977).

In response to the aforementioned inadequacies of the USLE, the Water Erosion Prediction Project (WEPP), a process-based model designed to predict soil erosion, has been developed. In this model, rill and inter-rill erosion are treated as separate components of erosion (Foster et al., 1977). The inter-rill detachment rate of soil material involves the inherent soil erodibility, rainfall intensity, and slope, while rill erosion is also based on soil resistance to detachment in response to the hydraulic shear stress imposed by flowing water. Furthermore, the soil erosion factors are calculated as precise or mathematical formulas based on the erosion process rather than regression equations based on empirical studies.

Climatic erosivity is controlled by the active agents of soil erosion, including raindrop impact, overland flow, wind, and wet/dry cycles. These climatic sub-factors affect the amount of soil loss from eroding surface soils. Topography, referring to the slope length, gradient, and shape, affects severity of climatic erosivity by influencing the velocity and hydraulic shear strength of overland flow and the soil displacement caused from raindrop impact. Vegetation lessens the severity of climatic erosivity by

protecting the soil from raindrop impact and reducing the volume and velocity of overland flow. With the addition of organic matter, vegetation also decreases soil erodibility by promoting soil structure and strength. The organic matter also acts as a binding agent between particles and aggregates and improves macro-pore space thereby facilitating infiltration of rainwater.

2.1 CLIMATIC EROSIVITY

Climatic erosivity is the ability of the climate to cause erosion and is the integrated effect of all climatic variables. The two most important climatic factors having direct effects on soil erosion are precipitation characteristics and wind velocity. Other climatic factors having indirect effects on erosion are: water balance, evapotranspiration, temperature, and relative humidity (Lal, 1990).

2.1.1 Rainfall

Soil erosion is influenced differently by the varying characteristics of rainfall events. The erosivity of rainfall is a function of its intensity, duration, timing, and amount. The amount of rainfall governs the input to the overall water balance, which in turn, affects the relative amount of rainfall that will become runoff. The intensity distribution of the rain can alter the amount and rate of runoff flow. Advanced storms, in which the highest intensity of rainfall occurs in the initial portion of the storm, common in humid, tropical areas, normally generate less runoff than delayed storms. During advanced storms, the soil's water storage capacity is under-utilized and the soil can continue to absorb rain water. Conversely, in delayed storms, in which rainfall intensity increases during the storm, the soil pores may reach their infiltration capacity and greater amounts of runoff will occur. As runoff volume increases, the critical flow

velocity increases. This, in turn, increases the hydraulic shear stress and the transport capacity of overland flow, and the size of particles that can be detached and transported (Lal, 1990).

An increase in raindrop size occurs with the high intensity rainfall events experienced in the humid tropics. The larger mass and terminal velocity of the larger raindrops increase the kinetic energy that impacts the soil surface, thereby increasing the amount of rain splash upon impact. Raindrops striking the soil surface cause inter-rill erosion by detaching soil particles, some of which may then be transported into soil pores by infiltrating water. Clogging of the pore space as the particles are filtered from the infiltrating water, along with other physical disturbances of the surface by the raindrop impact, leads to crusting and sealing of the soil surface, thereby decreasing the permeability of the soil and increasing the amount of runoff. Overland flow below its critical depth, the depth below which flow becomes turbulent, allows raindrop impact to create flow turbulence which increases the detachment and entrainment forces and increases soil erosion beyond what would occur with laminar flow (Emmett, 1978).

The erosivity of wind-driven rain depends on wind velocity, rainfall intensity, and slope characteristics. The accelerated horizontal velocity causes an increased impact velocity of wind-driven raindrops and increases their kinetic energy upon impact, thereby increasing the amount of soil displaced and distance of soil displacement. The combined effect of slope angle and increased velocity, and the angle of raindrops, accentuates the downslope displacement of soil particles by soil splash.

2.2 SLOPE

The gradient, length, and shape of a slope can influence the amount, type, and velocity of overland flow. Steep slope angles increase the downslope displacement of

soil particles by raindrop splash. Erosion generally increases with an increase in slope steepness due to the increased downslope component of gravity leading to higher runoff velocities which affect the shearing stress and transporting capacity imposed by flowing water. Rill erosion was observed to increase more rapidly with slope steepness than inter-rill erosion (Lettanzi et al., 1974). The shear stress of overland flow increases with slope length and gradient while the surface area available for impact from vertically-oriented raindrops decreases. Smith and Wischmeier (1962) established a relationship between slope steepness and soil loss - as slope gradient increases, the soil loss also increases.

Slope length, the distance from the point of origin of overland flow to the point where the amount and velocity of overland flow decrease enough for deposition to occur, affects both the detachment and transport of sediment by overland flow (Wischmeier and Smith, 1978). Rill erosion has been recorded to be greater on long slopes than on short ones. This increase in rill erosion on longer slopes is due to the greater detachment and transport capacities of the runoff overland flow. Longer slopes allow greater accumulated runoff on the lower part of the slopes due to runoff acceleration and increased fluid shearing capacity. These factors increase runoff detachment and entrainment capacities leading to greater sediment loads. With higher sediment loads, the abrasiveness of overland flow also increases, accentuating erosion within the rills (Lal, 1990).

Slope shape affects the localization of entrainment and deposition of soil material by influencing the amount and velocity of overland flow. Convex and concave slopes have differing effects on soil erosion. Convex slopes have less steep, upper slopes which lead to slow initial velocity of overland flow, but as the slope gradient

increases, the greater runoff velocity increases its detaching and transport capacity. With concave slopes, the initial velocity of overland flow is greater, but as the slope gradient decreases, the velocity decreases and deposition will occur (Lal, 1990).

2.3 VEGETATION

Vegetation acts as cover protection for the soil, dissipating the energy of raindrop impact, thereby reducing soil splash. Reducing raindrop impact is important in protecting soil structure. Crop canopy decreases the kinetic energy of raindrop impact by intercepting its path to the surface and reducing the potential energy of throughfall. Vegetative cover closer to the ground is more effective than tall canopies in reducing the potential energy of the throughfall kinetic energy (Figure 2-2) (Morgan, 1986).

Figure 2-2: Differences in Vegetation Cover (adapted from Hudson, 1995)

Vegetation also decreases the velocity of overland flow by impeding its downslope movement. Alley-cropping, a form of soil conservation where crops are grown along the contours of a slope, promotes the deposition of soil material. The alley crop interrupts the overland flow, decreasing its velocity and causing the entrained particles and aggregates to settle and deposit. The promotion of terraces and the

resulting reduction of slope angle are beneficial results of this type of conservation measure.

2.4 SOIL ERODIBILITY

Soil erodibility is defined as the reciprocal of soil resistance to the erosive detachment and transport forces of rainfall and overland flow (Morgan, 1986). Soil erodibility is simultaneously controlled by other soil characteristics such as organic matter, oxides, mineralogy, and texture. The degree of erodibility has been reported to be closely correlated with the stability of soil structure and its aggregates (Reichert and Norton, 1994; Romkens et al., 1977). Therefore, the analysis of influential soil properties in aggregation and structural formation is important in comprehending soil erodibility.

The aggregation of soil dictates its structure (Brady and Weil, 1996; Marshall and Holmes, 1988). Aggregation plays integral roles in soil susceptibility to erosion by determining the cohesiveness of soil, and thereby the soil's resistance to erosive overland flow shear stress and raindrop kinetic energy (Dexter, 1988). Aggregation affects soil permeability, determining the moisture detention capacity on the surface and the infiltration capacity of water within the soil (Marshall and Holmes, 1988). As the structure deteriorates, soil particles, microaggregates, and aggregates are detached and transported downslope by overland flow. Thus, the aggregation of a soil is an important consideration in soil erodibility.

2.4.1 Factors Influencing Aggregation and Stabilization

Soil aggregation is the binding of soil particles into secondary units. Soil aggregates are formed by the association of clay particles into silt-sized domains, domains and silt particles into microaggregates, and microaggregates and sand particles into aggregates (Figure 2-3 and Figure 2-4) (Lal, 1990).

Figure 2-3: Clay Domain (adapted from Williams et al., 1967)

Figure 2-4: Hypothetical Model of Aggregate Formation (adapted from Williams et al., 1967)

For aggregation to occur the clay must be flocculated and there must be an appropriate medium to facilitate the process of binding particles together (Hillel, 1980). Organic matter, exchangeable cations, and oxides of iron and aluminum are common binding materials.

Soil properties that influence aggregate stability can be categorized into physical, chemical, and mineralogical properties. Physical properties include the stability of structure and aggregation, particle-size distribution, pore arrangement, and infiltration capacity. Chemical properties include those which act as binding agents such as organic matter and certain exchangeable cations such as Ca^{+2} , Mg^{+2} , and K^{+1} . Mineralogical properties include the binding effects of clay minerals and sesquioxides (Lal, 1990). Aggregate stability is also influenced by processes such as organism activity and climatic wet-dry cycles.

Soil conditions which can affect the degree of soil erosion such as infiltration, heat transfer, aeration, and porosity are influenced by the structural condition of the soil (Brady and Weil, 1996). The infiltration capacity of a soil strongly influences its moisture capacity. As more water enters the soil pore system, the infiltration capacity is decreased and the moisture retention capacity is depleted (Haan et al., 1982). Also, the shear strength of aggregates decreases as moisture content increases, which decreases soil cohesiveness and allows aggregates to disintegrate and break apart (LeBissonais, 1996).

2.4.1.1 Texture

Texture influences structural conditions by determining the distribution of grain sizes and shapes which, in turn, influence the arrangement and packing of grains. The manner in which the material has been deposited or formed also influences the arrangement of grains (Hillel, 1980).

The amount of pore space, and consequently the degree of water movement and aeration of the soil, are influenced by texture. Fine-textured soils such as silt and clay loams generally have lower bulk densities due to their organization into porous granules, with pores occurring both between and within granules (Brady and Weil, 1996). Coarse-textured soils commonly have higher bulk densities due to less intra-ped pore space. This can consequently influence the translocation of fine materials, such as clays, oxides and organic matter, which can act as binding agents.

The clay fraction of a soil plays a principal role in the aggregation process. Clay particles act as binding agents, attaching to larger sand and silt particles through electrostatic charges (Marshall and Holmes, 1988). A clay content of less than ten percent tends to cause a soil to act as if it were non-aggregated (Marshall and Holmes, 1988). In soils which have a wide range of particle-sizes, smaller particles fit between larger particles, reducing pore space and the free movement of air and water. Smith et al. (1978) reported that oriented clay particles around sand grains may expand the matrix by pushing the sand grains apart. Presumably, this expansion would tend to increase the void ratio, but the presence of clay in the matrix interstices tends to decrease the void ratio.

2.4.1.2 Vegetation

Vegetation plays key roles in soil aggregation and aggregate stability. By covering the soil surface, plants provide protection against aggregate breakdown caused by rainsplash and the weathering effects of climate (Lal, 1990). As a source of food and energy for microbial organisms, plants indirectly assist the aggregation process. As plant residues are decomposed by organisms, the microbial products (humic compounds) which are produced bind particles together, encouraging crumb formation (Brady and Weil, 1996).

The root systems of plants also contribute to the amount of organic residues in the soil and are a factor in promoting the formation of stable aggregates (Baver et al., 1972). As plant roots expand and lengthen during growth they help to produce stable soil crumbs by exerting pressure on soil particles, binding them together (Hillel, 1980). Plant roots also remove water from the soil, a process which produces stresses and strains that push particles together and help to form stronger aggregates. The localized dehydration-hydration of the soil assists in aggregate formation by causing shrinkage upon dehydration and the formation of fracture surfaces between and within aggregates, thereby forming new aggregates (Baver et al., 1972). This dehydration effect also causes colloidal films to surround aggregates making them more resistant to decomposition (Allison, 1973).

2.4.1.3 Wetting and Drying

The role of wetting and drying cycles in aggregation involves several factors including: the texture of the soil (i.e. clay, silt, sand), the stability of aggregates, its antecedent air and moisture contents, and the extent and degree of wetting and drying.

Alternate wetting and drying cycles can cause differential expansion and shrinkage which may enhance soil aggregation or contribute to aggregate breakdown. Soils dominated by expanding clay minerals shrink upon drying, often leaving deep cracks. These cracks allow for horizontal and vertical movement of soil particles which infill the pores and reduce the soil permeability. The shearing movement upon wetting and expansion aligns clay particles, favouring the formation of dense masses with minimum air space. This process produces few aggregates of desirable size (Allison, 1973).

Russell (1938) reported that the drying of soil has a dual effect on aggregation: the dehydration of aggregating cements increases the inherent stability of aggregates; and, as aggregates become drier, there is an increase of disruptive forces due to water-slaking when re-wetting occurs. For small aggregates ($<0.25 \text{ mm } \varnothing$) the disruptive forces are small and the net effect of drying is stabilization. For larger aggregates ($>0.25 \text{ mm } \varnothing$), either effect may predominate, depending on the nature of the aggregates and the rate of wetting (Russell, 1938).

The stability of aggregates generally decreases upon wetting a dry soil. The stability decreases with increasing water content because of reduced cohesion between particles and softening of cements (Marshall and Holmes, 1988). Air entrapment plays a dominant role in aggregate breakdown. If the soil is wetted rapidly, entrapped air within the aggregate is compressed, increasing pressure beyond the tensile strength, thereby causing the aggregate to disintegrate. Slow absorption of water usually causes less disruption (LeBissonais, 1996).

High aggregate stability has been observed to decrease the erodibility of a soil because it increases the resistance of a soil to dispersion and detachment (Reichert

and Norton, 1994; Bryan, 1968). This is important to the erodibility of a soil because generally the larger the size of aggregates, the more they resist the runoff forces of erosion (Lal, 1990). The focus of the current research is not to dispute these findings, but rather to examine the properties that influence the stability and strength of microaggregates and to determine how these properties may influence soil erodibility.

2.4.2 Factors Involved in Microstructural Stability

Previous research on soil erodibility has concentrated on the importance of soil structure in soil erodibility. However, microstructure may play a critical role in structural stability and soil erodibility. Microstructural stability (i.e. microaggregate stability) can influence the nature of aggregate breakdown, and consequently the amount and type of sediment that is detached and transported away from a site. The significant substances involved in the stabilization of microaggregates are clay particles and exchangeable cations, oxides of iron and aluminum, and organic colloids (Quirk, 1994).

Cohesiveness between clay particles has been reported to be the ultimate internal binding force within microaggregates (Hillel, 1980). Calcium carbonates and iron and aluminum oxides can also impart considerable stability to aggregates (Hillel, 1980). A geometrical arrangement of particles in aggregates has been proposed by Emerson (1959) in a diagram illustrating the way in which particles are held together (Figure 2-5). Clay domains are attached to one another and larger particles by bonds of differing types. The bonds may be: electrostatic, as between positive-charge edges and negative-charge faces as at D (*domain edge-domain face*); or through a medium of organic matter as at A (*quartz-organic matter-quartz*), B (*quartz-organic matter-domain*), and C (*domain-organic matter-domain*) (Marshall and Holmes, 1988).

Figure 2-5: Arrangement in an Aggregate (adapted from Emerson, 1959)

2.4.2.1 Cation-Particle Interaction

As previously mentioned, clay particles function as binding agents in the aggregation process. Russell (1934) proposed an oriented-particle, oriented-water, water-particle linkage, where a portion of the clay must be smaller than 1 μm and have a high specific surface and a high base-exchange capacity with small exchangeable cations. The total cohesion between clay particles increases as the number of inter-particle links increases as the soil dehydrates, and the links becoming stronger as they become shorter. Molecular forces, primarily van der Waals, between colloidal surfaces also enhance the cementation action. Clay can also adsorb to the surfaces of sand grains, binding the grains together. This adsorption is only slowly reversible after dehydration (Baver et al., 1972).

The nature of cations present on the exchange complex influences the structural type and strength. Bivalent cations such as Ca^{+2} and Mg^{+2} improve structural stability more than monovalent cations such as Na^{+} and K^{+} (Collins, 1995). The presence of Na^{+} ions, a highly-hydrated monovalent cation, tends to encourage dispersion of soil particles, whereas bivalent and trivalent cations tend to encourage

aggregate formation through strong flocculation forces (Lal, 1990; Brady and Weil, 1996).

2.4.2.2 Iron and Aluminum Colloids

The low activity clays with low effective cation exchange capacities (such as kaolinite) found in tropical soils such as Oxisols and Ultisols, have high resistance to dispersion due to strong inter-particle forces caused by sesquioxides (Lal, 1990). The iron and aluminum oxides and hydrous oxides, constituents of the clay fraction, are prevalent in soils of tropical and sub-tropical regions and often serve as cementing agents in the stabilization of soil aggregates (Hillel, 1980). Furthermore, studies conducted on the ability of oxides to promote aggregation have shown beneficial results (El-Swaify and Emerson, 1975). Kroth and Page (1947) observed stable aggregates coated with iron and aluminum oxides. In their studies on aggregate stability, Romkens et al. (1977) found a positive correlation between Fe_2O_3 , in the range of 0.8% and 3.5%, and aggregate stability for clayey subsoils. A close relationship exists between the free oxides of iron and/or aluminum and the quantity of water-stable aggregates (Deshpande et al., 1968; Kemper, 1966).

There are two functions of the iron in aggregation. Iron which is in solution in ionic form may act as a flocculating agent upon the particles, and that which is a more gelatinous solid (an iron oxide form) may exert a cementation action upon the particles. The dehydration of the gel forms a strong cement for the binding of flocculated particles in that ferric hydroxide becomes almost completely insoluble upon dehydration (Baver, et al., 1972). This insolubility is an important factor in the production of stable aggregates in certain soils.

Gibbsite $[\text{Al}(\text{OH})_3]$ displayed stronger effects in promoting aggregate stability than Fe hydroxides, most likely due to the tendency of Fe hydroxides to crystallize, causing a lesser cementing effect (Reichert and Norton, 1994). This difference in the promotion of aggregate stabilization was less predominant in soils with alternating oxidized and reduced states. Hsu (1989) hypothesized two possibilities for the mechanism of aggregation in the presence of aluminum. First, small OH-Al polymers can be held more tightly than ordinary exchangeable cations in clay mineral interlayers. These polymers displace interlayer cations and, by bonding adjacent silica sheets together, reduce swelling and increase stabilization of the structure. Second, the OH-Al polymers and aluminum hydroxides may react with external surfaces and cement adjacent particles together. The cementation effect is presumed to increase with decreasing pH due to the increase in positive charge of hydroxy-Al ions with decreasing pH. With multiple positive charges, the positive charge of aluminum oxides interacts with more than one clay particle and acts to link the particles together.

2.4.2.3 Micro-organisms and Organic Matter

Micro-organisms play an essential role in the production of the soil organic compounds that act as a binding agent between soil particles (Figure 2-5). As soil organic matter – polysaccharides, polyuronides, and cellulose – decomposes, microbial gums which have stabilizing properties are produced. These microbial gums consist largely of humus breakdown products and linear organic polymers (Allison, 1973). The breakdown products, present as a mono-molecular film, may assist in the binding of inorganic soil constituents.

Allison (1973) believed that the strong correlation between water-stable aggregation and organic matter content is due to the protection of some organic matter

from microbial attack by its close association with clay. Edwards and Bremner (1967) concluded from their studies on aggregate stability that the process of microaggregate formation stabilizes some of the organic matter in soils by rendering it physically inaccessible to micro-organisms. For example, soil bacteria are usually 0.5-1.0 μm in size, while a layer of protein trapped inside the lattice of montmorillonite has a thickness of about 0.00048 μm . The smallest bacteria are about 1000 times thicker than the polysaccharide layer in stable aggregates (Allison, 1973). Thus, polysaccharides, which are a mixture of large, linear, flexible polymers having large numbers of OH groups in the chain, are well protected against decomposition when bound within an aggregate or in a clay lattice (Allison, 1973).

The stability of microaggregates of clay and organic matter may be long lasting (Tisdall and Oades, 1982). These microaggregates with high stability will resist breakdown processes and remain intact, while larger aggregates consisting of these stable microaggregates, sand, and silt particles are not protected and can break down due to microbial attack on accessible organic binding materials.

2.5 SUMMARY

Soil erosion involves a complex interaction of erosive climatic conditions, inherent soil properties, topography, and vegetation. Soil structure is an important consideration when investigating the susceptibility of a soil to erosion processes. It is a main factor in several processes which influence the erodibility potential of a soil including the resistance to dispersion, the transport of aggregates by overland flow and raindrop impact, and moisture infiltration capacity and rate.

Soil structure refers to the packing of soil material into aggregates. Aggregates are secondary units composed of soil particles, domains, and microaggregates.

Aggregate stability is influenced by soil properties which include the clay particles themselves, sesquioxides, and organic colloids acting as binding agents between aggregates, microaggregates, and particles. The degree of aggregate stability depends upon the cohesion between particles, microaggregates, and aggregates and is influenced by the resistance of the binding material to erosive agents. Highly stable aggregates may remain intact when subjected to erosive conditions, while unstable aggregates may disperse and increase erodibility. The size of stable aggregates also influences erodibility as smaller, lighter microaggregates may be preferentially detached and transported by raindrop impact and overland flow.

To control the amount of soil loss, vegetative cover provides protection against rainsplash and the weathering effects of climate which cause aggregate breakdown. Vegetation impedes the movement of overland flow, increases infiltration capacities, and decreases the velocity, shear strength, and transport capacity of overland flow. Aggregate stability may be breached when erosive forces such as raindrop impact, fluid stress of overland flow, or decreased cohesion due to absorbed moisture are greater than the cohesive strength of the soil. The resultant breakdown material, composed of dispersed soil material and stable microaggregates, facilitates a chain of events of pore infiltration, surface crusting, decreased moisture infiltration, and increased runoff. The material remaining on the soil surface may be transported downslope with turbulent overland flow contributing to the amount of soil loss.

The influence of soil structure and microstructure on the erodibility of a soil, and the physical and chemical factors which can affect the strength and stability of these properties, require greater understanding if we are to fully comprehend the dynamics of the soil erosion process. While soil structure has been empirically studied and proven

to be an important factor in soil erosion processes, microstructure, its formation, and stability are presently hypothesized to be important factors in the erodibility of certain soils.

3. SITE LOCATIONS AND EXPERIMENTAL METHODS

3.1 NETWORK BACKGROUND - IBSRAM ASIALAND SLOPING LANDS NETWORK

In 1988, IBSRAM coordinated the establishment of the ASIALAND Management of Sloping Lands Network, which aims to improve the sustainability of agriculture on steeply sloping farmlands by assisting member countries in soil conservation. The locations of IBSRAM research sites included in this analysis are identified in Figure 3-1.

Figure 3-1: Research Site Locations in Southeast Asia

Once positive soil conservation results on long-term experimental trials are obtained, the technologies are transferred from experimental plots to farmers for validation. Positive responses from farmers are prerequisite for the adoption and extension of the technologies to other farmers. The network now has seven participating countries in

Southeast Asia: Thailand, Laos, Vietnam, Philippines, Indonesia, Malaysia, and China (IBSRAM, 1996).

3.2 SAMPLE COLLECTION

At each IBSRAM land management site, soil samples were collected from a bare plot (BP); a plot where farmers' (traditional) practices (FP) were used; and a plot where a conservation practice (alley-cropping between hedgerows) was used. Sample pits were located on agricultural plots on similar slopes. Sample pit locations were selected near the centre of their respective plots, with extreme convex or concave slope segments being avoided. Plots without fertilizer application were selected for analysis to avoid chemical variation due to fertilizer nutrients. The abbreviations for site locations and agricultural practice are presented in Table 3-1. The locations of the sites are abbreviations of either the country name or site name (where two sites exist within one country).

Table 3-1: Site and Plot Descriptions and Abbreviations

Site	Location	Country	Soil Order	Slope	Climate	Farmer Practice	Conservation Practice
CR	Chiang Rai	Thailand	Ultisol	20-50%	Humid, tropical	Upland rice	Alley-cropping
CM	Chiang Mai	Thailand	Alfisol	12-35%	Humid, tropical	Upland rice	Alley-cropping
L	Vientiane	Laos	Ultisol	25-35%	Tropical, monsoon	Upland rice	Alley-cropping
V	Hoa son	Vietnam	Ultisol	20-30%	Humid, tropical	Corn/peanut	Alley-cropping
P	Mabini	Philippines	Entisol	18-20%	Humid, tropical	Corn/peanut	Alley-cropping
LB	Los Banos	Philippines	Inceptisol	18-20%	Humid, tropical	Corn/peanut	Alley-cropping
M	Kuala Dal	Malaysia	Oxisol	16%	Humid, tropical	Rubber/legume	Alley-cropping
C	Xinlong	China	Ultisol	40%	Humid, sub-tropical	Upland rice	Alley-cropping

Plot Practice	
BP	Bare Plot
FP	Farmer Practice
DA	Conservation Practice - Above Hedgerow
DB	Conservation Practice - Below Hedgerow

3.2.1 Undisturbed Samples

Undisturbed soil samples, for thin section and stub mount analysis of structural properties, were collected from the walls of 40x40x60cm pits which were excavated at each site, one pit in the farmers' practice (FP) and two in the Conservation Practice (DA and DB). From each pit, undisturbed samples were taken from 4-10 cm, 20-26 cm, and 45-50 cm depths (Figure 3-2).

Figure 3-2: Sample Pit

Kubiena boxes (60x30x30mm), vertically oriented, were pressed into the soil of the up-slope pit wall until imbedded approximately 1-2 cm beyond the trailing edge. Each box was carefully dug out using a garden trowel, and scraped clean of excess soil and trimmed on the exposed ends using a spatula. The trimmed samples were wrapped in cellophane, wooden plates were placed over exposed surfaces, and held by elastic bands. These precautions were taken to prevent disturbance and damage caused by moisture loss and consequent shrinkage during transport and storage. All samples were labelled and their orientations were recorded.

3.2.1.1 Conservation Practice (CP)

The Conservation Practice plots consisted of hedgerow alley-cropping and alleyway crops, in which the hedgerows are used to decrease the velocity and amount of overland flow and to trap the soil that is being eroded from upslope. Two pits were excavated in an alleyway that was mid-slope in the experimental plots: one 30 cm directly below a hedgerow (DB), where surface material has been removed by soil erosion; and the second, 30 cm directly above a hedgerow (DA) in the accumulation wedge where eroded surface material has been deposited (Figure 3-3).

Figure 3-3: Pit Locations in Conservation Practice Plots

3.2.1.2 Farmer Practice (FP)

Farmer practice represents the commonly used indigenous agricultural practices. Typically, these plots consisted of either up-and-down cultivation or random planting of upland rice or corn (Aneksamphant, et al., 1995). In the farmer practice plot, one centrally located pit was excavated (Figure 3-4).

Figure 3-4: Sample Pit Location in Farmer Practice

3.2.2 Bulk Samples

Bulk surface samples were collected from three different practice plots: one sample from the bare plot (BP), one from the farmer practice (FP), and two from the Conservation Practice (DA and DB). Collection involved obtaining soil from 0-5 cm depth, from a location in close proximity to each excavation pit. These bulk surface samples were used for laboratory analysis of soil chemical and physical properties at each collection site.

3.3 FRAMEWORK FOR EXPERIMENTAL ANALYSIS

Experiments which examined the soil structure and which measured the soil properties which may be determinants of soil strength and erodibility formed the basis of the laboratory experimental analysis. Soil structure was investigated using optical and scanning electron microscopy (SEM) to examine soil microstructure, matrix, and pedofeatures using thin sections and stub mounts. Other selected soil physical and chemical properties investigated for their role in aggregate and microaggregate stability include: Small aggregate dry crushing strength, clay mineralogy, iron and aluminum oxide content, microaggregate bulk density, particle-size distribution, soil pH, carbon

and nitrogen content, exchangeable cations, and effective cation exchange capacity (ECEC). Aggregate dispersion tests were performed as an indicator of aggregate dispersibility. The following are general descriptions of the experimental tests. Unless otherwise indicated, tests were based on standard procedures.

3.3.1 Microstructural Behaviour

A binocular microscope was used to analyze microstructural behaviour, where representative aggregates were saturated and disturbed, observing the results. Full experiment methodology for microstructural behaviour is provided in Appendix 7.1.

3.3.2 Soil Physical Properties

Soil physical properties investigated included: microstructure, microaggregate bulk density and porosity, small aggregate dry crushing strength, soil texture, mineralogy, and aggregate dispersibility.

3.3.2.1 Microaggregate Bulk Density

Ten randomly-chosen, pre-weighed air-dried aggregates ($< 5 \text{ mm } \varnothing$) from all practices at each site were subjected to bulk density tests. Due to the small size of microaggregates, bulk density was determined by saturation of the pore space with water. Slowly introducing water to one side of the aggregate with a syringe allowed time for complete saturation of the pores. The increase in weight (in grams) equals the pore volume (cm^3) as the density of water is 1.00 gcm^{-3} . Errors in this procedure arising from incomplete saturation would lead to an overestimation of the bulk density. The volume of the mineral fraction was calculated by assuming its particle density to be 2.65 gcm^{-3} .

3.3.2.2 Particle-Size Distribution

Particle-size distribution was determined on disturbed surface samples for all practices at each site by standard sedimentation and pipette procedures (Gee and Bauder, 1986). Soil texture was reported according to the USDA classification.

3.3.2.3 Dry Aggregate Crushing Strength

The crushing strength of small, air-dried aggregates was determined by an aggregate crushing test. An apparatus was designed to subject small aggregates of known weight to a normal stress by slowly increasing a vertical load. The weight at which aggregate fracture occurred was determined to be the aggregate crushing load. A ratio of crushing load to aggregate dry weight was determined. This ratio gives a relative measure of dry aggregate strength. Six to ten aggregates (approximately 2-3 mm $\varnothing$) from each bulk sample were crushed and the mean dry aggregate crushing strength per unit weight was determined.

3.3.2.4 Clay Mineralogy

A qualitative analysis of clay mineralogy was determined by X-ray diffraction, using a Philips PW 1710 diffractometer. Samples (< 2 μm $\varnothing$) were subjected to three treatments: untreated, K-saturation and 350° C heating, and Mg-saturation with ethylene glycol treatment (Whittig, 1965). X-ray diffraction peaks and spacing were recorded. The peaks were then cross-referenced and identified with known spacing of reflection as described by Brindley and Brown (1980).

3.3.2.5 Aggregate Dispersibility

Aggregate dispersibility was determined by ultrasonic dispersion. Aggregates were dry-sieved through a No.10 ASTM sieve (2 mm $\varnothing$) and the retained aggregates

were collected. Weighed samples of aggregates (approximately 2 g in weight) were submerged in a plastic beaker filled with 30 ml of water and subjected to ultrasonic energy using a high-intensity probe-type ultrasound generating unit. The probe output was calibrated by Gregorich (1988). The probe was operated at a constant power level with the time of exposure regulated to produce total ultrasonic energy inputs of 40, 60, 100 J/ml, according to:

$$\text{Total ultrasonic energy (J/ml)} = 120 \text{ J/s} \times \text{time of sonification (s)} / 30 \text{ ml water}$$

The dispersed samples were carefully wet-sieved through a No.20 ASTM sieve (1 mm $\varnothing$). The retained aggregates were dried and weighed. The amount of aggregates (>1 mm $\varnothing$) which survived ultrasonic treatment was subtracted from the original weight of aggregates (>2 mm $\varnothing$). This value, which represents the weight of microaggregates less than 1 mm $\varnothing$, was then divided by the original weight.

$$\text{Aggregate Dispersion} = \frac{\text{Original Weight} - \text{Remaining Weight}}{\text{Original Weight}}$$

3.3.2.6 Stub Mounts of Aggregates

Representative aggregates (≥ 5 mm $\varnothing$) from farmer practice (FP) and the conservation plots (DA and DB) were fractured to obtain a fresh surface. They were mounted on stubs with silicone adhesive, and sputter-coated with Gold-palladium. Aggregate fracturing and microaggregate structure were examined using a JEOL-JSM 6400 scanning electron microscope. Digital images of the fractured surfaces were obtained at four magnifications (100x, 400x, 1000x, and 5000x).

3.3.2.7 Thin Section Preparation

Thin sections were prepared according to Fitzpatrick (1984) and characterized according to Bullock et al. (1985). Soil microstructure, matrix, and pedofeatures were examined by optical and scanning electron microscopy (SEM).

3.3.3 Soil Chemical Properties

Soil chemical properties determined were: soil pH, nitrogen and carbon content, iron and aluminum oxide content, exchangeable cations and effective cation exchange capacity.

3.3.3.1 Soil pH

Soil pH, taken to two decimal places, was determined electrometrically on all disturbed samples, in a 2:1 water-soil solution.

3.3.3.2 Total Nitrogen and Carbon Content

Total nitrogen and carbon contents were measured by combustion using an Carlo Erba NC2500 Elemental Analyzer.

3.3.3.3 Iron and Aluminum Oxide Content

Fe and Al oxide contents were determined by Dithionite-Citrate extraction and atomic absorption spectrophotometry analysis (AAS) (Sheldrick, 1984). This procedure was used to remove free oxides and sesquioxide coatings from soil particles, providing an estimate of free non-silicate Fe and Al.

3.3.3.4 Exchangeable Cations and ECEC

Exchangeable cations (K^{+1} , Mg^{+2} , and Ca^{+2}) and the effective cation exchange capacity were determined by NaCl extraction and AAS analysis (Sheldrick, 1984).

3.3.4 Data Analysis

3.3.4.1 Soil Erosion Data

Soil erosion data were collected and synthesized into a useable format from original data files from IBSRAM network collaborators and from network documents. The data used in this analysis consisted of annual records of precipitation, soil loss, and runoff. An index of annual soil loss ($\text{t ha}^{-1}\text{yr}^{-1}$) per annual precipitation (mm yr^{-1}) was used to relate soil loss per unit amount of precipitation ($\text{t ha}^{-1}\text{mm}^{-1}$). An index of annual soil loss to total runoff (m^3) was used to relate soil loss per unit runoff (t m^{-3}).

3.3.4.2 Slope Standardization

Using a slope-standardizing soil loss curve (Figure 5-2, p.84), soil loss from each site was standardized to a common slope (20%) to produce a slope-standardized soil loss per unit rainfall index. This index attempts to neutralize the variation in soil erodibility caused by slope steepness. The similar vegetation among sites (except Malaysia) largely eliminates the soil loss variability caused by the vegetation.

3.3.4.3 Site Comparison

The reliability of a statistical analysis based on a sample consisting of 7 sites is questionable. Therefore, the analysis was restricted to a site comparison based on experimental observations and soil loss results. In Chapter 4, the sites are grouped based on observed similarities in microstructural behaviour. In Chapter 5, the soil loss data are ranked and subjectively grouped into clusters of similar values. The microstructural behaviour of each site was compared to its actual and slope-standardized soil loss per unit rainfall and soil loss per unit runoff results. For each site, an evaluation of the influence of its microstructural behaviour in soil loss was given.

4. SITE DESCRIPTIONS AND SOIL CHARACTERIZATIONS

This chapter provides an overview of the climatic, topographic, and soil characteristics of each research site. These site descriptions include: location, topography, climate, soil type, clay mineralogy, annual soil loss, and indices of annual soil loss per unit rainfall. The results of analyses of the physical and chemical soil properties include: particle-size distribution, clay mineralogy, microaggregate bulk density and porosity, aggregate dry crushing strength, effective cation exchange capacities, iron and aluminum oxide contents, total nitrogen and carbon contents, and aggregate dispersibility (aggregate stability). The microstructure characteristics are based on observations of soil thin sections and SEM images of aggregate fracture surfaces. Microstructural behaviour observations are based on the method described in Chapter 3. Figure 3-1 exhibits the site locations within Southeast Asia.

The delineation of aggregate-size varies within the literature. To maintain consistency in this analysis, an aggregate is based on the arrangement of increasingly-sized conglomerations of soil particles forming discrete units. The smallest units, domains ($< 1 \text{ mm } \varnothing$), adhere to one another forming larger groupings. These groupings, termed microaggregates ($1 \text{ to } 2 \text{ mm } \varnothing$), form larger groupings termed aggregates ($> 2 \text{ mm } \varnothing$).

The stability of an aggregate is typically dependent on the stability of its composite matrix of smaller units, their inherent stability, and cohesion. Microaggregates often have greater stability than the larger units of which they are part. Their optimal size and weight suggest that microaggregate detachment from aggregates and their entrainment by water require less force from erosive agents than

larger aggregates. Observing the microstructural behaviour of a soil when it is subjected to erosive conditions may be relevant in the erosion process of some soils. This scale of analysis is analogous to studying the stress behaviour of construction material in regards to the structural stability. In this context, microaggregate stability may be a useful guideline for the structural stability and erodibility of a soil.

The research sites are grouped based upon observed similarities in microstructural behaviour. Three clusters of sites are observed: sites having microstructures with stable microaggregates composed of stable domains; sites having unstable microaggregates composed of stable domains; and sites having unstable microaggregates composed of unstable domains. The relationship between these microstructural behaviours and erosion rates is discussed in the following chapter.

4.1 STABLE MICROAGGREGATES AND STABLE DOMAINS

These sites have similar microstructures composed of stable microaggregates which, in turn, are conglomerates of stable sub-units (i.e. domains). The stable domains, typically high in clay content and stable when saturated, form secondary groupings of highly cohesive microaggregates, which in turn, comprise the aggregates. The stability of microaggregates at these sites is believed to result from the cohesion between domains and the inherent stability of individual domains. The sites possessing these characteristics include: Chiang Rai, Thailand; Vientiane, Laos; and Kuala Dal, Malaysia.

4.1.1 Chiang Rai, Thailand

The Chiang Rai site was established as a research site in 1989. It is located in the mountainous area of northern Thailand on convex slopes ranging between 16-59%. The geology consists of granite, granodiorite, and porphyry rock base. The soil is classified as a Ustic Kandihumult. The climate is classified as a tropical savannah, with annual wet and dry seasons and an annual precipitation of approximately 1800 mm (Attaviroj, 1996).

The annual soil losses at this site averaged $313.28 \text{ t ha}^{-1}\text{yr}^{-1}$ in the bare plot, $187.20 \text{ t ha}^{-1}\text{yr}^{-1}$ in the farmer practice, and $26.13 \text{ t ha}^{-1}\text{yr}^{-1}$ in the alley cropping conservation practice. The annual soil loss per unit rainfall ratios ranged from 0.18 to $0.015 \text{ t ha}^{-1}\text{mm}^{-1}$. X-ray diffraction results confirm that the clay fraction is abundant in kaolinite and quartz, containing smaller amounts of illite. Experimental data on soil properties are presented in Table 4-1.

4.1.1.1 Physical Properties

Microaggregate bulk density is low to moderate, ranges from 0.90 to 1.15 g cm^{-3} , with CR-BP and CR-FP having denser microaggregates than CR-DA and CR-DB. Porosity is high in all plots, ranging from 57% to 66%, with CR-DA and CR-DB having more porous microaggregates. The soil is classified as clay with texture high in both clay ($\bar{x}$ 42%) and sand ($\bar{x}$ 37%).

Aggregate dry crushing strength is moderate ($\bar{x}$ 28156:1), greater on the bare plot (from which the A-horizon had been largely eroded) than on the cultivated plots. The plots have a wide range of average aggregate dispersibility results, ranging from 0.25 to 0.82 consisting of stable microaggregates less than 1 mm in size. The CR-DA

samples consistently contain the highest proportion of stable (<1 mm $\varnothing$) microaggregates (0.80), possibly due to accumulation of material eroded from upslope.

Table 4-1: Chiang Rai - Soil Properties (1997)

Property\Plot	BP	FP	DA	DB	Mean
Soil Loss Per Unit Rainfall (t ha ⁻¹ mm ⁻¹)	0.17919	0.10707	0.01495	0.01495	0.07819
Microaggregate Bulk Density (gcm ⁻³)	1.00	1.15	0.98	0.90	1.00
Microaggregate Porosity (% volume)	62.14	56.62	62.89	65.95	61.90
Microaggregate Dry Strength (g g ⁻¹)	42794	24296	28323	24592	28155.7
% Clay	44	45	40	37	41.57
% Silt	22	21	22	22	21.55
% Sand	34	34	38	42	36.88
Soil pH	4.05	3.86	3.94	4.10	3.99
Fe Oxide Content (% mass)	5.49	6.12	4.90	5.95	5.61
Al Oxide Content (% mass)	2.77	2.62	2.32	2.49	2.55
Oxide Content (% mass)	8.26	8.73	7.22	8.44	8.16
Exch. Ca (meq/100 g)	1.81	0.76	0.83	1.05	1.11
Exch. Mg (meq/100 g)	0.48	0.45	0.42	0.80	0.54
Exch. K (meq/100 g)	1.37	1.96	2.63	3.46	2.35
ECEC (meq/100 g)	3.66	3.18	3.88	5.31	4.01
Total C Content (% mass)	1.26	0.89	1.63	1.91	1.42
Total N Content (% mass)	0.09	0.06	0.12	0.14	0.10
Aggregate Dispersion (40J/ml)	0.59	0.51	0.77	0.57	0.61
Aggregate Dispersion (60 J/ml)	0.70	0.47	0.82	0.53	0.63
Aggregate Dispersion (100 J/ml)	0.62	0.52	0.80	0.25	0.54
Avg. Aggregate Dispersion	0.63	0.50	0.80	0.45	0.60

4.1.1.2 Chemical Properties

The ECEC of the soil is low ($\bar{x}$ 4.01 meq/100g). Potassium dominates the exchange complex, followed by Ca⁺², and Mg⁺². Soil pH is strongly acid ($\bar{x}$ 3.99), with very little variation between practices.

Oxide contents are relatively high (Fe₂O₃ $\bar{x}$ 5.61%; Al₂O₃ $\bar{x}$ 2.55%). Both Fe₂O₃ and Al₂O₃ contents exhibit little variability among plots. The total C ($\bar{x}$ 1.43%) and N ($\bar{x}$ 0.10%) contents are slightly below the average of all sites. CR-FP samples display the lowest N content (0.06%) while the samples from the conservation practice (CR-DA and CR-DB) display the highest N contents (0.12% and 0.14% respectively). Samples

CR-DA and CR-DB display the highest C percentages (1.63% and 1.91% respectively) while CR-FP display the lowest value (0.89%).

4.1.1.3 Microstructure

Plate 4-1 displays scanning electron (SEM) images of fractured surfaces of aggregates and scanned images of thin sections from FP, DA, and DB plot locations.

Note: dark lines in the CR-FP and CR-DA thin section images are cracks in the petrograph slide caused during the polishing procedure. Microaggregates are identified by (A) and pores identified by (B).

Farmer Practice: CR-FP has a moderate to strongly developed, fine crumb microstructure with porous, rough-surfaced microaggregates (A) partially accommodated by randomly distributed, compound packing meso-voids and irregular macro-vughs (B). Inter-aggregate voids comprise 25% of the total area. Intra-aggregate voids consist of randomly distributed, irregular meso-vughs due to the re-packing of microaggregates and domains composing aggregates. The microaggregates have a clayey groundmass with 20% sand content (by volume).

Conservation Practice: CR-DA has a moderately developed, very fine sub-angular blocky microstructure (A). Microaggregates are rough-surfaced and partially accommodated by randomly distributed macro-vughs and/or incomplete irregular curved planar meso-voids caused by slight fracturing between microaggregates (B). Inter-aggregate voids comprise 15% of the total area. Intra-aggregate voids consist of randomly distributed, irregular meso-vughs due to the re-packing of microaggregates and domains composing aggregates. The microaggregates have a dense, clayey groundmass, with 10% sand content (by volume).

Plate 4-1: Chiang Rai, Thailand – SEM Images of Aggregate Fracture Surfaces and Scanned Images of Soil Thin Sections

CR-DB has a moderately developed, fine sub-angular microstructure (A), partially accommodated by randomly distributed macro-vughs, short, irregular curved planar macro-voids, and compound packing macro-voids (B). Inter-aggregate voids comprise 20% of the total area. Intra-aggregate voids consist of randomly distributed, irregular meso-vughs. The microaggregates are larger than CR-DA with a dense, clayey groundmass and higher sand contents (15% by volume).

4.1.1.4 Microstructural Behaviour

Farmer Practice: The aggregates of CR-FP are porous and fairly stable when saturated. When disturbed, they break down into stable sand-sized microaggregates (approximately 1 mm Ø). Microaggregates are composed of linked discrete domains which remain cohesive unless disturbed. When the domains are manually separated, the clay from the domains does not disperse, even after agitation in water.

Conservation Practice: The aggregates of CR-DA have a porous crumb structure which is fairly stable when saturated. When disturbed, the conglomerated aggregates break into sand-sized, crumb-shaped microaggregates which remain stable in saturation. Microaggregates are composed of linked discrete domains which seem to remain cohesive unless disturbed. When the domains are manually separated, the clay from the domains does not disperse, even after agitation in water.

When saturated and then disturbed, the porous aggregates of CR-DB break down to fairly stable crumb-shaped microaggregates composed of linked domains which seem to remain cohesive unless disturbed. When the domains are manually separated, the clay from the domains does not disperse, even after agitation in water.

4.1.1.5 Synthesis

Chiang Rai is located on very steep, convex slopes which can accentuate the erosivity of the high intensity rainfall events. The increased runoff velocity and energy of overland flow increases the erosivity, creating conditions conducive to rill flow and development.

The aggregate dispersibility test results indicate that the breakdown material consists largely of microaggregates less than 1 mm in size. The aggregate dry crushing strength results indicate moderate cohesive strength between stable microaggregates, except for CR-BP where aggregate dry crushing strength is high. Iron oxide contents of 4.9 to 6.1% are within the range that Romkens (1977) found to positively influence aggregate stability. The mineralogy, consisting of kaolinite (1:1) and illite (2:1), does not produce expansion upon saturation, minimizing the shrinkage effect of drying. In strongly acid conditions, the negatively-charged clay particles attracting to positively-charged iron oxides provide microaggregates and domains with cohesive strength.

The high intra-aggregate porosity within the crumb and sub-angular blocky microstructure suggests that microaggregates are conglomerated units of domains. The potential breakdown of aggregates to microaggregates is a two stage process of raindrop impact disrupting aggregates; and water infiltrating the macro- and micro-pores, reducing cohesive strength between aggregates and microaggregates. The high microaggregate clay and oxide contents facilitate the cohesive strength between stable domains, allowing saturated microaggregates to remain intact during an erosive event, although microaggregate disruption can result from severe erosive forces.

4.1.2 Vientiane, Laos

Established in 1995, this site is relatively new. It is located in the low hills of the Vientiane province of Laos, at an elevation of 250 masl. The uniform slopes range from 30% to 35%. The geology consists of red sandstone. The soil is classified as a Typic Haplustult. The climate is classified as wet/dry monsoon, with annual precipitation of 2000 mm (Phommasack et al., 1996).

Annual soil losses at this site are: 54.19 t ha⁻¹yr⁻¹ in the bare plot, 47.57 t ha⁻¹yr⁻¹ in the farmer practice, and 42.56 t ha⁻¹yr⁻¹ in the alley cropping conservation practice. Soil loss per unit rainfall ranged from 0.027 to 0.021 t ha⁻¹mm⁻¹. The clay fraction (< 2 µm Ø) consists of illitic and vermiculitic 2:1 mineralogy, which was confirmed by X-ray diffraction. Experimental data on soil properties are presented in Table 4-2.

Table 4-2: Vientiane, Laos - Soil Properties (1997)

Property\Plot	BP	FP	DA	DB	Mean
Soil Loss Per Unit Rainfall (t ha ⁻¹ mm ⁻¹)	0.02710	0.02379	0.02128	0.02128	0.02405
Microaggregate Bulk Density (gcm ⁻³)	1.25	1.31	1.24	1.35	1.29
Microaggregate Porosity (% volume)	53.01	50.52	53.29	48.94	51.44
Microaggregate Dry Strength (g g ⁻¹)	39226	38410	21266	32951	32949
% Clay	41	47	40	45	43.34
% Silt	33	36	34	31	33.41
% Sand	26	17	26	24	23.25
Soil pH	3.53	3.79	4.06	3.81	3.80
Fe Oxide Content (% mass)	2.07	1.95	2.12	1.81	1.99
Al Oxide Content (% mass)	1.34	1.29	1.32	1.41	1.34
Oxide Content (% mass)	3.41	3.23	3.44	3.21	3.32
Exch. Ca (meq/100 g)	4.20	2.17	1.52	1.84	2.43
Exch. Mg (meq/100 g)	1.49	1.06	1.13	1.19	1.22
Exch. K (meq/100 g)	2.45	2.35	2.76	3.86	2.85
ECEC (meq/100 g)	8.14	5.58	5.41	6.88	6.51
Total C Content (% mass)	1.57	1.41	1.63	1.48	1.52
Total N Content (% mass)	0.13	0.13	0.13	0.13	0.13
Aggregate Dispersion (40J/ml)	0.49	0.27	0.32	0.40	0.37
Aggregate Dispersion (60 J/ml)	0.53	0.30	0.27	0.32	0.35
Aggregate Dispersion (100 J/ml)	0.68	0.26	0.36	0.38	0.42
Avg. Aggregate Dispersion	0.57	0.28	0.32	0.37	0.38

4.1.2.1 Physical Properties

Microaggregate bulk density and porosity are moderate, displaying little variability ($\bar{x}$ 1.29 gcm⁻³ and $\bar{x}$ 51.44%, respectively). Soil texture is classified as clay, with low sand contents ($\bar{x}$ 23%) and high silt contents ($\bar{x}$ 33%). The moderate aggregate dry crushing strength ($\bar{x}$ 32949:1) is consistent with the high clay content ($\bar{x}$ 43%).

The soil displays low percentages of stable microaggregates less than 1 mm in size ($\bar{x}$ 0.38). The bare plot consistently displays the highest percentage of stable microaggregates less than 1 mm (0.57) while L-FP displays the lowest (0.28). In the Conservation Practice plot, L-DA consistently displays lower percentages than L-DB (0.32 and 0.37, respectively).

4.1.2.2 Chemical Properties

The ECEC is relatively low ($\bar{x}$ 6.51 meq/100g), with K⁺ the most abundant ($\bar{x}$ 2.85 meq/100g), followed by Ca⁺² ($\bar{x}$ 1.22 meq/100g), and Mg⁺² ($\bar{x}$ 1.22 meq/100g). Soil pH is strongly acid ($\bar{x}$ 3.8), with little variability between plots.

Oxide contents are relatively low (Fe₂O₃ $\bar{x}$ 1.99%; Al₂O₃ $\bar{x}$ 1.34%) with little variability between plots. Total N content ($\bar{x}$ 0.13%) is close to average for these sites, with negligible variation between plots. Total C content ($\bar{x}$ 1.57%) is above average for these sites.

4.1.2.3 Microstructure

Plate 4-2 displays SEM images of fractured surfaces of aggregates and scanned images of thin sections from FP, DA, and DB plot locations. **Note:** dark lines in the L-FP thin section images is a crack in the petrograph slide caused during the polishing procedure. Microaggregates are identified by (A); pores identified by (B); and infillings identified by (C).

Farmer Practice: L-FP has a moderately developed, very fine sub-angular blocky microstructure (A), partially accommodated by irregular planar macro-voids, macro-channels, and macro-vughs (B). Inter-aggregate voids comprise 30% of the total area. Loose continuous infillings of ultra-fine crumbs, possibly caused by agitation of the original structure, occur frequently within the inter-aggregate voids (C). Intra-aggregate voids consist of few randomly distributed meso-vughs.

Conservation Practice: L-DA has a moderately developed, fine sub-angular blocky microstructure (A) unaccommodated by irregular planar meso- and macro-voids (B). Inter-aggregate voids comprise 30% of the total area. Loose continuous infillings of fine granular peds frequently occur in macro-channels throughout the sample (C). Intra-aggregate voids consist of randomly distributed meso-vughs.

L-DB has a moderately developed, very fine to fine sub-angular blocky microstructure (A) partially accommodated by irregular planar meso- and macro-voids, connected macro-vughs, and macro-channels (B). Inter-aggregate voids comprise 15% of the total area. Loose continuous infillings of very fine crumbs occur in the inter-aggregate voids (C). Intra-aggregate voids consist of randomly distributed meso-vughs.

Plate 4-2: Vientiane, Laos – SEM Images of Aggregate Fracture Surfaces and Scanned Images of Soil Thin Sections

4.1.2.4 Microstructural Behaviour

Farmer Practice: Aggregates in L-FP are stable and very hard when dry. Water enters aggregates through both the macro-pores (between microaggregates) and through micro-pores (within microaggregates). No slaking was observed but when strongly disturbed the saturated aggregates break into stable angular blocky microaggregates. When sufficient force is applied to fracture the microaggregates, the resulting breakdown material consists of stable domains. The force required to fracture the microaggregates would generally exceed that produced by raindrop impact or overland flow.

Conservation Practice: Saturated aggregates from L-DA are stable. Water enters aggregates through both the macro-pores (between microaggregates) and through micro-pores (within microaggregates). Upon physical disturbance, slaking was not observed; rather, aggregates separate as water saturates fracture cracks (macro-pores) where roots have penetrated into the aggregate, creating stable angular blocky microaggregates and some domains. The microaggregates remain stable when saturated. The domains are relatively stable, tending not to slake or disperse. No differences were observed between pit locations in the conservation practice as L-DB behaves in a similar manner to L-DA.

4.1.2.5 Synthesis

The erodibility of the Laos site is fairly low considering the high amount of rainfall it experiences. Little variability in soil loss between plots is most likely due to the site's recent establishment two years prior to the field work being undertaken. The relative uniformity of slope gradient among plots suggests that slope has little effect upon soil loss variation.

The low to moderate aggregate dispersibility indicates that the microstructure largely consists of stable microaggregates ($> 1 \text{ mm } \varnothing$). The moderate aggregate dry crushing strength indicates that the microaggregates are fairly resistant to the disruptive, erosive forces. Iron oxides contents are within the range found by Romkens et al. (1977) to correlate with good aggregate stability. The high clay content, consisting of illite and vermiculite, should contribute to microaggregate stability by providing cohesive strength.

The porous, sub-angular blocky microstructure and the occurrence of loose continuous infillings, consisting of ultra-fine crumbs, suggests that the microstructure can collapse when subjected to erosive forces. The most probable cause of microaggregate collapse is their high permeability. The high silt content found in the microaggregates (mean 33%) increases their permeability by providing continuous pore space large enough for water to infiltrate the pores, saturate the microaggregate, and decrease the inter-particle and inter-domain cohesive strength.

The silty texture of the sub-angular fracture surfaces of the microaggregate and the ease of separation when saturated indicate that fracturing occurs between silt-sized particles. The SEM analysis, which revealed a random orientation of particles on fracture surfaces, confirms this hypothesis.

4.1.3 Kuala Dal, Malaysia

This site, established in 1992, is located in the mountainous area of Kuala Kangsar district, Perak, Malaysia on 16% slopes. The soil is classified as a Xanthic Hapludox, developed on shale. Rubber is the major crop grown. The annual precipitation averages about 1987 mm (Eusof et al., 1996).

Annual soil losses at this site range from $12.59 \text{ t ha}^{-1}\text{yr}^{-1}$ in the bare plot, $0.44 \text{ t ha}^{-1}\text{yr}^{-1}$ in the farmer practice, and $1.24 \text{ t ha}^{-1}\text{yr}^{-1}$ in the alley cropping conservation practice. Annual soil loss per unit rainfall range from 0.00997 to $0.00035 \text{ t ha}^{-1}\text{mm}^{-1}$. The clay mineralogy is dominantly kaolinite, confirmed by X-ray diffraction. Experimental data on soil properties are presented in Table 4-3.

Table 4-3: Kuala Dal, Malaysia - Soil Properties (1997)

Property\Plot	BP	FP	DA	DB	Mean
Soil Loss Per Unit Rainfall ($\text{t ha}^{-1}\text{mm}^{-1}$)	0.00997	0.00035	0.00098	0.00098	0.00377
Microaggregate Bulk Density (gcm^{-3})	1.35	1.23	1.27	1.16	1.25
Microaggregate Porosity (% volume)	49.22	53.43	52.08	56.39	52.78
Microaggregate Dry Strength (g g^{-1})	38797	29956	25393	29190	29034
% Clay	46	57	54	62	54.90
% Silt	18	21	19	15	18.10
% Sand	36	22	27	23	27.00
Soil pH	3.65	3.42	3.94	3.75	3.69
Fe Oxide Content (% mass)	3.66	3.95	3.59	4.08	3.82
Al Oxide Content (% mass)	1.85	1.89	1.76	2.04	1.89
Oxide Content (% mass)	5.50	5.84	5.35	6.13	5.71
Exch. Ca (meq/100 g)	0.54	0.40	1.22	0.48	0.66
Exch. Mg (meq/100 g)	0.20	0.22	0.22	0.30	0.23
Exch. K (meq/100 g)	0.95	1.06	1.14	0.88	1.01
ECEC (meq/100 g)	1.69	1.69	2.59	1.66	1.91
Total C Content (% mass)	1.49	1.78	1.35	1.10	1.43
Total N Content (% mass)	0.11	0.15	0.12	0.09	0.12
Aggregate Dispersion (40J/ml)	0.23	0.30	0.35	0.57	0.36
Aggregate Dispersion (60 J/ml)	0.37	0.30	0.47	0.52	0.42
Aggregate Dispersion (100 J/ml)	0.30	0.38	0.47	0.58	0.43
Avg. Aggregate Dispersion	0.30	0.33	0.43	0.56	0.40

4.1.3.1 Physical Properties

Microaggregate bulk density ($\bar{x}$ 1.25 gcm⁻³) is moderate to high, dense in M-BP (1.35 gcm⁻³) and porous in M-DB (1.16 gcm⁻³). Microaggregate porosity is moderate and ranges from 49% to 56%. The texture is classified as clay. The sand content is the most variable (22% to 36%, $\bar{x}$ 27%) with BP containing the most (36%). Clay is also very high ($\bar{x}$ 55%), with the lowest amounts in M-BP (46%).

Aggregate dry crushing strength ($\bar{x}$ 29034:1) is moderate, but the aggregates of M-BP (38797:1) are substantially stronger than the others. When subjected to ultrasonic dispersion, the site consistently displays moderate to low percentages of stable microaggregates less than 1 mm in size ($\bar{x}$ 0.40).

4.1.3.2 Chemical Properties

The ECEC of this soil is low ($\bar{x}$ 1.91 meq/100g). M-DA contained the highest ECEC (2.59 meq/100g) while all other plots display low ECECs (1.66-1.69 meq/100g). Potassium was measured the highest ($\bar{x}$ 1.01 meq/100g) followed by Ca⁺² ($\bar{x}$ 0.66 meq/100g) and Mg⁺² ($\bar{x}$ 0.23 meq/100g). Soil pH is strongly acid ($\bar{x}$ 3.69) with very little variability between sites. Oxide contents are moderate (Fe₂O₃ $\bar{x}$ 3.82%; Al₂O₃ $\bar{x}$ 1.89%). Both total N and C contents are average (0.12% and 1.43%, respectively).

4.1.3.3 Microstructure

Plate 4-3 displays SEM images of fractured surfaces of aggregates and scanned images of thin sections from FP, DA, and DB plot locations. Microaggregates are identified by (A); pores identified by (B); and infillings identified by (C).

Plate 4-3: Kuala Dal, Malaysia – SEM Images of Aggregate Fracture Surfaces and Scanned Images of Soil Thin Sections

Farmer Practice: M-FP has a weakly developed, fine angular blocky microstructure (A) partially accommodated by incomplete planar cracking macro-voids which initiate aggregate formation (B). The very fine angular blocky microaggregates forming along the fracture cracks between aggregates are unaccommodated by irregular compound packing macro-voids. Loose continuous infillings of clayey domains (C) occur in meso-vughs and channel voids. Inter-aggregate voids comprise 5% of the total area.

Conservation Practice: M-DA has a moderately developed, fine crumb microstructure (A) with unaccommodating, interconnected macro-vughs and compound packing macro-voids (B). Loose discontinuous infillings of very fine crumbs (possibly translocated) occur along the microaggregate surfaces (C). Inter-aggregate macro-channels comprise 35% of the total area, causing a porous structure. Intra-aggregate voids consist of meso-channels and meso-vughs.

M-DB has a weakly developed, very fine angular blocky microstructure (A) with accommodating incomplete planar meso-voids and channels (1-2 mm) (B). Angular blocky microaggregate formation can be observed along the larger cracks (C). Inter-aggregate voids comprise 10% of the total area. Intra-aggregate voids consist of meso-channels and meso-vughs.

4.1.3.4 Microstructural Behaviour

Samples from all the Malaysian plots seem to break down in a similar manner. Fracturing possibly occurs along brittle fracture planes caused by root penetration and desiccation. Moisture is rapidly absorbed into the aggregates through both macro- and micro-pores. M-FP has strong aggregates which naturally fracture into stable angular-blocky microaggregates along brittle failure planes most likely caused by wetting and

drying cycles. This indicates that microaggregates are strongly welded together. No slaking was observed during the breakdown process, indicating the water-stability of the microaggregates.

M-DA has strong aggregates which break down to stable angular blocky microaggregates. Water infiltration into macro-pores creates major failure planes by reducing cohesive strength within the aggregates. The microaggregates are composed of stable domains (clay with some sand) which are observed after strong disturbance.

M-DB has a similar microstructural behaviour as M-DA. When saturated, microaggregates separate along brittle fracture planes. The microaggregates will consequently break down to stable angular blocky domains in a similar manner when some strong, disruptive force is applied.

4.1.3.5 Synthesis

Malaysia is unique among the study sites, in that it has a constant canopy cover of rubber trees. This cover significantly reduces the amount of direct raindrop impact, allowing only throughfall and stem flow to occur, thereby effectively reducing the climatic erosivity.

The low to moderate aggregate dispersibility results and moderate to low aggregate dry crushing strength results indicate that the breakdown material consists of microaggregates mostly greater than 1 mm in size. Fine-textured kaolinite clay and moderate oxide contents may play an influential role in microaggregate water-stability.

The angular blocky microstructures of M-FP and M-DA indicate that fracturing occurs along weak failure planes caused by fracturing due to wetting and drying cycles and root penetration. As water enters inter-aggregate pores, stable microaggregates with high clay contents and low to moderate silt contents, fracture along brittle failure

planes. Microaggregates are groupings of massive domains, well accommodated to one another, and when densely-packed form microaggregates with high micro-pore volume. With a water-repellent nature, the microaggregates remain very stable in saturated conditions. With greater erosive forces, the microaggregates will disrupt into stable angular blocky domains. This phenomenon is exemplified by the infillings observed in the thin sections.

4.2 UNSTABLE MICROAGGREGATES AND STABLE DOMAINS

The sites in this cluster have common microstructures, composed of unstable microaggregates which are conglomerates of stable domains. The stable domains, often high in clay content, lack cohesion between themselves, thereby causing the microaggregates to be unstable. The domains are highly stable, tending not to disperse. The sites possessing these characteristics include: Hoa Son, Vietnam; and Chiang Mai, Thailand.

4.2.1 Hoa Son, Vietnam

The Hoa Son site, established in 1992, is located near Hanoi in the northern uplands of Hoa Binh province of Vietnam. The topography is undulating hills and the site is situated on 30% slopes. The geology consists of schist and old alluvium. The soil is classified as a typic Paleustult. The climate of this site is classified as humid tropical, with the influence of cold winds and an annual precipitation of 1800 mm (Phien, 1996).

Annual soil losses at this site are: $43.94 \text{ t ha}^{-1}\text{yr}^{-1}$ in the bare plot, $25.29 \text{ t ha}^{-1}\text{yr}^{-1}$ in the farmer practice, and $4.87 \text{ t ha}^{-1}\text{yr}^{-1}$ in the alley cropping conservation practice. Soil loss per unit rainfall ranged from 0.036 to $0.00395 \text{ t ha}^{-1}\text{mm}^{-1}$. The clay mineralogy

consists of quartz, kaolinite, and chlorite, as confirmed by X-ray diffraction. Experimental data on soil properties are presented in Table 4-4.

Table 4-4: Hoa Son, Vietnam - Soil Properties (1997)

Property\Plot	BP	FP	DA	DB	Mean
Soil Loss Per Unit Rainfall ($\text{t ha}^{-1} \text{mm}^{-1}$)	0.03564	0.02051	0.00395	0.00395	0.02422
Microaggregate Bulk Density (gcm^{-3})	1.10	0.91	1.01	1.08	1.02
Microaggregate Porosity (% volume)	58.34	65.79	61.96	59.25	61.33
Microaggregate Dry Strength (g g^{-1})	26395	26664	31668	30504	30688
% Clay	48	55	54	57	53.59
% Silt	45	38	39	36	39.41
% Sand	7	7	7	7	7.00
Soil pH	4.18	3.71	4.79	3.80	4.12
Fe Oxide Content (% mass)	7.56	7.57	8.21	8.75	8.02
Al Oxide Content (% mass)	4.74	3.94	4.34	5.30	4.58
Oxide Content (% mass)	12.30	11.51	12.56	14.05	12.60
Exch. Ca (meq/100 g)	2.65	0.84	4.73	1.11	2.33
Exch. Mg (meq/100 g)	0.80	0.35	2.67	0.57	1.10
Exch. K (meq/100 g)	1.62	1.11	1.78	1.10	1.40
ECEC (meq/100 g)	5.07	2.29	9.18	2.78	4.83
Total C Content (% mass)	2.54	1.97	2.47	2.48	2.37
Total N Content (% mass)	0.15	0.12	0.15	0.16	0.15
Aggregate Dispersion (40J/ml)	0.36	0.44	0.41	0.10	0.33
Aggregate Dispersion (60 J/ml)	0.50	0.44	0.55	0.15	0.41
Aggregate Dispersion (100 J/ml)	0.53	0.53	0.53		0.53
Avg. Aggregate Dispersion	0.46	0.47	0.50	0.12	0.39

4.2.1.1 Physical Properties

Microaggregate bulk density is moderate to low ($\bar{x}$ 1.02 g/cm^3). Soil porosity is moderate to high ($\bar{x}$ 61.33%). Variability of both bulk density and porosity is low. The site has a very high clay content ($\bar{x}$ 54%) and a very low sand content ($\bar{x}$ 7%). The soil texture is classified as clay, except V-BP which falls within a silty clay. Although high in clay content, the dry microaggregate strength ($\bar{x}$ 30688:1) is moderate to low. The soil contains a moderate percentage of resistant microaggregates less than 1 mm in size ($\bar{x}$ 0.39), with aggregate dispersibility ranging from 0.10 to 0.55.

4.2.1.2 Chemical Properties

The ECEC is low ($\bar{x}$ 4.83 meq/100g). Calcium is the most abundant ($\bar{x}$ 2.33 meq/100g) of the cations measured, followed by K^+ ($\bar{x}$ 1.40 meq/100g), and Mg^{+2} ($\bar{x}$ 1.10 meq/100g). The variability of both Ca^{+2} and Mg^{+2} among plots is most apparent. The pH of the soil is strongly acid ($\bar{x}$ 4.12).

The Fe and Al oxide contents of this soil are relatively high (Fe_2O_3 $\bar{x}$ 8.01%; Al_2O_3 $\bar{x}$ 4.58%). The highest contents of both oxides are found in V-DB. Both total N and C contents are slightly above average ($\bar{x}$ 0.15% and 2.37%, respectively).

4.2.1.3 Microstructure

Plate 4-4 displays SEM images of fractured surfaces of aggregates and scanned images of thin sections from FP, DA, and DB plot locations. Note: linear dark lines in the V-FP thin section images is a crack in the petrograph slide caused during the polishing procedure. Microaggregates are identified by (A); pores identified by (B); and infillings identified by (C).

Farmer Practice: V-FP has a weakly developed, fine sub-angular blocky microstructure (A) with partially accommodating, incomplete planar meso-voids (B). Inter-aggregate voids comprise 10% of the total area. The microaggregates consist of weakly bound, very fine crumbs. Ultra-fine crumbs (or granules) comprise loose continuous infillings within some inter-aggregate voids (C). The upper half of the sample consists of loosely packed, very fine sub-angular blocky peds (1 mm), moderately developed with compound packing macro-voids and incomplete planar meso-voids.

Plate 4-4: Hoa Son, Vietnam – SEM Images of Aggregate Fracture Surfaces and Scanned Images of Soil Thin Sections

Intra-aggregate meso-vughs seem to be caused by drying and cracking around domains and microaggregates.

Conservation Practice: V-DA has a loosely-packed, strongly developed, fine to medium crumb microstructure (A) unaccommodated by an inter-aggregate pattern of compound packing macro-voids and incomplete macro-vughs (B) caused from previous infilling of aggregate breakdown material into the pores. Inter-aggregate voids comprise 20% of the total area. Intra-aggregate voids consist of randomly distributed meso-vughs which indicate tight packing of domains.

V-DB has a relatively massive and weakly developed microstructure (A) with fine angular blocky peds (5-10 mm) cracking in a curved pattern of partially accommodating planar meso- and macro-voids (B). Within some larger cracks and in the upper surface, there are loose discontinuous infillings of strongly developed, very fine sub-angular blocky microaggregates and domains (C), unaccommodated by macro-vughs and compound packing macro-voids. Inter-aggregate voids comprise 10% of the total area. Intra-aggregate voids consist of micro- and meso-vughs.

4.2.1.4 Microstructural Behaviour

Farmer Practice: Water enters the aggregates through both the macro-pores between microaggregates and through the micro-pores within microaggregates. The aggregates of V-FP saturate rapidly and remain stable. With slight disturbance, the aggregates tend to separate along fracture cracks into angular blocky microaggregates. Saturation also causes the microaggregates to lose structural stability, fracturing into very small and stable angular blocky domains (< 1 mm Ø). No slaking was observed indicating clean separations between domains.

Conservation Practice: Water enters aggregates through both the macro-pores between microaggregates and through micro-pores within microaggregates. Saturated aggregates from V-DA and V-DB easily separate into relatively unstable angular blocky microaggregates. The saturated microaggregates easily fracture into relatively stable angular blocky domains. Samples from both V-DA and V-DB did not slake.

4.2.1.5 Synthesis

Low to moderate aggregate dry crushing strength and moderate to low aggregate dispersibility indicate that the structure will easily break down to microaggregates, mostly greater than 1 mm in size. The soil has high clay (kaolinite and chlorite) and oxide contents, which could play important roles in microaggregate stability.

Angular microaggregate fracturing suggests that the texture, high in silt content ($\bar{x}$ 39.4%), may influence microaggregate breakdown by increasing the rate of moisture infiltration and capacity of the microaggregates. Consequently, microaggregate cohesive strength is reduced, facilitating the fracturing of microaggregates to domains. Root penetration observed along fracture planes in microaggregates influences the location and ease of fracturing.

4.2.2 Chiang Mai, Thailand

The Chiang Mai site, established in 1989, is located in the hilly terrain of northern Thailand at an elevation of 700 masl. The slightly concave slopes range from 12-35%. The geology is sedimentary and metamorphic, consisting mainly of limestone and shale. The soil is classified as a Ustic Haplustalf. The climate is classified as a

tropical savannah, with rainy and dry seasons and an annual precipitation of 1400 mm (Boonchee, et al., 1996).

Annual soil losses at this site are: 8.37 t ha⁻¹yr⁻¹ in the bare plot, 1.10 t ha⁻¹yr⁻¹ in the farmer practice, and 0.05 t ha⁻¹yr⁻¹ in the alley cropping conservation practice. Soil loss per unit rainfall ranges from 0.00730 to 0.00005 t ha⁻¹mm⁻¹. The clay fraction contains kaolinite and illite-vermiculite integrated (2:1) mineralogy, confirmed by X-ray diffraction results. Experimental data on soil properties are presented in Table 4-3.

Table 4-5: Chiang Mai – Soil Properties (1997)

Property\Plot	BP	FP	DA	DB	Mean
Soil Loss Per Unit Rainfall (t ha ⁻¹ mm ⁻¹)	0.00730	0.00096		0.00005	0.00238
Microaggregate Bulk Density (gcm ⁻³)	0.87	1.01		1.26	1.05
Microaggregate Porosity (% volume)	67.10	62.06		52.41	60.52
Microaggregate Dry Strength (g g ⁻¹)	4699	24526		21155	21591
% Clay	21	27		35	27.63
% Silt	26	40		38	34.70
% Sand	53	33		27	37.67
Soil pH	4.97	4.65		4.10	4.57
Fe Oxide Content (% mass)	2.72	1.70		2.14	2.19
Al Oxide Content (% mass)	1.07	1.38		1.75	1.40
Oxide Content (% mass)	3.79	3.08		3.89	3.58
Exch. Ca (meq/100 g)	4.35	6.67		3.64	4.89
Exch. Mg (meq/100 g)	2.66	3.70		3.23	3.19
Exch. K (meq/100 g)	3.40	2.66		2.43	2.83
ECEC (meq/100 g)	10.41	13.03		9.30	10.91
Total C Content (% mass)	1.54	2.49		1.96	2.00
Total N Content (% mass)	0.10	0.15		0.15	0.13
Aggregate Dispersion (40J/ml)	0.71	0.61		0.17	0.50
Aggregate Dispersion (60 J/ml)	0.77	0.59		0.16	0.51
Aggregate Dispersion (100 J/ml)	0.65	0.57		0.27	0.50
Avg. Aggregate Dispersion	0.71	0.59		0.20	0.50

4.2.2.1 Physical Properties

Microaggregate bulk density is relatively low for CM-BP and CM-FP (0.87 and 1.01 gcm⁻³, respectively), but is high in CM-DB (1.26 gcm⁻³). Microaggregate porosity is relatively high ($\bar{x}$ 60.52%), except CM-DB which has low porosity (52.41%). Chiang Mai

ranges in soil texture, sandy clay loam (CM-BP), loam (CM-FP), and clay loam (CM-DB). The amount of clay is moderate in all plots ($\bar{x}$ 27.63%). The largest proportion of clay was observed in CM-DB (35%). The bare plot contains the most sand (53%) while CM-DB has the lowest amount (27%). Silt contents are consistently moderate to high ($\bar{x}$ 34.70%)

Aggregate dry crushing strength is low ($\bar{x}$ 21597:1). The bare plot contains very weak microaggregates ($\bar{x}$ 4699:1) having a high sand content, while CM-FP and CM-DB both contain relatively weak microaggregates (24526:1 and 21155:1, respectively). When subjected to ultrasonic dispersion, the plots display a range of resistant aggregate sizes (0.16 to 0.77). On average, the site displays high aggregate dispersibility ($\bar{x}$ 0.50). Resistant aggregate size increases with higher clay contents (CM-DB 35%; CM-BP 21%) and lower sand contents (CM-BP 53%; CM-DB 27%). Ultrasonic duration had little effect on the size of resistant aggregates.

4.2.2.2 Chemical Properties

The ECEC of this soil is moderate ($\bar{x}$ 10.91 meq/100g of soil). Calcium ($\bar{x}$ 4.89 meq/100g) is highest in CM-FP (6.67 meq/100g) and lowest in CM-DB (3.64 meq/100g). Magnesium is lower than calcium ($\bar{x}$ 3.19 meq/100g) having less variability among practices; CM-FP contains the most (3.70 meq/100g). Potassium is least abundant ($\bar{x}$ 2.83 meq/100g) with the bare plot containing the highest levels (3.40 meq/100g) and CM-DB, the lowest (2.43 meq/100g). Soil pH is strongly acid ($\bar{x}$ 4.57).

Oxide contents are moderate (Fe_2O_3 $\bar{x}$ 2.19%; Al_2O_3 $\bar{x}$ 1.40%). Iron oxides are highest in CM-BP (2.73%) and lowest in CM-FP (1.70%). Aluminum oxides are highest

in CM-DB (1.75%) and the lowest in CM-BP (1.07%). The variation among plots is very low for oxides.

Total N contents ($\bar{x}$ 0.13%) are slightly above average. The bare plot displays the lowest value (0.10%), while both CM-FP and CM-DB display above average values (0.15% for both). Total C contents ($\bar{x}$ 2.00%) ranged slightly above average. Farmer practice is highest (2.49%), followed by CM-DB (1.96%) and CM-BP (1.54%).

4.2.2.3 Microstructure

Plate 4-5 displays SEM images of fractured surfaces of aggregates and scanned images of thin sections from FP, DA, and DB plot locations. Microaggregates are identified by (A); pores identified by (B); and infillings identified by (C).

Farmer Practice: CM-FP has a moderately developed, very fine to medium crumb microstructure (A), partially accommodated by curved planar meso- and macro-voids and/or unaccommodating compound packing macro-voids (B). Inter-aggregate voids comprise 10% of the total area. Loose discontinuous infilling consisting of very fine sub-angular blocky microaggregates occur in macro-channels (C). Microaggregates are high in sand and silt. Intra-aggregate pores consist of randomly distributed, irregular meso-vughs.

Conservation Practice: CM-DA has moderately developed, very fine sub-angular blocky microstructure (A) partially accommodated by planar macro- and meso-voids and compound packing macro-voids (B). Frequent macro-channels occur, containing little to no infillings. Inter-aggregate voids comprise 20% of the total area. Intra-aggregate voids are randomly distributed, irregular shaped macro- and meso-vughs. The groundmass is a loamy mixture of clay, silt, sand, and visible organic matter.

Plate 4-5: Chiang Mai, Thailand – SEM Images of Aggregate Fracture Surfaces and Scanned Images of Soil Thin Sections

CM-DB has a strongly developed, very fine sub-angular blocky microstructure (A) with partially accommodating, interconnected planar macro-voids (caused by root penetration) and frequent macro-vughs (B). Within macro-vughs, there are loose-discontinuous infillings of ultra-fine sub-angular blocky microaggregates (C). Inter-aggregate voids comprise 20% of the total area. Intra-aggregate voids consist of meso-vughs. The groundmass is clayey and high in sand content (15% by volume).

4.2.2.4 Microstructural Behaviour

Farmer Practice: As the aggregates from CM-FP are saturated, rapid water infiltration decreases the intra-aggregate cohesive strength, causing aggregates to break down into microaggregates. The unstable microaggregates, in turn, easily break down, with slight teasing, into fairly stable crumb domains high in clay content. The dispersion of coarse particulate material during the agitation process indicates the instability of the microstructure.

Conservation Practice: The water infiltration rate of these samples was rapid, saturating both macro- and micro-pores. Saturated aggregates of CM-DB remain fairly stable unless disturbed, whereupon the aggregates break apart, first into microaggregates then into fairly stable domains. Root penetration into the microaggregates may account for domain stability (i.e. shrinkage and compaction) and microaggregate instability.

4.2.2.5 Synthesis

Aggregate dispersibility indicates that the size of breakdown material ranges among the plots. In CM-BP and CM-FP, the breakdown material consists mostly of material less than 1 mm in size. The breakdown material of CM-DB mostly consists of material greater than 1 mm in size. The low aggregate dry crushing strengths and high

aggregate dispersibility of CM-BP and CM-FP indicate that these soils will easily disperse to finer material ($< 1 \text{ mm } \varnothing$). The low aggregate dispersibility and low microaggregate strength of CM-DB indicates that this soil will mostly break down to microaggregates ($> 1 \text{ mm } \varnothing$) with relative ease. Higher clay contents in CM-DB may improve microaggregate stability.

In most cases, aggregates have low stability when saturated, probably due to high silt and sand contents which increase water infiltration capacities and decrease aggregate cohesive strength and stability. Consequently, the breakdown material consists of unstable microaggregates which lose stability when saturated and are easily broken down to stable domains. Furthermore, root penetration into microaggregates may influence the behaviour of microaggregate fracturing.

4.3 UNSTABLE MICROAGGREGATES AND UNSTABLE DOMAINS

This cluster, including Mabini and Los Baños, Philippines, represents a very different soil from the other study sites. These two sites have little aggregate stability when saturated. When the samples are saturated, they do not break down into microaggregates or domains, but rather the aggregates lose internal cohesive strength and disintegrate to particulate material (i.e. slake).

4.3.1 Mabini, Philippines

The Mabini site, established in 1989, is located in Batangas, Philippines on a hilly land, middle footslope at an elevation of 100 masl. The slope is gradual and relatively long, ranging from 18-25%. The soil is classified as an Ustorthent, a young soil developed from volcanic ash material with recent geomorphologic surfaces

(Paningbatan et al., 1995). The climate is classified as humid tropical with annual precipitation of about 1500 mm (Patingbatan, et al., 1995).

The annual soil losses at this site are: 52 t ha⁻¹yr⁻¹ in the farmer practice, and 0.73 t ha⁻¹yr⁻¹ in the alley cropping conservation practice (soil loss data was not available for the bare plot). Annual soil loss per unit rainfall ranged from 0.035 to 0.0005 t ha⁻¹ mm⁻¹. The mineralogy was unidentifiable by X-ray diffraction due to its volcanic origin and amorphous structure. Experimental data on soil properties are presented in Table 4-6.

Table 4-6: Mabini, Philippines - Soil Properties (1997)

Property\Plot	BP	FP	DA	DB	Mean
Soil Loss Per Unit Rainfall (t ha ⁻¹ mm ⁻¹)		0.0352	0.0005	0.0005	0.02150
Microaggregate Bulk Density (gcm ⁻³)	1.30	1.14	1.12	1.10	1.16
Microaggregate Porosity (% volume)	51.04	57.06	57.66	58.57	56.08
Microaggregate Dry Strength (g g ⁻¹)	31943	34911	40809	26996	33461
% Clay	8	12	14	12	11.57
% Silt	26	38	42	38	35.93
% Sand	66	50	44	50	52.50
Soil pH	5.03	5.10	3.96	3.91	4.50
Fe Oxide Content (% mass)	1.08	1.20	1.42	1.13	1.21
Al Oxide Content (% mass)	0.77	0.85	1.09	0.82	0.88
Oxide Content (% mass)	1.85	2.05	2.52	1.95	2.09
Exch. Ca (meq/100 g)	18.26	18.57	16.25	16.27	17.34
Exch. Mg (meq/100 g)	6.32	5.64	5.82	6.44	6.05
Exch. K (meq/100 g)	5.97	6.02	9.77	10.78	8.13
ECEC (meq/100 g)	30.54	30.23	31.84	33.49	31.52
Total C Content (% mass)	0.18	0.24	0.65	0.87	0.49
Total N Content (% mass)	0.02	0.03	0.07	0.09	0.05
Aggregate Dispersion (40J/ml)		0.12	0.38	0.27	0.26
Aggregate Dispersion (60 J/ml)		0.13	0.34	0.34	0.27
Aggregate Dispersion (100 J/ml)		0.17	0.38	0.28	0.27
Avg. Aggregate Dispersion		0.14	0.36	0.29	0.27

4.3.1.1 Physical Properties

Microaggregate bulk density is moderate to high (1.10 to 1.30 gcm⁻³). The moderate porosity ($\bar{x}$ 56%) corresponds to the bulk density. The percentage of sand is

relatively high ($\bar{x}$ 53%) with P-BP recorded at 66%, while the percentage of clay is relatively low ($\bar{x}$ 12%). The aggregates from P-BP are very low in clay (8%). Soil texture is classified as a loam with the exception of P-BP, which is classified as a sandy loam.

Aggregate dry crushing strength is moderate to low (40809:1 to 26996:1). Samples from P-DA recorded the highest strength (40809:1). Ultrasonic dispersion results are low, ranging from 0.12 to 0.38, indicating a high proportion of resistant microaggregates greater than 1 mm, but the results are exaggerated due to a large portion of particles greater than 1 mm in size.

4.3.1.2 Chemical Properties

The ECEC of this soil is very high ($\bar{x}$ 31.52 meq/100g) with little variability between sites. Calcium is the most abundant ($\bar{x}$ 17.34 meq/100g), followed by K^+ ($\bar{x}$ 8.13 meq/100g), and Mg^{+2} ($\bar{x}$ 6.05 meq/100g). The soil pH is strongly acid ($\bar{x}$ 4.5).

Oxide contents are low (Fe_2O_3 $\bar{x}$ 1.21%; Al_2O_3 $\bar{x}$ 0.88%) compared to other sites. Total N and C contents are low ($\bar{x}$ 0.05% and $\bar{x}$ 0.49%, respectively), with variability between sites. P-BP contains very low amounts of C (0.18%) while in P-DB, there are higher levels (0.87%).

4.3.1.3 Microstructure

Plate 4-6 displays SEM images of fractured surfaces of aggregates and scanned images of thin sections from FP, DA, and DB plot locations. Microaggregates are identified by (A); pores identified by (B); and infillings identified by (C).

Plate 4-6: Mabini, Philippines— SEM Images of Aggregate Fracture Surfaces and Scanned Images of Soil Thin Sections

Farmer Practice: P-FP has a strongly developed, very fine sub-angular blocky microstructure (A) with frequent, randomly-distributed macro-particles occurring throughout the sample. Inter-aggregate voids consist of partially accommodating, continuous planar macro-voids and unaccommodating compound packing macro-voids (B). The voids in the upper surface are filled with loose continuous infillings of ultra-fine crumbs (C). Inter-aggregate voids comprise 25% of the total area.

Conservation Practice: P-DA has a strongly developed, fine to medium crumb microstructure (A), consisting of randomly distributed, crumbs with partially accommodating, continuous compound packing macro-voids (B). Few very large, sub-rounded particles occur within the structure. Loose discontinuous infillings of very fine crumbs occur near the upper surface, within the inter-aggregate voids (C). Inter-aggregate voids comprise 15% of the total area.

P-DB has a strongly developed, very fine sub-angular blocky microstructure (A) partially accommodated by interconnected irregular, planar macro- and meso-voids and macro-vughs (B). Microaggregates are composed of smaller, weakly-bound domains and sand-sized particles. Large particles occur frequently within the structure. Inter-aggregate voids comprise 10% of the total area. The microstructure has a compacted appearance.

4.3.1.4 Microstructural Behaviour

The samples are low in clay content and high in sand and silt. When saturated, aggregates from all plots rapidly absorb water and immediately slake. With this rapid loss of structural stability, the aggregates disintegrate into particulate material and few unstable domains.

4.3.1.5 Synthesis

Moderate aggregate dry crushing strengths and low aggregate dispersibility indicate that the soil breaks down easily to stable material greater than 1 mm in size. These results may be influenced by the high percentage of particles greater than 1 mm in size.

The loosely packed microstructures of P-DB and P-DA, with crumbs infilling inter-aggregate pores, indicate that infiltrating water translocates dispersed fine material into the pores, creating surface crusts. P-FP had little signs of infilling, possibly due to the higher percentage of larger stable microaggregates with different compositions than those from the conservation plot.

The immediate disintegration of aggregates upon saturation indicates that the cohesive strength is significantly reduced when saturated. The low amount of binding agents, including clay, oxides, and carbon, limits the cohesive strength between or within microaggregates. The breakdown material consists of unstable crumb domains and loose particulate material. The instability of microaggregates plays a role in erosion.

4.3.2 Los Baños, Philippines

This site, established in 1992, is located in Los Baños, Laguna, Philippines on slopes ranging from 18 to 20 percent. The soil is classified as an Eutropept, a young soil at beginning of its profile development (Paningbatan et al., 1995). The climate is humid tropical with wet and dry seasons. The annual precipitation is about 1800 mm (Maglinao et al., 1996).

Annual soil losses at this site are: $64.67 \text{ t ha}^{-1}\text{yr}^{-1}$ in the farmer practice, and $8.33 \text{ t ha}^{-1}\text{yr}^{-1}$ in the alley cropping conservation practice. Annual soil loss per unit rainfall ranged from 0.0063 to $0.049 \text{ t ha}^{-1}\text{mm}^{-1}$. Due to the soil's origin from volcanic tuff, the mineralogy is unidentifiable by x-ray diffraction. Experimental data on soil properties are presented in Table 4-7.

Table 4-7: Los Baños, Philippines - Soil Properties (1997)

Property\Plot	BP	FP	DA	DB	Mean
Soil Loss Per Unit Rainfall ($\text{t ha}^{-1}\text{mm}^{-1}$)		0.0486	0.0063	0.0063	0.02776
Microaggregate Bulk Density (gcm^{-3})	1.18	0.89	1.11	0.97	1.05
Microaggregate Porosity (% volume)	55.51	66.32	57.95	63.37	60.79
Microaggregate Dry Strength (g g^{-1})	65816	55452	23484	36933	45381
% Clay	9	11	12	14	11.88
% Silt	44	45	71	62	55.12
% Sand	47	44	17	24	33.00
Soil pH	6.22	6.05	5.76	6.22	6.06
Fe Oxide Content (% mass)	2.40	2.11	2.56	3.05	2.53
Al Oxide Content (% mass)	1.35	1.38	1.48	1.64	1.46
Oxide Content (% mass)	3.75	3.49	4.04	4.69	3.99
Exch. Ca (meq/100 g)	20.70	21.92	17.25	11.75	17.91
Exch. Mg (meq/100 g)	9.26	8.74	6.85	6.32	7.79
Exch. K (meq/100 g)	4.09	4.90	7.51	9.34	6.46
ECEC (meq/100 g)	34.04	35.56	31.62	27.41	32.16
Total C Content (% mass)	0.26	0.49	1.08	1.09	0.73
Total N Content (% mass)	0.03	0.05	0.11	0.18	0.09
Aggregate Dispersion (40J/ml)	0.29	0.65	0.86	0.93	0.68
Aggregate Dispersion (60 J/ml)	0.16	0.61	0.90	0.97	0.66
Aggregate Dispersion (100 J/ml)	0.23	0.60	0.92	0.94	0.67
Avg. Aggregate Dispersion	0.23	0.62	0.89	0.95	0.67

4.3.2.1 Physical Properties

The microaggregate bulk density is moderate to low, ranging from 0.89 to 1.18 gcm^{-3} . Porosity ranges from 66% to 56%. Soil texture in LB-BP and LB-FP are classified as loams, high in sand (47% and 44%, respectively) and LB-DA and LB-DB are classified as silt loams, both high in silt (71% and 62%, respectively). Clay is low in all plots ($\bar{x}$ 12%).

The average aggregate dry crushing strength is moderate ($\bar{x}$ 45381:1) with a substantial range. LB-BP and LB-FP recorded high crushing strengths (65816:1 and 55452:1, respectively). LB-DA recorded a low crushing strength (25393:1). Aggregate dispersibility results are variable, displaying a wide range of resistant microaggregate sizes (0.16 and 0.97). The low values in LB-BP indicate a different structure with higher ultrasonic resistance.

4.3.2.2 Chemical Properties

Similar to the Mabini site, this site has a very high ECEC ($\bar{x}$ 32.16 meq/100g), yet the ECECs of the conservation plot (LB-DA and LB-DB) are relatively lower than both LB-BP and LB-FP. Calcium is most abundant ($\bar{x}$ 17.91 meq/100g), followed by Mg^{+2} ($\bar{x}$ 7.79 meq/100g), and K^{+1} ($\bar{x}$ 6.46 meq/100g). Potassium is most abundant in the conservation practice and Ca^{+2} and Mg^{+2} are more abundant in LB-BP and LB-FP. Soil pH is moderately acid ($\bar{x}$ 6.06) with little variability.

Oxide contents are moderate (Fe_2O_3 $\bar{x}$ 2.53%; Al_2O_3 $\bar{x}$ 1.46) with the highest amounts observed in the conservation plot (LB-DA and LB-DB). Total N and C contents (N $\bar{x}$ 0.09%; C $\bar{x}$ 0.73%) are below average. LB-BP and LB-FP contain very low N and C contents, increasing the variability of this site.

4.3.2.3 Microstructure

Plate 4-7 displays SEM images of fractured surfaces of aggregates and scanned images of thin sections from FP, DA, and DB plot locations. Microaggregates are identified by (A); pores identified by (B); infillings identified by (C); and domains identified by (D).

Plate 4-7: Los Baños, Philippines – SEM Images of Aggregate Fracture Surfaces and Scanned Images of Soil Thin Sections

Farmer Practice: LB-FP has a strong to moderately developed, very fine angular blocky microstructure (A) partially accommodated by interconnected planar macro-voids with slight horizontal orientations (B). Inter-aggregate macro-vughs often occur at the junctions of peds. Inter-aggregate voids comprise 20% of the total area. No infillings were observed.

Conservation Practice: LB-DA consists of moderately developed fine crumb microaggregates (A) composed of conglomerated, very fine crumbs. SEM analysis confirms that the microaggregates are conglomerates of fine domains and particles (D). Aggregate-sized particles occur frequently within the structure. Inter-aggregate voids are partially accommodating irregular macro-vughs, compound packing meso-voids, and incomplete planar cracking meso-voids with slight horizontal orientation (B). Loose continuous infillings of fine crumbs and particles create a surficial crust (C). Inter-aggregate voids comprise 10% of the total area.

LB-DB has a moderately developed, very fine sub-angular blocky microstructure (A) consisting of loosely-packed conglomerates of domains and particles. Microaggregates are partially accommodated by irregular planar cracking macro-voids and interconnected macro-vughs (B) with loose continuous infillings of very fine crumbs (C). Inter-aggregate voids comprise 20% of the total area.

4.3.2.4 Microstructural Behaviour

Similar to Mabini, aggregates from all plots immediately slake upon saturation, lose structural stability, and disintegrate into particulate material consisting of unstable crumb domains and loose particulate material. Aggregates, low in clay content and high in sand and silt, have very low intra-aggregate cohesive strength, providing little resistance to dispersion.

4.3.2.5 Synthesis

Moderate to high aggregate dispersibility, except in LB-BP which is highly stable, and moderate to low aggregate dry crushing strength indicate that aggregates break down mostly to material greater than 1 mm in size when dispersed. These results are influenced by the high percentage of particles greater than 1 mm in size. The actual material remaining after dispersion is unstable and less than 1 mm in size. The microstructure consists of loosely packed conglomerates of unstable domains and particles which can easily be dispersed. Large inter-aggregate pores yield a high moisture infiltration capacity, which facilitates the attaining of high moisture contents during intense rainfalls.

The immediate slaking upon saturation confirms that microaggregate stability is very low. The low cohesive strength between or within microaggregates is consistent with the low amounts of potential binding agents including clay, oxides, and carbon. The breakdown material consists of unstable crumb domains and loose particulate material. Infilling of pores is common in LB-DA and LB-DB, indicating the occurrence of surface crusting.

4.4 SYNTHESIS OF EXPERIMENTAL ANALYSIS

From the site descriptions of soil properties and microstructural behaviours, it becomes clear that, while specific sites share some properties in common, each site has its own unique set of properties. Some of the similarities between specific sites provide insight into the properties influencing their microstructural behaviours. In particular, the sites cluster into three groupings based on similarities in their microstructural behaviours: sites with stable microaggregates composed of stable domains (Chiang Rai, Thailand; Vientiane, Laos; and Kuala Dal, Malaysia); sites with

unstable microaggregates composed of stable domains (Chiang Mai, Thailand; and Hoa Son, Vietnam); and sites with unstable microaggregates and unstable domains (Mabini and Los Baños, Philippines).

The following is a synthesis of the general similarities and differences in site characteristics, soil properties, and microstructural behaviours within each of these three clusters. These include soil characteristics such as: physical and chemical properties; microstructure type; microstructural behaviour; microaggregate fracturing; moisture infiltration; and infilling patterns. Site characteristics include: soil type; rainfall amount; slope; and vegetation.

4.4.1 Stable Microaggregates and Stable Domains

These sites have strongly acid soils with high clay contents and moderate silt contents. The low-activity clay soils have low ECECs and moderate N and C contents. Physically, they possess moderate aggregate dry crushing strengths (Table 4-8).

Chiang Rai has steeply-inclined convex slopes which allow high runoff velocities. This site experiences high soil loss per unit rainfall, possessing soils with moderate aggregate dispersibility indices (aggregates break down to smaller microaggregates). In Laos, the slope is moderately-inclined and uniform which also allows high runoff velocities. Laos experiences moderate soil erosion loss per unit rainfall with soils having low aggregate dispersibility indices (aggregates break down to microaggregates mostly greater than 1 mm in size). Well-protected from the effects of raindrop impact, Malaysia's canopied soil, situated on a gentle slope, experiences low amounts of soil erosion loss per unit rainfall. The soils from Malaysia, like Laos, had low aggregate dispersibility indices.

Table 4-8: Comparison of Properties (Chiang Rai; Laos; and Malaysia)

SOIL LOSS			
Property	Chiang Rai	Laos	Malaysia
Soil Loss per Unit Rainfall	H	M	L
SIMILARITIES AMONG SITES			
Property	Chiang Rai	Laos	Malaysia
Soil pH	Strongly Acid	Strongly Acid	Strongly Acid
N and C contents	M	M	M
ECEC	L	L	L
Crushing Strength	M	M	M
Carbon Contents	M	M	M
Clay Contents	H	H	H
Silt Contents	M	M	M
Sand Contents	M	M	M
Clay Contents	H	H	H
DIFFERENCES AMONG SITES			
Property	Chiang Rai	Laos	Malaysia
Aggregate Dispersibility	M	L	L
Bulk Density	L	M	M
Porosity	H	L	L
Oxides	H	L	M

*(L = low; M = moderate; H = high)

The soils from Laos and Malaysia, composed of microaggregates with high bulk densities and low porosity, possess low aggregate dispersibility indices. Their oxide contents are high to moderate. Chiang Rai's microaggregates are smaller with low bulk densities, high porosity, and high oxide contents. Moderate aggregate dispersibility and moderate crushing strength contribute to increased susceptibility of Chiang Rai's microaggregates to erosive forces; and their low bulk density is suitable for transport.

4.4.2 Unstable Microaggregates and Stable Domains

These sites have very different compositions (Table 4-9). Generally, the soils are strongly acid, both with moderate to high porosity, and high C contents. The aggregates at these two sites, Vietnam and Chiang Mai, are composed of weakly-

linked sub-units (microaggregates). Although the two sites are categorized within the same group, their microstructures vary in behaviour, yielding different erodibility and soil loss.

Table 4-9: Comparison of Properties (Vietnam and Chiang Mai)

SOIL LOSS		
Property	Vietnam	Chiang Mai
Soil Loss per Unit Rainfall	M	L
SIMILARITIES BETWEEN SITES		
Property	Vietnam	Chiang Mai
Soil pH	Strongly Acid	Strongly Acid
Bulk Density	L-M	L-M
Porosity	M-H	M-H
Carbon Contents	H	H
DIFFERENCES BETWEEN SITES		
Property	Vietnam	Chiang Mai
Aggregate Dispersibility	M	H
Crushing Strength	M	L
ECEC	L	M
Oxides Content	H	M
Clay Content	H	M
Silt Content	H	M
Sand Contents	L	H

*(L = low; M = moderate; H = high)

The well-fractured and highly porous aggregates of Chiang Mai with low bulk densities, high sand, and moderate silt contents, allow water to enter along large fracture cracks. A low aggregate dry crushing strength indicates that the strength among microaggregate linkages is low, creating unstable microaggregates, which easily break down into weakly-bonded domains. The microstructural behaviour at Chiang Mai is more closely related to the *unstable microaggregates/unstable domains* category, due to the ease of aggregate separation and the low-stability of its microaggregates.

Microaggregates from Vietnam are very stable. They have moderate to low bulk density and have more uniform textures, high in clay and silt. When the aggregates are wetted, the rapid saturation of the microaggregates occurs due to the infiltration of water. Saturation causes their cohesive strength to decrease and the microaggregates become easily separable into angular blocky domains of relatively high stability, as indicated by the moderate aggregate dispersibility results. The Vietnam soil has many similarities to the *stable microaggregates/stable domains* category, except that its microaggregates are less stable when saturated.

4.4.3 Unstable Microaggregates and Unstable Domains

These soils, from the Philippines, are derived from volcanic material. They are similar in soil properties and are very different from the soils at the other sites (Table 4-10). The similarities in soil properties between these two sites include: moderate soil loss per unit rainfall; low oxide contents; low clay contents of amorphous properties; low C and N contents; moderate to low aggregate dry crushing strengths; high ECECs; and high silt and sand contents.

The microstructures at these sites have low stability, easily dispersing upon saturation. Water enters the highly-porous aggregates which absorb water through well-linked patterns of inter- and intra-aggregate pores. With little cohesive strength, waterlogged aggregates quickly disintegrate into individual particles and/or microaggregates. The microaggregates possess minimal binding agents required to remain stable. When saturated, they readily break down to individual particles.

Table 4-10: Comparison of Properties (Mabini and Los Baños)

SOIL LOSS		
Property	Mabini	Los Baños
Soil Loss per Unit Rainfall	M	M
SIMILARITIES BETWEEN SITES		
Property	Mabini	Los Baños
Crushing Strength	M-L	M-L
N and C Contents	L	L
Oxides	L	L
Clay Content	L	L
Sand Content	H	H
Silt Content	H	H

*(L = low; M = moderate; H = high)

5. EVALUATION OF THE SOIL EROSION PROCESS

Soil erosion involves a two stage process of detachment and transport of soil material. Differences in erosion factors result in different amounts of soil loss. To assess the erosion process accurately, the factors must be considered simultaneously in an interactive system. Such an approach ideally dictates a very large study with sufficient variation and replication for all factors to be varied independently at each location. Regardless, an attempt must be made to assess the reasons why the amounts of soil loss differ at each site.

In the widest sense, erodibility is the reciprocal of resistance to erosion. Therefore, to quantify the erodibility of a site is to account for the amount of soil loss caused by either its inherent erodibility caused by soil properties or that caused by factors such as topography and vegetation. The variability in soil loss caused by topography and vegetation would be eliminated when these factors are made constant among all sites. Thus, the remaining variability in soil loss would be caused by the difference in inherent erodibility among the sites.

The process that will be adopted for this purpose is to “standardize” the data in various ways. The first step in this process involves converting the soil loss at each site from its absolute value to “soil loss per unit rainfall” (Table 5-1) and to “soil loss per unit runoff” (Table 5-2) for both Farmers’ Practice and the Conservation Practice plots. The assumption that rainfall intensity is similar among sites is made because all sites experience broadly similar humid to sub-humid tropical climatic conditions. With this method of accommodating for the different annual rainfalls at the sites, the remaining major difference is to attempt to “neutralize” or adjust the amount of soil loss to a

common slope angle (i.e. 20% slope) to produce what will be called “slope-standardized soil loss”.

Table 5-1: Ranking of Soil Loss per Unit Rainfall

FARMERS' PRACTICE					
Site	Rainfall (mm)	Soil Loss (t ha ⁻¹ yr ⁻¹)	Soil Loss per Unit Rainfall (t ha ⁻¹ mm ⁻¹)	Rank	Cluster
M	1263	0.44	0.00035	1	1
CM	1147	1.10	0.00096	2	1
V	1233	25.29	0.02051	3	2
L	2000	47.57	0.02379	4	2
P	1479	52.00	0.03515	5	2
LB	1332	64.67	0.04856	6	3
CR	1748	187.2	0.10707	7	4
CONSERVATION PRACTICE					
Site	Rainfall (mm)	Soil Loss (t ha ⁻¹ yr ⁻¹)	Soil Loss per Unit Rainfall (t ha ⁻¹ mm ⁻¹)	Rank	Cluster
CM	1147	0.05	0.00005	1	1
P	1479	0.73	0.00050	2	2
M	1263	1.24	0.00098	3	2
V	1233	4.87	0.00395	4	3
LB	1332	8.33	0.00626	5	3
CR	1748	26.13	0.01495	6	4
L	2000	42.56	0.02128	7	4

Table 5-2: Ranking of Soil Loss per Unit Runoff

FARMERS' PRACTICE									
Site	Runoff ($\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$)	Rank	Cluster	Soil Loss per Unit Runoff (t m^{-3})	Rank	Cluster	Runoff per Unit Rainfall ($\text{m}^3\text{ha}^{-1}\text{mm}^{-1}$)	Rank	Cluster
M	143	1	1	0.00308	1	1	0.11	1	1
CM	199	2	1	0.00510	2	1	0.17	2	1
L	3321	7	3	0.01432	3	2	1.66	7	3
V	1286	5	2	0.02473	4	2	1.04	6	3
P	1107	4	2	0.04466	5	3	0.75	4	2
CR	1420	6	2	0.13363	6	4	0.81	5	2
LB	500	3	1	0.18000	7	4	0.38	3	1
CONSERVATION PRACTICE									
Site	Runoff ($\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$)	Rank	Cluster	Soil Loss per Unit Runoff (t m^{-3})	Rank	Cluster	Runoff per Unit Rainfall ($\text{m}^3\text{ha}^{-1}\text{mm}^{-1}$)	Rank	Cluster
CM	87	2	1	0.00055	1	1	0.08	2	1
M	453	3	2	0.00274	2	1	0.36	4	2
P	76	1	1	0.00741	3	2	0.05	1	1
LB	580	5	2	0.01207	4	3	0.44	5	2
L	3161	7	3	0.01346	5	3	1.58	7	3
V	704	6	2	0.01458	6	3	0.57	6	2
CR	571	4	2	0.04849	7	4	0.33	3	2

5.1 SLOPE STANDARDIZATION

The various sites from which undisturbed soil samples were obtained have slopes ranging from 12% to 40%, which make comparison difficult. Soil loss data from Chiang Rai from two plots with different slopes provide the opportunity to neutralize the role of slope steepness in the soil erosion process. At the Chiang Rai site, identical farmer practice treatments were applied in the first year (1989) of experimentation to the plot (40% slope) from which samples for this project were taken and a plot (20% slope) from which samples were earlier taken for microstructural investigation (Collins, 1995). The microstructures and other conditions except slope are similar and the erosion loss differences are believed to be attributable to the different slope conditions.

A polynomial relationship between slope steepness and soil erosion, established by Smith and Wischmeier (1962), correlated with a manually extrapolated soil loss relationship from Chiang Rai from 0% to 10% slopes (Figure 5-1). Accepting that the Smith and Wischmeier (1962) relationship can be reasonably applied to 10% slopes, soil losses from the Chiang Rai site and from the polynomial relationship were combined to create a hybrid slope-standardizing soil loss curve (Figure 5-2) to be applied to other sites where slope differs from 20%.

To create the curve, soil losses were obtained from the polynomial relationship on 0% to 10% slopes; between 20% and 40% slopes, soil losses were interpolated from the 1989 data; and between 10% and 20% slope, soil losses were interpolated by smoothly connecting the two curve fragments. On the assumption that this difference in soil loss has continued for subsequent years, the Chiang Rai soil losses from the 40% slope plot can be standardized to 20% slope. Applying the same proportional factor per unit difference in slope to the other sites where the slopes differ from 20%, soil loss

standardized to 20% can be calculated for all sites. The slope-standardized soil loss per unit rainfall at other sites was calculated by proportionally re-scaling the y-axis (soil loss) of Figure 5-2 and calculating the proportional difference in soil loss with slope change. The assumptions behind this standardization process may legitimately be criticized, but such a process is necessary to allow comparative analysis across the sites.

The slope-standardized soil losses per unit rainfall and per unit runoff are presented, ranked and clustered in Table 5-3 for the Farmers' Practice. The agricultural plots will be analyzed separately, beginning with the Farmers' Practice plots.

Figure 5-1: Soil Loss Related to Slope Steepness

Figure 5-2: Slope-Standardizing Soil Loss Curve

5.2 FARMERS' PRACTICE

The analysis of the nature of relationships between microstructure and soil erodibility will be addressed on a site-by-site basis, commencing with the sites that group into Cluster 1 (lowest in soil loss per unit rainfall and per unit runoff) and proceeding stepwise to Cluster 4 (highest). The only site which falls in a different cluster on the two criteria (standardized soil loss per unit rainfall and per unit runoff) is the Los Baños site which rates as more problematic on the runoff than on the rainfall basis and was grouped into Cluster 3.

The use of the terms "low", "moderate", and "high" soil loss are not absolute standards, but are chosen to discriminate ranges of soil loss internal to this investigation. "Low" soil loss ranges from 0 to 10 t ha⁻¹; "moderate" ranges from 10 to 75 t ha⁻¹; and "high" is greater than 75 t ha⁻¹. With this scale, only the "low" range would be considered "acceptable" by USDA recommendations of 11 t ha⁻¹ as the maximum tolerable soil loss (Brady, 1990).

Table 5-3: Slope-Standardized Soil Loss Results for Farmers' Practice

FARMERS' PRACTICE												
Site	Slope (%)	Δ Slope	Actual Soil Loss (t ha ⁻¹ yr ⁻¹)	Standard-ized Soil Loss (t ha ⁻¹ yr ⁻¹)	Rainfall (mm)	Standard-ized SL/RF (t ha ⁻¹ mm ⁻¹)	Rank/Cluster		Runoff (m ³ yr ⁻¹)	Standard-ized SL/RO (t m ⁻³)	Rank/Cluster	
M	16	+4	0.44	0.51	1263	0.00040	1	1	143	0.0036	1	1
CM	12	+8	1.10	1.67	1147	0.00146	2	1	199	0.0084	2	1
V	30	-10	25.29	22.31	1233	0.01809	3	2	1286	0.0173	4	2
L	30	-10	47.57	41.96	2000	0.02098	4	2	3321	0.0126	3	2
P	20	0	52.00	52.00	1479	0.03156	5	3	1106	0.0470	5	3
LB	20	0	64.67	64.67	1332	0.04855	6	3	500	0.1293	7	4
CR	40	-20	187.2	154.78	1748	0.08855	7	4	1420	0.1090	6	4

5.2.1 Cluster 1 – Malaysia and Chiang Mai

The sites in this cluster experience low soil loss, less than $10 \text{ t ha}^{-1}\text{yr}^{-1}$.

5.2.1.1 Malaysia

This site is unique within the study in that it is the only site with a substantial tree canopy. Rubber is grown on all plots and the difference between the Farmers' Practice plots and the Conservation Practice plots is based on the method of crop planting under the immature rubber trees. The extent of the rubber tree canopy is such that it intercepts a substantial portion of the rainfall and thereby decreases the amount of soil dispersion by raindrop impact. In a soil which exhibits high resistance to ultrasonic dispersion and which exhibited stable aggregates with stable domains in the microstructural behaviour analysis, it is not surprising that very little erosion occurred. The vegetative factors and the soil structural stability combine to protect this site.

5.2.1.2 Chiang Mai

The low standardized soil loss at this site appears to be related primarily to the low total runoff from the plot. A low total runoff suggests that individual runoff events are not large and with low flow there will be only a limited capacity to entrain and transport soil particles, even when the microaggregates are unstable and presumably susceptible to dispersion by raindrop impact. It would also appear that breakdown of the microaggregates into stable domains by raindrop impact does not lead to clogging of surface pores and a serious decrease in the infiltration capacity of the soil, which if it occurred would lead to increased amounts of runoff and more serious erosion. The stable domain structure would appear to have a protective role in soil erodibility at this site.

5.2.2 Cluster 2 – Vietnam and Laos

The sites in this cluster experience moderate soil loss ranging from 10 to 50 t ha⁻¹yr⁻¹ and experience much greater soil loss per unit rainfall than sites in Cluster 1.

5.2.2.1 Vietnam

The moderate standardized soil loss at this site appears to be primarily related to the moderate total runoff. A moderate total runoff suggests that individual runoff events have sufficient flow capacity to entrain and transport soil particles. The unstable microstructure suggests that soil material is susceptible to detachment by raindrop impact. As the material is detached, the runoff can entrain and transport breakdown material consisting largely of stable domains. The substantially higher runoff compared to Chiang Mai suggests that a portion of the breakdown material may enter the pores with infiltrating water, reducing infiltration capacity and facilitating runoff and erosion.

5.2.2.2 Laos

The moderate standardized soil loss at this site under conditions of high total runoff appears to be related to its stable structure. The very high runoff volume (more than twice that from any other site) suggests that individual runoff events are large and should have substantial entrainment and transport capacities. A stable macrostructure inhibits detachment of soil material by raindrop impact, thereby limiting the available material for transport by overland flow. Nonetheless, the runoff events are able to entrain and transport a substantial amount of soil material, probably mostly as stable, detached microaggregates. Without the stable soil structure at this site, very large losses of soil would be expected.

5.2.3 Cluster 3 – Mabini and Los Baños

The sites in this cluster experience moderate soil loss ranging from 50 to 75 t ha⁻¹yr⁻¹. These sites are clustered separately from Laos and Vietnam due to the substantial difference in soil loss and microstructural behaviour.

5.2.3.1 Mabini

The moderate soil loss at this site appears to be related to the moderate total runoff and an unstable microstructure. A moderate runoff volume suggests that individual runoff events have sufficient flow capacity to entrain and transport soil particles. The unstable microstructure and unstable domains suggest that the soil is susceptible to dispersion by raindrop impact leading to rapid structural breakdown. A portion of the breakdown material may enter the pores with infiltrating water, reducing infiltration capacity and resulting in increased runoff. The runoff is able to entrain dispersed material and transport it downslope. The unstable microstructure and unstable domains make this soil more susceptible to erosion than the sites of Cluster 1 and 2 where microstructure and/or domains are stable.

5.2.3.2 Los Baños

The moderate soil loss at this site seems to be related to the combined effect of low total runoff and an unstable microstructure. The low total runoff suggests that individual runoff events are small but are still able to entrain and transport a substantial amount of soil. The unstable microstructure gives the soil a high susceptibility to dispersion by raindrop impact and the low-volume runoff is able to entrain and transport a remarkable amount of soil material per unit runoff (Table 5-3). The dispersed material must be of a particle size that is very easily transported.

5.2.4 Cluster 4 – Chiang Rai

This site experiences high soil loss, greater than $70 \text{ t ha}^{-1}\text{yr}^{-1}$ and is clustered separately due its high soil loss.

5.2.4.1 *Chiang Rai*

The high standardized soil loss at this site appears to be related to both a stable microstructure and high total runoff. The moderately stable microaggregates are very susceptible to detachment by raindrop impact. A high total runoff suggests that individual runoff events have sufficient flow capacity to entrain and transport detached microaggregates, leading to high soil erosion at this site. In contrast to other sites, a stable microstructure, rather than an unstable microstructure, appears to enhance the soil erodibility at this site. These findings are in agreement with Collins (1995) who suggests that a porous, granular structure at Chiang Rai allows microaggregates to be dispersed from aggregates under high rainfall erosivity, whereas a low microaggregate bulk density, coupled with a transportable size, allows for ready transport downslope.

Interestingly, the standardized soil loss per unit runoff is slightly less than that of Los Baños while the soil loss per unit rainfall is much higher. These discrepancies appear to be related to the differences in capability of maintaining dispersed material in suspension at the two sites; microaggregates at Chiang Rai are less easily suspended than the finer (probably individual particles) dispersed material at Los Baños.

5.3 CONSERVATION PRACTICE

A comparison of “slope-standardized soil loss per unit rainfall” values between differing agricultural practices between sites is not possible. That is, these values are comparable only among similar crops. The Conservation Practice plots are segmented along contours by hedgerows which lead to a decreased effective slope length and which, by trapping some eroded material on their upslope side, gradually decrease the effective slope steepness. Therefore, the slope-standardized soil loss per unit rainfall value may not properly neutralize the effect of slope steepness on soil loss for the Conservation Practice plots because the standardizing curve was obtained from the Farmers’ Practice data where plots are not segmented. The actual soil loss from the Conservation Practice plot and Farmer Practice plot can be compared in terms of soil loss reduction (Table 5-4).

Table 5-4: Comparison of Soil Loss and Runoff Between Agricultural Plots

COMPARISON OF SOIL LOSS AND RUNOFF BETWEEN PLOTS							
Site	Rainfall (mm)	Farmers' Practice		Conservation Practice		Comparative Soil Loss (CP/FP)†	Comparative Runoff (CP/FP)†
		Soil loss (t ha ⁻¹ yr ⁻¹)	Runoff (m ³ yr ⁻¹)	Soil Loss (t ha ⁻¹ yr ⁻¹)	Runoff (m ³ yr ⁻¹)		
P	1479	52	1107	0.73	76.67	0.044	0.069
CM	1147	1.10	199	0.05	87.67	0.045	0.440
LB	1332	64.67	500	8.33	580.00	0.129	1.160
CR	1748	187.2	1420	26.13	570.67	0.140	0.402
V	1233	25.29	1286	4.87	704.33	0.193	0.548
L	2000	47.57	3321	42.56	3161.00	0.895	0.952
M	1263	0.44	143	1.24	453.00	2.820	3.170

† CP = Conservation Practice value; FP = Farmers' Practice value.

In Table 5-1, the ranking order of soil loss of the Conservation Practice results among sites shifted from that in the Farmers' Practice. A decrease in soil loss can be observed in the Conservation Practice plot in all cases except Malaysia where canopy cover prevents a comparison between plots. Chiang Mai, Mabini, Malaysia, Vietnam, and Los Baños experience low soil loss, whereas Chiang Rai and Laos experience moderate soil loss.

The amount of soil loss and runoff in the Conservation Practice proportional to the amount in the Farmers' Practice are given in the "Comparative Soil Loss" and "Comparative Runoff" columns in Table 5-4. The reduction in soil loss between the Farmers' Practice and Conservation Practice plots indicates that the contour hedgerows are effective in reducing soil loss. There is a lesser proportional amount of runoff reduction in the Conservation Practice. This indicates that the interruption of runoff caused by the Conservation Practice hedgerows reduces runoff volume and velocity and its erosivity. It can be concluded that the soil conservation practices are beneficial in reducing soil loss.

5.4 CHAPTER SUMMARY

The elimination of the soil loss factors vegetation and slope, a necessary step to an accurate site comparison of the effect of soil erodibility on soil loss, resulted in an observed difference in slope-standardized soil loss per unit rainfall among the sites. This difference indicates an influence of soil erodibility in soil loss. Furthermore, soil erodibility was influenced by soil structural stability.

Malaysia experienced the least standardized soil loss per unit rainfall indicating the beneficial effect of its canopy cover in protecting the moderately erodible soil structure. Chiang Mai experienced very low standardized soil loss per unit rainfall due

to a low runoff. Vietnam and Laos experienced comparable standardized soil loss per unit rainfall. The runoff is much greater at Laos indicating its higher resistance to erosion. Mabini and Los Baños experience moderate soil loss, having high soil loss per unit runoff which indicates high susceptibility to runoff. Finally, Chiang Rai has the highest standardized soil loss per unit rainfall. An unstable structure and stable microstructure makes this site very susceptible to erosion.

6. CONCLUSIONS

The rates of erosion observed at the IBSRAM Asialand Sloping Lands research sites are a product of many factors which include precipitation, topography, soil characteristics, and land use. The goal of this research was to explore the role of microstructure in soil erodibility and erosion at these sites based on the following research objectives: (1) examine and characterize the structural and microstructural properties of the soils from IBSRAM research sites; (2) investigate the soil properties which might influence aggregate and microaggregate stability at each site; and (3) explore the possible associations between soil microstructure and its behaviour, other soil properties, and soil erodibility. This research yields evidence that soil structural size and stability are factors in soil erodibility at these sites.

The first step in this investigation was to characterize the soil structural stability at each site. Based on experimental results, the sites were clustered into three different groups of structural stability: Cluster 1 – stable microaggregates and stable domains; Cluster 2 – unstable microaggregates and stable domains; and Cluster 3 – unstable microaggregates and unstable domains. The soil properties considered to influence aggregate and microaggregate stability are clarified in the following summary.

The next step in this investigation was to examine the effect of microstructural stability in soil erodibility, and consequently, in soil loss. The “slope-standardized soil loss per unit rainfall” index standardizes soil loss by neutralizing the slope and rainfall factors, providing a proportional scale of soil loss against which to compare the effects of different microstructural characteristics. These values were ranked and clustered to compare with the clustered results of microstructural behaviour. The ranking of sites

indicates that, other factors remaining constant, soil loss is affected by the interplay of soil erodibility and rainfall erosivity. The following is a synthesis of the soil erosion process at each site. Clustering of sites is based on microstructural behaviour.

Sites in Cluster 1 have stable microaggregates composed of stable domains (Chiang Rai; Laos; and Malaysia). These soils are strongly acid with high clay contents and moderate carbon contents. Oxide contents ranged from low (Laos) to high (Chiang Rai and Malaysia). The aggregates from Laos and Malaysia have low dispersibility, and moderate bulk density. Whereas, the aggregates from Chiang Rai have moderate dispersibility and low bulk density. Standardized soil loss per unit rainfall indices differ among these sites, reflecting the effect of different erodibility and/or erosivity.

Chiang Rai has unstable, porous, crumb aggregates composed of moderately- to strongly-developed, sub-angular microaggregates. The highly-porous microaggregates possess moderate strength probably due to high clay and oxide contents and moderate carbon contents. Moderate aggregate dispersibility indicates high microaggregate susceptibility to detachment by raindrop impact. Moderate microaggregate strength and low bulk density increase susceptibility to transport. These factors combine to increase the erodibility of this soil. A high erodibility and high erosivity contribute to high soil loss at this site.

Laos has stable macro-aggregates composed of moderately-developed, sub-angular blocky microaggregates. The stability of macro-aggregates produces low aggregate dispersibility which indicates a low microaggregate susceptibility to detachment by raindrop impact. The microaggregates have high clay and moderate oxide and carbon contents and possess high bulk density and moderate strength which decrease their susceptibility to transport. These properties produce a soil of low

erodibility which, when subjected to rainfall of high erosivity, yields a moderate amount of soil loss.

Malaysia has stable macro-aggregates composed of weakly-developed, angular blocky microaggregates. The microaggregates are high in clay and oxide content which provide moderate microaggregate stability. The low aggregate dispersibility and moderate bulk density decrease microaggregate susceptibility to detachment and transport. The rubber tree canopy effectively reduces the erosivity of raindrop impact, producing low erosivity. A moderate erodibility and low erosivity combine to yield low soil loss at this site.

Two sites are grouped into Cluster 2, both having unstable microaggregates and stable domains (Vietnam; and Chiang Mai). High to moderate oxide and clay contents and high carbon contents were observed at these sites. However, differences in soil erodibility and climatic erosivity between these sites led to different amounts of soil loss.

Vietnam has weakly-developed macroaggregates composed of moderately stable microaggregates. The moderate aggregate dispersibility indicates a moderate susceptibility to dispersion by raindrop impact. The microaggregates have moderate dispersibility, and with disturbance, break down into stable, angular blocky domains. Detached microaggregates and domains may clog pores causing decreasing transport material for runoff. The combination of a moderate erodibility and moderate erosivity yields moderate soil loss at this site.

Chiang Mai has structurally unstable macro-aggregates composed of moderately- to strongly-developed sub-angular or crumb microaggregates. The microaggregates have high dispersibility when saturated and are easily broken down

into stable domains. High dispersibility and low microstructural stability increase susceptibility to detachment and dispersion by raindrop impact, but the stable domains decrease susceptibility to transport by runoff, causing a low erodibility. Due to the low amount of rainfall causing low runoff erosivity and the soil's low susceptibility to transport, this site yields a low amount of soil loss.

Two sites are grouped into Cluster 3, both possessing unstable structures composed of unstable microaggregates and unstable domains (Mabini, and Los Baños, Philippines). These soils are easily dispersed and have low clay, oxide, and carbon contents and high silt and sand contents which lead to low microaggregate stability.

The low structural stability at these sites increases susceptibility to dispersion by raindrop impact and is also suspected of increasing susceptibility to runoff, with a pronounced effect at Los Baños. These structurally unstable soils experience moderate soil loss because they are highly susceptible to dispersion by raindrop impact and have moderate to high susceptibility to transport by overland flow.

In summary, the sloping topography and humid climatic conditions at all of these sites cause highly erosive rainfall events on potentially erodible soils. Chiang Rai is the anomalous site according to "conventional wisdom" of the influence of structural stability on soil erodibility, in that it experiences high soil loss but exhibits microstructural stability. All other sites follow the pattern that would be expected from the combination of structural (macro- and micro-) characteristics and rainfall characteristics. This contradiction in conventional wisdom at Chiang Rai suggests that a closer consideration of the interaction between the level of structural stability and climatic erosivity may improve the accuracy of assessing soil erodibility.

Regardless of erodibility or erosivity, the actual soil loss and soil loss per unit rainfall results indicate that the Conservation Practice is generally effective in reducing soil loss at all sites when hedgerow development has been established. Hedgerows reduce runoff velocity, causing entrained material to deposit and form accumulation wedges upslope of the hedgerows. This soil conservation measure progressively reduces slope gradients while maintaining shorter effective slope lengths, thereby reducing the erosive effects of runoff and the susceptibility to soil erosion. This gradual process is an low input system of soil conservation intended to increase agricultural sustainability.

6.1 LIMITATIONS

Several limitations were encountered during this project. The soil property database was too small to perform a reliable analysis from which generalizations could be made. While more replications from each plot would have provided a larger sample for a statistical analysis of the effect of soil properties on soil erodibility, this is not considered to be a serious limitation because of the exploratory nature of the research.

Soil erosion data retrieved from the IBSRAM files were incomplete. This complication limited the ability to conduct site-to-site comparisons through which analysis of the erosion during similar rainfall events at different sites could have neutralized the rainfall erosivity factor. These limitations forced assumptions to be made in the soil erosion process at each site, such as similar rainfall intensities.

6.2 RESEARCH RECOMMENDATIONS

Recommendations for future work include the collection of a larger suite of soil samples to facilitate better characterization of soil properties and the collection of rainfall data on a time scale that would allow rainstorm profiling and correlation of the rainfall interval with erosion measurement interval. Interactive observations of rainfall events during initial crop development stages, when the soil is most susceptible to erosion, would greatly improve the accuracy and precision of recording the erosion process. Infiltration tests at each site would improve the analysis of the influence of runoff in erosion.

With regards to laboratory methods, the Aggregate Dispersibility Index concept has potential to improve the assessment of the role of microstructure in soil erodibility. A post-treatment measurement of the size distribution of resistant material and the proportion of the resistant material consisting of aggregated material would improve the assessment of aggregate breakdown behaviour. Furthermore, rather than a change in the duration of exposure to a given ultrasonic intensity, exposure to a range of different energy intensities would provide an assessment of the relative resistance of the aggregates to dispersion.

7. APPENDICES

7.1 METHOD FOR MICROSTRUCTURAL BEHAVIOUR ANALYSIS

Apparatus: Binocular microscope; watch-glasses; syringe and water; needle probe.

- 1) Select representative aggregates and break apart. Slowly apply a constant drip of water over aggregates until either (A) the aggregate breaks apart or (B) the aggregate is half-submerged in water.
 - a) If (A) occurs, then describe the breakdown behaviour;
 - b) if (B) occurs, then tease aggregates with constant moderate stirring action (recreating turbulence in runoff) until the aggregate collapses.
- 2) Describe the microaggregate structure and behaviour (i.e. fracture patterns; water infiltration rates; water movement through inter- and/or intra-microaggregate pores). Tease microaggregates with same action as with the aggregates.
 - a) If the microaggregates remain stable, then describe microaggregate nature.
 - b) If the microaggregate collapses, then describe the breakdown process and material.
 - c) If the domains remain stable, describe their appearance.

7.2 SOIL EROSION DATA

Site	Year	Annual Prec'n (mm)	Soil Loss (t ha ⁻¹)			Runoff (m ha ⁻¹)			SLRF (t ha ⁻¹ yr ⁻¹)			SLRO (t ha ⁻¹ m ⁻¹)		
			BP	FP (T1)	CP (T2)	BP	FP (T1)	CP (T2)	BP	FP	CP	BP	FP	CP
Chiang Mai	1982	1085	14.07	1.88	0.07	1413.61	301.00	90.00	0.01297	0.00173	0.00006	0.00995	0.00825	0.00072
	1993	854	2.67	0.29	0.01	291.45	73.00	36.00	0.00313	0.00034	0.00001	0.00617	0.00395	0.00028
	1994	1502	no data	1.15	0.09	no data	224.00	134.00	no data	0.00076	0.00006	no data	0.00511	0.00054
	Avg	1147	8.37	1.10	0.05	852.53	199.33	87.67	0.00730	0.00096	0.00003	0.00956	0.00510	0.00055
Chiang Rai	1982	1425	no data	146.80	41.80	no data	827.00	483.00	no data	0.10302	0.02933	no data	0.17751	0.06054
	1993	1615	313.28	88.70	9.70	2480.76	982.00	337.00	0.19368	0.05492	0.00601	0.12528	0.09033	0.02878
	1994	2205	no data	326.10	26.90	no data	2451.00	882.00	no data	0.14789	0.01220	no data	0.13305	0.03016
	Avg	1748	313.28	187.20	26.13	2480.76	1420.00	570.67	0.17919	0.10707	0.01493	0.12628	0.13363	0.04849
Laos	1995	2000	BP	FP (T1)	T2	BP	FP (T1)	CP (T2)	BP	FP	CP	BP	FP	CP
			54.19	47.57	42.56	3682.00	3321.00	3161.00	0.02710	0.02379	0.02128	0.01361	0.01432	0.01346
Vietnam	1982	818	BP	FP (T1)	T3	BP	FP (T1)	T3	BP	FP	CP	BP	FP	CP
	1993	976	24.91	19.99	8.07	715.00	551.00	301.00	0.03045	0.03443	0.00987	0.03484	0.03627	0.02882
	1994	1905	89.63	35.11	5.05	2123.00	1295.00	317.00	0.08081	0.03597	0.00518	0.04175	0.02775	0.01594
	Avg	1233	18.28	20.77	1.48	2057.00	2042.00	1495.00	0.08959	0.01090	0.00077	0.00989	0.01017	0.00399
Mabini	1982	1093	43.94	25.29	4.87	1631.67	1286.00	704.33	0.03564	0.02031	0.00395	0.02849	0.02473	0.01458
	1991	1932	no data	18.00	0.20	no data	640.00	90.00	no data	0.08875	0.00183	no data	0.07898	0.02000
	1992	1413	no data	41.09	0.00	no data	1420.00	40.00	no data	0.06832	0.00010	no data	0.03813	0.00222
	Avg	1479	no data	32.00	0.73	no data	1106.67	76.67	no data	0.03515	0.00250	no data	0.04466	0.00741
Los Baños	1982	336	BP	FP (T1)	CP (T2)	BP	FP (T1)	CP (T2)	BP	FP	CP	BP	FP	CP
	1993	2510	no data	9.00	4.00	no data	1280.00	100.00	no data	0.02879	0.01190	no data	no data	no data
	1994	1148	no data	95.00	14.00	no data	no data	no data	no data	0.03785	0.00558	no data	no data	no data
	Avg	1332	no data	90.00	7.00	no data	500.00	580.00	no data	0.07833	0.00908	no data	0.18000	0.01207
Malaysia	1994	1263	BP	FP	CP	BP	FP	CP	BP	FP	CP	BP	FP	CP
			12.59	0.44	1.24	1291.00	143.00	453.00	0.00997	0.00035	0.00098	0.00975	0.00308	0.00274
China	1982	773	BP (T4)	FP (T2)	CP (T3)	BP (T4)	FP (T2)	CP (T3)	BP (T4)	FP (T2)	CP (T3)	BP (T4)	FP (T2)	CP (T3)
	1993	1180	80.54	3.99	0.87	2172.77	896.35	226.81	0.10423	0.00516	0.00113	0.03707	0.00445	0.00383
	1994	685	342.12	112.24	57.42	6452.59	3243.01	6452.59	0.28996	0.06513	0.04867	0.05302	0.03481	0.00980
	1995	1067	107.90	1.35	0.00	3088.37	1417.89	3088.37	0.15761	0.00197	0.00000	0.03517	0.00065	0.00000
	Avg	926	97.62	4.20	0.25	4580.68	2062.16	2056.88	0.09152	0.00364	0.00023	0.02140	0.00204	0.00012
	1995	1067	107.90	1.35	0.00	3088.37	1417.89	3088.37	0.15761	0.00197	0.00000	0.03517	0.00065	0.00000
	Avg	926	157.05	30.45	14.64	4063.60	1904.85	2951.14	0.16960	0.03288	0.01580	0.03653	0.01253	0.00301

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