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The Potential of Agroforestry Systems in Controlling Soil Erosion on Sloping Lands, St. Vincent, West Indies.

by

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ABSTRACT

A comparative study of soil erosion was conducted in the Lauders region of the Union Watershed in St. Vincent, West Indies. The primary objective was to assess the potential of agroforestry systems in controlling soil erosion on sloping lands. Water erosion processes were measured based on runoff and sediment loss in three agroforestry systems and one monoculture system.

The results of the study indicate that total sediment loss was relatively low in the four sites. Sediment loss ranged from 24.0kg/ha in the Dasheen/Agroforestry site to 17.0kg/ha in the Yam/Agroforestry site. Total runoff values ranged from 0.71L/m^2 in the Yam site to 0.21L/m^2 in the Dasheen monoculture site.

Agroforestry systems in combination with the presence of a continuous ground cover and the use of soil conservation measures, were effective in controlling soil erosion by reducing runoff and sediment loss on moderately sloping lands.

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DEDICATION

I dedicate this thesis to my parents, Rob and Bacarra. Thank you for putting up with me!

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1.1 Rationale

Soil degradation is defined as a reduction in the soil conditions and the biological components that cannot be replenished by natural inputs to their original state, resulting in a loss of actual or potential soil productivity (Brown and Lugo, 1994). The forces of weathering and gravity acting on the soil cause the naturally occurring process of soil degradation. However, this process is accelerated when the protective vegetative cover has been removed because of human activities (Blum, 1998). Deforestation is one of the primary causes of soil degradation in the humid tropics. The problems caused by deforestation are often the result of past mismanagement and inappropriate land use (Lugo, et al., 1981). Soil degradation has profound effects on both the physical and human environment, particularly in developing countries where there is a lack of infrastructure and capital to implement costly solutions. The challenge of balancing the need to preserve forests and the clearing of forests for human activities is even greater on a small and densely populated island with a limited resource base.

Rainforest destruction has become a significant problem on the eastern Caribbean Island of St. Vincent, the largest of the St. Vincent and the Grenadines Islands archipelago. The removal of forests in the rugged, mountainous interior of the Colonarie River Watershed for agriculture, timber and charcoal has led to accelerated soil erosion, causing greater sedimentation of rivers, increased flooding in lower areas, and a loss of slope stability (Reid Collins and Associates, 1994).

These problems become intensified on steeper slopes often resulting in slumping and landslides. Soil loss and a decline in soil fertility leads to lower agricultural productivity, which is the dominant sector of the Vincentian economy. The dangers of flooding, mass movement processes, and the contamination of the water supply by sedimentation of the rivers and the use of fertilizers also pose risks to human health and well being.

The cultivation of bananas or "green gold" is the most important agricultural activity in St. Vincent, supporting approximately 60 to 85 percent of the population and providing the country's largest export (Caribbean Conservation Association [CCA], 1991). Banana cultivation has also been the most significant cause of land degradation in the upper and middle regions of the Colonarie River Watershed. The natural vegetation is cleared to establish banana crops, commonly planted on steep slopes without a protective ground cover. This clearing and planting pattern has resulted from the limited availability of arable farm land at lower elevations, the low productivity of bananas, insecure land titles, and the economic needs of farmers (CCA, 1991; Trevin, 1993). In 1981, there was no evidence of banana crops in the lower watershed, however approximately 70 percent of the cultivated land was in banana production by 1992 (Reid Collins and Associates, 1994). Another consideration is the lack of soil conservation measures used by farmers, although 50 percent of farmers reported erosion problems on their land (Anderson, 1992). Financial needs and/or the lack of knowledge about soil conservation methods have led farmers to maximize the more immediate short-term gains from commercial banana production, rather than investing in conservation measures that require long-term commitment and support.

In response to a growing concern over the island's resources, the Government of St. Vincent implemented a Forestry Development Project in 1989. This was intended to increase awareness among the local population about environmental degradation and appropriate land use practices, to develop soil and water conservation techniques, and to conserve the remaining natural forests (Reid Collins and Associates, 1994). In 1994, a Watershed Management Plan was prepared for the Colonarie River Basin, which included a five-year reclamation plan for disturbed areas. The reclamation plan was designed to convert agricultural areas on Crown Lands (all land above 1000 feet) to pure forest or agroforestry practices in the upper watershed (Reid Collins and Associates, 1994). Agroforestry practices and soil conservation measures will be introduced in the upper and middle parts of the watershed as a transitional land use to reverse the trend of illegal clearing and cultivation. Six combinations of agroforestry practices have been developed according to a land suitability analysis of the watershed (Limbird, 1992). Each combination is based on the location within the watershed, the degree of slope, soil erodibility, and landslide potential. Agroforestry practices include using mixed fruit trees in combination with soil conservation measures, and multipurpose trees as windbreaks and live hedges (Reid Collins and Associates, 1994; Trevin, 1993).

Proper management and appropriate land use practices are necessary to reduce soil degradation and protect the limited resources in the Colonarie Watershed. The need to reclaim disturbed areas in the middle and upper basin is essential to reduce soil erosion and stabilize the landscape. The flexibility and adaptive capabilities of agroforestry systems serves as an important tool for multiple use management in the watershed (Trevin, 1993).

1.2 Research Objectives

The principal objective of this research study is to assess the potential of agroforestry systems in reducing soil erosion on sloping lands within the management boundary of the Colonarie River Watershed. This will be determined with four specific objectives:

(1) To quantitatively measure water erosion processes based on runoff and sediment yield under three different types of agroforestry systems and a monoculture system.

(2) To conduct a chemical and physical analysis of the soil types and collected sediments to determine the fertility levels and nutrient losses of the soils at each location.

(3) To examine the relationships between sediment loss, water runoff, nutrient loss, rainfall amounts and intensities, with the soil and vegetation characteristics at each site.

(4) To develop recommendations for suitable land use practices based on the knowledge acquired.

1.3 Thesis Organization

Chapter One presents the rationale and research objectives for the thesis project with a discussion of the environmental challenges facing St. Vincent, and the introduction of agroforestry as a potential reclamation technique in the Colonarie Watershed. A comprehensive literature review of agroforestry systems and soil erosion processes is presented in Chapter Two. Chapter Three describes the biophysical setting of the island of St. Vincent and of the study area. A description of the methodology in Chapter Four includes the field study design, as well as the methods used in the laboratory and statistical analyses. Chapter Five is a description of the results consisting of the data on soil type, sediment loss, runoff and soil chemistry. This chapter also contains the results of the statistical analysis conducted on the data collected. Chapter Six is a discussion of the relationships and dynamics between the site characteristics and erosional processes occurring at each location, as well as a comparison of nutrient losses and soil fertility levels between the sites. Chapter Seven presents conclusions, recommendations and limitations of the study based on the effectiveness of agroforestry systems in reducing soil erosion on sloping lands.

2. CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter begins with definitions of reclamation and bioengineering to gain an understanding of why agroforestry systems have been proposed as a suitable alternative for restoring degraded lands. The chapter also provides an examination of the scientific, economic and social basis of agroforestry, and its relevance in erosion control. The literature review concludes with a discussion of the present use of and need for agroforestry systems in St. Vincent.

2.2 Reclamation and Bioengineering

The ecosystem approach to reclamation examines an ecosystem as a whole, and is based on the ecological interactions and interrelationships amongst all of the components within the system. The primary goal of reclamation is to establish a permanently stable landscape, which is both aesthetically and environmentally compatible with the surrounding undisturbed land (Naeth, et al., 1991). This includes restoring some level of productivity back to the land (defined by the function of the reclaimed landscape). The stability of the landscape is determined by a number of factors: the climate; bedrock lithology and structure; pedogenic processes; vegetation characteristics and structure; hydrology; and the geomorphic history of the area, including mass movement processes (Chatwin, et al., 1994; Wells and Potter, 1986).

Revegetation or bioengineering is one reclamation approach to prevent slope failure and control surface runoff. Revegetation is an effective method for the humid tropics because of the high intensity of rainstorms and the fragility of the environment. This method is less costly and simpler to establish and maintain than building artificial structures such as concrete retaining walls. The function of the vegetation for the reclaimed area determines what species are selected for revegetation. The role of vegetation is most often a protective one, such as erosion control, however the role of vegetation may also be productive.

The natural process of soil erosion in the humid tropics is accelerated greatly by the removal of vegetation. Without a vegetative cover the bare soil is exposed to the high erosive power of raindrops, causing detachment of the soil particles which are then carried away by overland flow (Greenland, 1975). The increase in erosion rates and, subsequently, the loss of nutrients and organic matter from the topsoil leads to a decline in soil fertility. Under a vegetative cover, organic matter, root growth, decaying roots and a high level of biological activity in the soil increase infiltration, the process by which water enters the soil, by maintaining a continuous pore system and a higher hydraulic conductivity (Styczen and Morgan, 1995). Vegetation may not only decrease the amount of runoff, but may increase the time it takes for runoff to occur.

The roots of the vegetation also help to stabilize the soil by enhancing its shear strength. Two opposing forces determine the stability of a slope. The load or slope stress is the pressure placed on the slope and is the main source of failure. The resistance is a combination of the strength of the soil material and the soil-root system (Wu, 1995). The weight of the trees growing on the slope increases the load but the roots help reinforce the soil and strengthen the resistance. Roots reinforce the soil by increasing the cohesion or binding action of the roots and rhizomes with the soil, and the adhesion of the soil particles with the roots (Styczen and Morgan, 1995). Belt and Woo (1984, p.214) noted that "in the absence of geological controls produced by bedrock benches and berms, rooting structures of trees and other vegetation anchor and bind materials to the slope, and stand out as the most important *natural* contributor to failure resistance." The effectiveness of the vegetation is determined by the total root biomass and the tree root morphology (O'Loughlin, 1984).

2.3 Introduction to Agroforestry

2.3.1 Definition and Classification of Agroforestry

Agroforestry is defined as "a dynamic, ecologically based natural resources management system that, through the integration of trees in farmland and rangeland, diversifies and sustains production for increased social, economic and environmental benefits for land users of all levels" (Leakey, 1996, p.6).

Agroforestry is practiced in most ecological and geographical areas in the tropics. Young (1989, p.12) defines an agroforestry *practice* as a "distinctive arrangement of components in space and time," whereas an agroforestry *system* is "a specific local example of a practice, characterized by environment, plant species and arrangement, management, and social and economic functioning." An inventory of agroforestry systems and practices used in developing countries was compiled by the International Centre for Research in Agroforestry (ICRAF) between 1982 and 1987, and identified approximately twenty different agroforestry practices and hundreds of agroforestry systems (Nair, 1990b; Nair, 1993; Young, 1989). With an increasing trend of adopting agroforestry systems as a suitable land use model in developing countries, this inventory will continue to grow.

The classification of agroforestry practices adopted by the ICRAF, the FAO (Food and Agricultural Organization of the United Nations) and the World Bank are based on the following criteria outlined by Nair (1990a, p.35):

- *Structural basis*: refers to the composition of the components, including the spatial arrangement of the woody component, vertical stratification of all the components, and the temporal arrangement of the different components.

- *Functional basis*: refers to the main function or role of the system, usually determined by the woody components, i.e. as a service or protective nature.

- *Socio-economic basis*: refers to the level of inputs of management (high or low) or intensity or scale of management and commercial goals (subsistence, intermediate, or commercial).

- *Ecological basis*: refers to the environmental conditions and ecological suitability of systems, based on the assumption that specific types of systems can be more appropriate for certain ecological conditions.

The structural basis is the most commonly used criterion in classifying agroforestry practices. There are three predominant agroforestry practices based on the nature of components: agrisilviculture, silvopasture and agrosilvopasture. Young (1989) subdivides this classification even further into rotational and spatial practices, which differentiates the relationship between trees and crops into either a temporal (combination over time) or spatial arrangement (combination over space). Spatial systems are defined as mixed (trees intermixed with crops) or zoned (systematic arrangement of trees). The different spatial arrangements of crops and trees are illustrated in Figure 2.1.

Agrisilviculture is the most common and widely recognized practice. It is the practice of planting trees, shrubs and/or vines with annual crops. Rotational types include shifting cultivation, improved tree fallow, and taungya (planting crops during the initial stages of a forest plantation development). In spatially mixed types, trees are distributed over the entire land area in an intimate mixture with the crops. Examples include trees on cropland, plantation crop combinations, and multistory tree gardens. Trees that are grown in a systematic arrangement or at a specific location to be used as boundaries or soil conservation structures are defined as spatially zoned systems. Hedgerow intercropping (alley cropping, barrier hedges), boundary planting, trees on erosion control surfaces, windbreaks and shelterbelts are all examples of this practice.

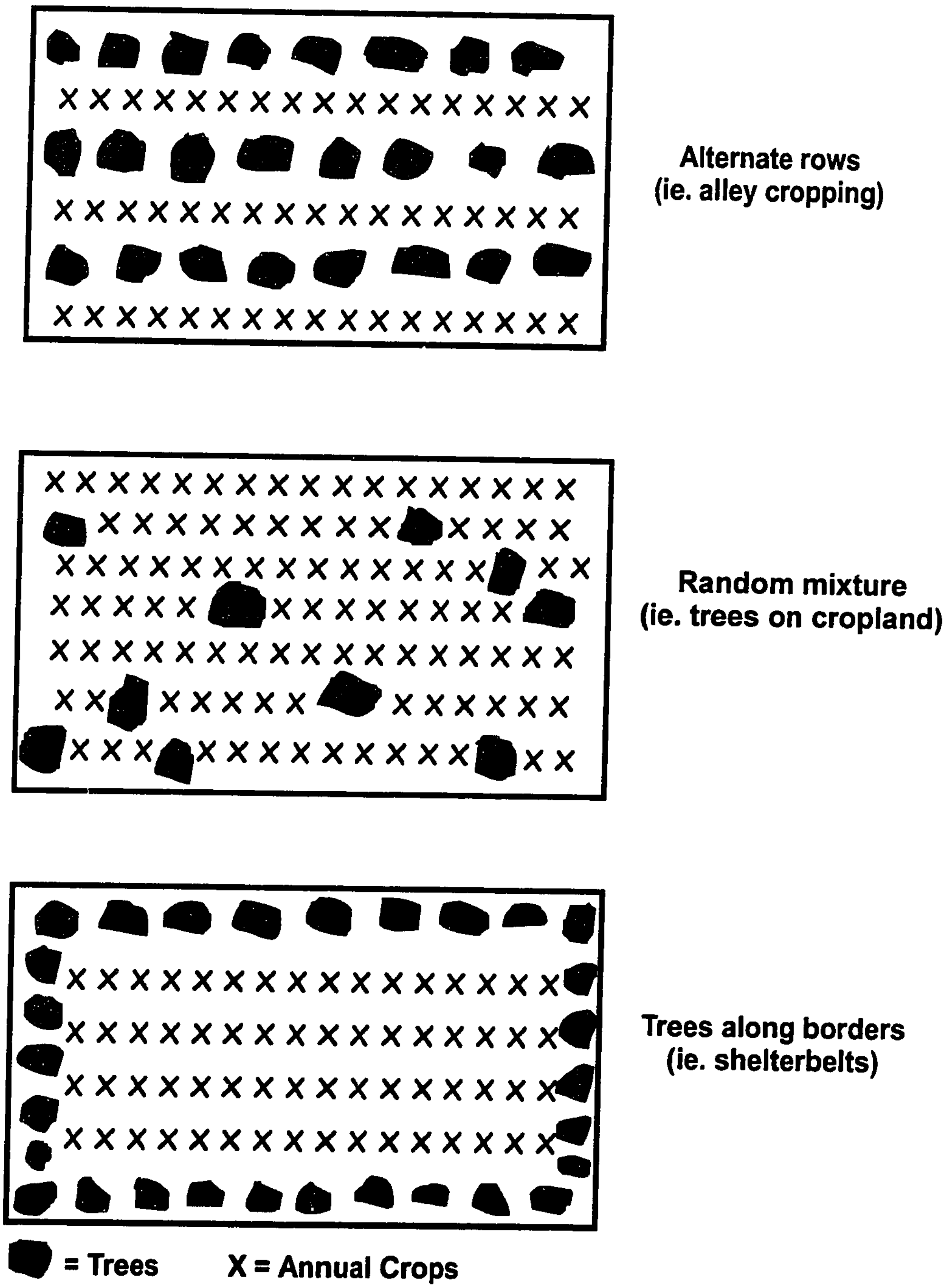

Figure 2.1 Spatial arrangements of crops in agroforestry (Lal, 1991).

The two other recognized agroforestry practices based on the component composition are silvopastoral (trees with pastures and livestock) and agrosilvopastoral (trees with crops, pastures and animals). These are often grouped together because of the overlap between the types of systems. Examples of spatially mixed types are trees on rangeland or pasture, and plantation crops with pastures. Spatially zoned types include live fences and fodder banks. Alley cropping, windbreaks and shelterbelts also may be used in agrosilvopastoral or silvopastoral practices.

2.3.2 Agroforestry Systems

Agroforestry systems attempt to overcome social and environmental problems by diversifying crop production while minimizing land degradation. Each system is site specific and should be compatible with the agricultural practices of the region (Von Maydell, 1978). The cooperation of the local population is also needed to ensure the system's productivity and sustainability.

All agroforestry systems have a protective and/or productive function, based on the dominating role (Gujral, 1991). The sustained production of food, fodder, fuelwood and other products is generally the most important function of agroforestry systems. Protective functions include soil and moisture conservation, erosion control, soil improvement, and shade for crops and animals.

Nair (1990b, p.1) outlines a number of key concepts that have gained general acceptance over the last decade supporting the role of agroforestry as a suitable land use option. Agroforestry,

- combines the production of multiple outputs with the protection of the resource base.
- emphasizes the use of indigenous, multipurpose trees and shrubs.
- is particularly suitable for low-input conditions and fragile environments.
- is more concerned with socio-cultural values than most other land use systems.
- is structurally and functionally more complex than a monoculture system.

2.4 Economic and Socio-Cultural Factors in Agroforestry

2.4.1 Economic Factors

Economic considerations play a primary role in determining the suitability of an agroforestry system to the land user. Unfortunately, there have been difficulties in developing an overall assessment of agroforestry systems because of limited research data. In developing an agroforestry system, the leading objective of most research projects is to develop a new or improved land use practice that will fulfill the needs of the land users or community before an economic analysis has been performed.

Another factor is the difficulty in quantifying the non-monetary and indirect benefits of agroforestry systems. Indirect benefits of agroforestry systems are: shade, improved moisture retention, increased organic matter in the soil, suppression of weeds, and reductions in wind, soil erosion, and albedo (Cook and Grut, 1989). Some of the benefits directly derived from the trees and crops are the fruit and leaves for food and fodder, wood for fuel and building materials, and bark for tanning and medicine (Cook and Grut, 1989; Cooper, et al., 1996). Both the direct and indirect benefits are often cited as important factors in ensuring the sustainability of an agroforestry system. Sustainable agriculture may be defined as a farming system that produces adequate amounts of high quality food, protects its resources and is both environmentally safe and profitable (Brown, 1990). The following table was prepared for the World Bank and outlines the main costs and benefits of agroforestry:

Benefits and Opportunities	Costs and Constraints
Maintains or increases site productivity through nutrient recycling and soil protection at low capital and labour costs	Reduces output of staple food crops where trees compete for use of arable land and/or depress crop yields through shade, root competition, or allelopathic interactions
Increases the value of output from a given area of land through spatial or temporal intercropping of trees and other species	Incompatibility of trees with agricultural practices such as free grazing, burning, common fields, etc., which make it difficult to protect trees
Diversifies the range of outputs from a given area in order to increase self-sufficiency, and/or reduce the risk to income from adverse climatic, biological or market impacts on particular crops	Trees can impede cultivation of monocrops and introduction of mechanization, and thus, increase labour costs in situations where the latter is appropriate and/or inhibit advances in farming practices
Spreads the need for labour inputs more evenly throughout the year, thus reducing the effects of sharp peaks and troughs in activity, characteristic of tropical agriculture	Where the planting season is very restricted, i.e. in arid and semi-arid conditions, demands on available labour for crop establishment may prevent tree planting
Provides productive applications for under-utilized land, labour or capital, and creates capital stocks available to meet intermittent costs or unforeseen contingencies	The relatively long production period of trees delays returns beyond what may be tenable for poor farmers, and increases the risks to them associated with insecurity of tenure

Table 2.1 Benefits and costs of agroforestry systems (Arnold, 1987; Nair, 1990b).

How farmers perceive the costs and benefits of agroforestry will determine whether or not they adopt an agroforestry system. Another important consideration is the costs of implementing and maintaining the system. Cook and Grut (1989) suggest that the resources required for implementation are less than the total resources used for agricultural activities on farms. The financial capital needed is primarily for the cost of seedlings, and the labour needed to prepare the initial area and for year round maintenance. Many surveys have indicated that farmers are willing to plant trees if seedlings are free, crop yields are not significantly reduced, and the trees offer some economic potential (Scherr, 1995). However, the amount of time needed before there is a return may introduce difficulties to the farmer in the short-term. The length of time will depend on the size and type of system, and ecological factors such as climate, topography and soil type (Scherr, 1995). Once established, opportunities for earning greater income per hectare per year have been documented by a number of researchers (MacDicken and Vergara, 1990). Thus, the design of an agroforestry system must offer short-term as well as long-term benefits to the farmer.

2.4.2 Socio-Cultural Factors

The social acceptability of agroforestry systems is influenced by socio-economic, cultural, and biophysical factors (Nair, 1990b). Land tenure, labour availability and marketability of tree products are the predominant considerations.

Land Tenure

A farmer is more likely to adopt an agroforestry system if he/she has long-term control or ownership of the land (Cooper, et al., 1996; Nair, 1990b; Vergara, 1987). However, if their tenure over the land is insecure, they will try to maximize production over the short-term. Family ownership of land is often based on occupancy and use, and is not recognized by the local government (Barker, 1990). State government can encourage agroforestry practices by modifying tenure ownership laws and granting long-term leases to farmers.

Labour Requirements

Rural family farms develop labour strategies using the inputs of most family members for different tasks at various times of the year (Nair, 1990b). Therefore, changes in labour patterns must be considered when deciding to adopt a new land use system. Agroforestry systems may be an advantage by spreading out labour requirements throughout the year.

Marketability of Tree Products

Direct and immediate income is a very important factor in any land use system. The sale and/or processing of agricultural products and the rural industries based on these products are essential sources of off-farm income (Nair, 1990b). The access to raw materials and markets and the organization and management skills of the land user will determine the success of an agroforestry system. Roads may be severely limited in tropical highland areas due to rugged topography, distances from major cities and highways, and scattered populations (Barker, 1990). Lack of infrastructure and the perishability of food items are often great constraints in marketing local products internationally (Winterbottom and Hazlewood, 1987). There is also the need for farmers to understand the local or international markets for which they are developing products. Brown (1990) discusses three other marketing considerations for the landholder. These are the availability of shipping and storage facilities, the seasonal and yearly price changes, and the market desirability of the product.

Other socio-cultural issues in determining the acceptability of an agroforestry system are: the ways in which knowledge is transferred to the farmer, the level of local participation in the planning and implementation of the project, and the land user's age, occupation, gender, education and income level (Winterbottom and Hazlewood, 1987).

2.5 The Scientific Basis of Agroforestry

The potential for any agroforestry practice to become a sustainable land use system is based on the ecological interactions among all of the components within the system. The system must be evaluated as a whole, rather than by the individual components. Therefore, the scientific basis of agroforestry must examine the effects of trees on soils, and the component interactions between trees and crops. The role of multipurpose trees and shrubs also is discussed.

2.5.1 The Effects of Trees on Soils

The assumption that trees improve the soil beneath them is based on a number of studies of natural ecosystems that support the following general findings (Nair, 1993, p.269; Young, 1989, p.93):

- Soils that develop under natural woodland and forest are known to be well structured, with good moisture holding capacity and high organic matter content.

- Unlike agricultural systems, a forest ecosystem is a relatively closed system in terms of nutrient transfer, storage and cycling.

- The ability of trees to restore soil fertility is illustrated by experiences in many developing countries, which indicate that the best way to reclaim degraded land is through afforestation or a similar type of tree-based land use.

- The conversion of natural ecosystems to arable farming systems leads to a decline in soil fertility and the degradation of other soil properties unless appropriate and often expensive, corrective measures are taken.

Trees have both beneficial and non-beneficial or adverse effects on soils. A summary of the effects that are discussed was compiled from Cooper, et al., (1996), Huxley, (1983), MacDicken and Vergara, (1990), Nair, (1990b, 1993), Sanchez, (1976) and Young, (1989).

Beneficial Effects of Trees

The beneficial effects or additions to the soil include maintaining or increasing organic matter through litterfall or pruning, and increased nitrogen fixation by some tree species. In addition, there is greater nutrient uptake from deeper soil horizons by deep rooted trees, and a significant contribution to nutrient cycling by atmospheric inputs by rainfall and dust, especially in humid areas.

Other beneficial effects of trees are the reduction of losses from the soil. Nutrient loss is reduced by the interception of the tree roots in absorbing and recycling nutrients that would be lost to the soil by leaching. Protection from erosion will also minimize the loss of organic matter and nutrients from the surface soil horizons (Young, 1989). A more thorough examination of agroforestry for erosion control is discussed in Section 2.6.

The maintenance or improvement of the physical properties of the soil is well documented, where trees may enhance soil structure, porosity, moisture retention and resistance to erosion by decreasing runoff (Greenland, 1975; MacDicken and Vergara, 1990; Wiersum, 1988a; Young, 1989). These authors also present evidence regarding the decline in these properties when the forest cover has been removed. Furthermore, leaf litter cover and the shade produced by trees modifies extremes in soil temperature. In the tropics, ground surface temperatures may reach extremes of 50° Celsius on bare slopes which adversely affects plant growth (Young, 1989). The lowering of ground surface temperatures by shade also may reduce the rate of decomposition of organic matter. Additional effects on the chemical properties are a reduction of acidity by the addition of bases to the soil from trees, and the reduction of salinity or sodicity in the soil.

Soil biological processes include the production of a range of different qualities of plant litter through the mixture of the woody and herbaceous material, including root residues from trees. This has the effect of distributing the release of nutrients mineralized from litter decay over time (Young, 1989). The potential also exists to control litter decay through the selection of tree species and management of pruning, to synchronize the timing and release of nutrients with the plant's nutrient uptake requirements (MacDicken and Vergara, 1990; Wiersum, 1988b; Young, 1989).

Adverse Effects of Trees

Adverse effects of trees on soils include increased competition for nutrients, growing space and solar energy between trees and annual crops (Connor, 1983; MacDicken and Vergara, 1990; Young, 1989). Many of these drawbacks can be minimized if tree species with deep roots and limited lateral spread, and narrower crowns are chosen. Competition for moisture also may exist between trees and crops in arid and semi-arid areas. The ability of the soil to store water is determined by the soil depth and the physical characteristics such as texture and permeability. Changes in the level of soil water depend on rainfall patterns, but storage water losses also occur from surface evaporation and from the movement of water below the root zone (Connor, 1983). The competition for moisture is determined by the root profiles of the component species, which subsequently depends on the soil type, moisture regime, and whether the soil is relatively fertile or degraded (Connor, 1983; Huck, 1983; Young, 1989). Generally, the shallow, high root density of most annual crops and the deep taproots of most trees will reduce the competition for soil water. However, the relationship may be more complex in specific locations (Connor, 1983).

Additional negative effects are the loss of organic matter and nutrients from harvesting the trees, and the potential for increased erosion if the tree canopy is high above the ground and there is minimal ground cover. Raindrops intercepted by leaves can coalesce and form larger drops that have greater erosivity than unintercepted rainfall (Wiersum, 1988a). MacDicken and Vergara (1990) and Young (1989) discuss other adverse effects that may be particularly harmful in an agroforestry system. These include: allelopathy or the inhibiting of seed germination and plant growth by the release of naturally occurring compounds from roots and tissues of other plants; damage to tree and crop components from livestock; improved habitat for pests such as birds, rodents, snakes and insects; and mechanical damage from cultivating and harvesting because of irregular spacings between tree and crop components.

2.5.2 Interactions Between Trees and Crops

The interaction between trees and crops or even among different plants is described as competitive (Nair, 1990b). This competitiveness for resources occurs in all ecosystems including natural forests, agroforestry systems and agricultural systems. An understanding of the interactions involved is needed to effectively manage a mixed plant community. These processes are divided into *above-ground* and *below-ground* interactions.

Above-Ground Interactions

Insolation and solar radiation received by plants are the most important factors in managing above-ground interactions in agroforestry systems. Scientific research supports that mixed plant communities are more efficient photosynthetically than monocultural stands (Nair, 1990b). This is due to the increased space utilization from a multistory canopy that increases total biomass production. A mixed canopy also creates microclimatic conditions that often benefit underlying crops. A higher tree canopy may decrease solar radiation and wind speed, lower soil temperatures, and increase humidity at soil level for plants growing beneath the canopy (Wiersum, 1988a).

Below-Ground Interactions

The structure and efficiency of the root systems are the most significant factors in the below-ground interactions. Roots determine the uptake of and competition for moisture and nutrients (Nair, 1990b). A significant portion of a plant's nutrient store is also contained in the root system (Young, 1989). Tree root systems generally make up approximately 20 to 30 percent of the total plant biomass and consist of four components. The components of a tree root system are: relatively permanent structural roots that are medium to large in diameter; fine or feeder roots, with a diameter of one to two millimetres; very fine root hairs; and symbiotic associations between plant roots and soil fungi called mycorrhizae (Young, 1989). Trees require root systems that function all year long to stabilize their environment and adapt to changing growing conditions. They also redistribute or cycle nutrients and increase the soil organic matter content. Conversely, the root systems of annual crops are shallow, seasonally based and not as flexible to change. Combining trees and crops increases root densities and reduces inter-root distances, which increases the likelihood of inter-plant competition (Ong, et al., 1991; Young, 1989). However, most research to date has failed to separate nutrient competition at the tree/crop interface from the effects of shading, moisture competition and nutrient recycling by litter (Young, 1989). To decrease the competitive interaction in an agroforestry system, the rooting patterns of trees and crops should differ in both structure and depth.

Sustainable agroforestry tries to maximize the positive interactions between the tree and crop components, and minimize the competitive aspects by planting trees and crop species that differ in light requirements, root development and height. This will ensure a more efficient use of solar radiation, moisture and nutrients. A comparison of the "ideal" agroforestry system with a common agricultural and forestry system is presented in Figure 2.2.

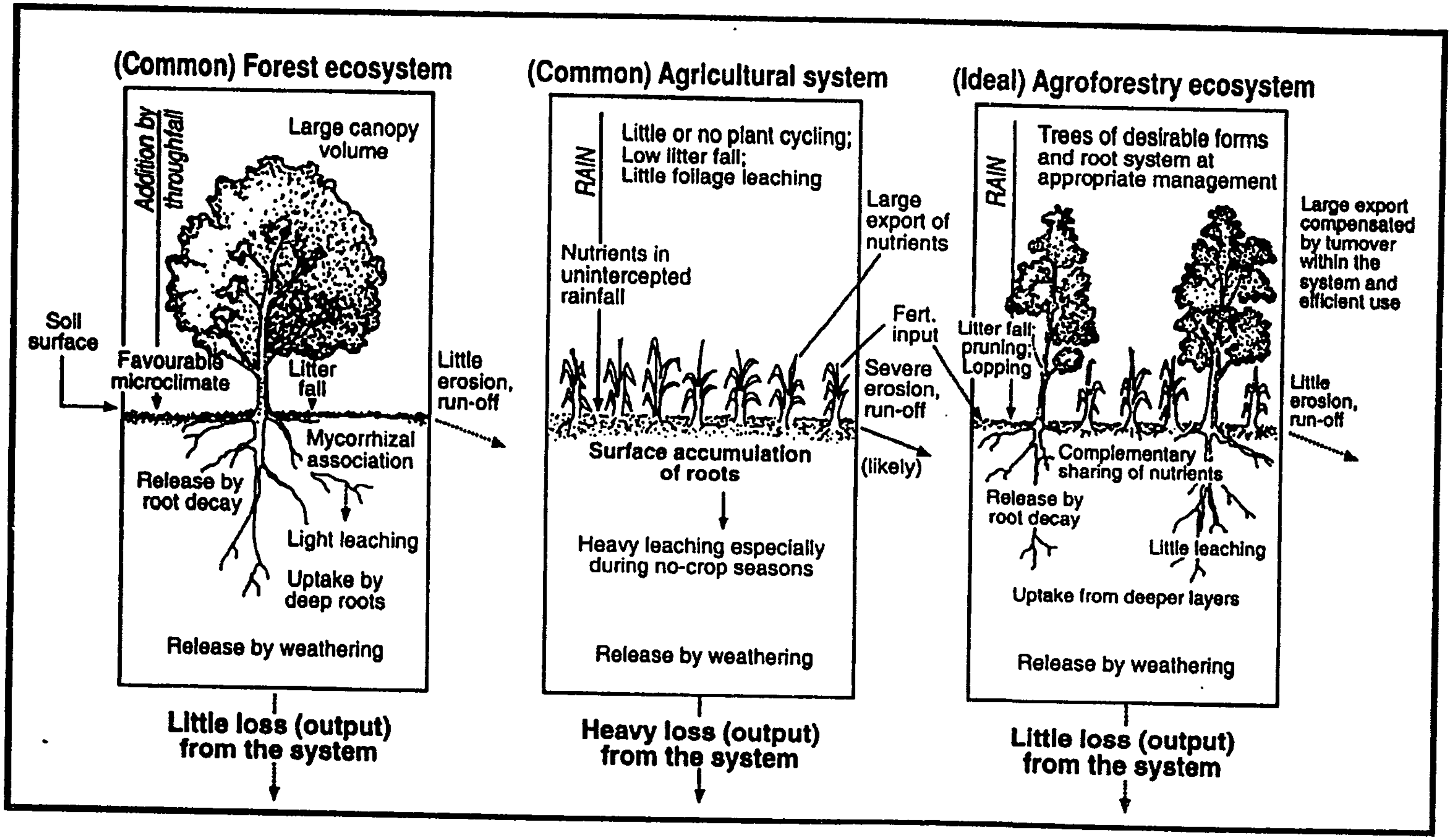

Figure 2.2 Schematic Representation of the Advantages of Agroforestry Systems in Comparison with Forestry and Agricultural Systems (Lugo, et al., 1987).

2.5.3 Multipurpose Trees and Shrubs

Nair (1993, p.172) defines multipurpose trees (MPT) or shrubs in agroforestry as those "which are deliberately kept and managed for more than one preferred use, product and/or service; the retention or cultivation of these trees is usually economically but also sometimes ecologically motivated, in a multiple output land use system." Multipurpose trees are the most distinctive components of any agroforestry system by providing both productive and protective functions. The main productive roles of MPTs are for food, fodder, fuelwood and timber. Protective functions are erosion control, soil improvement, shade, and soil or moisture conservation. Many species are chosen because they grow quickly and have nitrogen-fixing capabilities. Other attributes may be based on height, rooting patterns, wood quality, stem form, crown size, shape, density, site adaptability and ecological range (Nair, 1993; Wood, 1990). A comprehensive review of multipurpose tree and shrub species is found in Nair (1993).

2.6 Agroforestry and Soil Erosion

2.6.1 Soil Erosion Processes and Factors

Morgan (1979, p.5) defines soil erosion as "a two-phase process consisting of the detachment of individual particles from the soil mass and their transport (downslope) by erosive agents such as running water, wind or ice." Deposition occurs when there is no longer sufficient energy to transport the particles further. The most common cause of detachment is by rainsplash, where soil particles may be thrown several centimetres through the air (Morgan, 1979). Over time, continuous exposure to intense rainstorms will weaken the soil, increasing the rate of detachment (Morgan, 1979). Mechanical and chemical weathering and disturbances like tillage or trampling are also causes of soil particle detachment. Transporting agents include wind, splash or interrill erosion, overland flow, rill erosion and gully erosion.

Splash or Interill Erosion

Splash or interrill erosion is caused by the impact of raindrops falling directly on exposed soil particles (Gray and Leiser, 1982). Splashed particles may move up to a metre vertically and over a metre laterally on a level surface, and causes a net downslope movement of soil on steep slopes (Gray and Leiser, 1982; Laflen and Roose, 1998). The downslope momentum of an individual soil particle falling back to the surface will be transferred to other particles, repeating the process (Morgan, 1979). Raindrops may also cause the formation of a surface crust, as a result of clogging the pores by compaction of the soil surface (Morgan, 1979). The effects of splash erosion increase if raindrops fall on surface water in the form of puddles or overland flow (Morgan, 1979). Splash or interrill erosion acts uniformly over a slope as long as soil and surface properties remain constant (Laflen and Roose, 1998; Morgan, 1979).

Overland Flow

Overland flow occurs on hillslopes when the soil moisture storage and/or the infiltration capacity of the soil are exceeded. This causes the water and soil particles to move downslope in a thin, relatively uniform sheet or as braided water courses with no prominent channels (Gray and Leiser, 1982; Lal, 1990; Morgan, 1979). In the latter form, vegetation and large stones redirect the flow in a sinuous pattern. The eroding and transporting power of overland flow varies with the velocity, turbulence and spatial extent of the flow for a given size, shape and density of soil particles or aggregates (Gray and Leiser, 1982; Morgan, 1979). A continuum exists between well-vegetated areas where overland flow rarely occurs to repeated occurrences on bare soil, covering two-thirds or more of a hillslope during a rainstorm (Morgan, 1979).

Rill Erosion

Rill erosion is the removal of soil by water from well-defined channels only a few millimetres wide and deep, where there is a concentration of overland flow (Gray and Leiser, 1982; Lal, 1990). Rills are ephemeral features, frequently forming a new network of channels during subsequent storms that are unrelated to former rills, and are often discontinuous (Morgan, 1979). Rills develop downslope when overland flow becomes channelized and runoff velocities are increased. Rill erosion leads to greater losses than overland flow and is most damaging in intense storms or in areas with loose, shallow topsoil (Gray and Leiser, 1982). Rills are large and stable enough to be seen readily, but could be removed easily by tillage and grading operations (Gray and Leiser, 1982). By controlling rill erosion, gully erosion can be prevented.

Gully Erosion

Gullies are relatively permanent steep-sided channels that carry water during and immediately after a rainstorm (Gray and Leiser, 1982; Morgan, 1979). They are often associated with accelerated erosion and are not destroyed by normal tillage (Lal, 1990; Morgan, 1979). Gullies are formed by a number of processes often involving a combination of surface erosion and mass wasting (Gray and Leiser, 1982; Morgan, 1979). Gray and Leiser (1982) have identified four stages of gully development: downward cutting, headward erosion and enlargement, healing, and stabilization. Active gullies continue to erode and expand, while vegetation begins to grow during the healing stage. Stabilization occurs when the vegetation becomes well established and protects the soil against further erosion by stabilizing the gully walls (Gray and Leiser, 1982). Stabilized gullies are not as significant as rills in the quantity of soil eroded, but they are difficult to control and stop their development once gully formation begins.

Soil Erosion Factors

Soil erosion results from a combination of a number of factors: rainfall erosivity, soil erodibility, slope steepness, slope length, vegetation cover, and management including conservation practices (Morgan, 1986; Young, 1988). These factors are calculated in formulas such as the Universal Soil Loss Equation (USLE) to predict the estimated impact of erosion over the long-term (Foster, 1988). Rainfall characteristics such as frequency, intensity and duration are independent values that cannot be altered, whereas slope steepness can be modified by terracing. The soil erodibility, slope length and soil cover factors may be manipulated by the choice of land use (Foster, 1988). Slope length may be modified with the use of runoff barriers or other soil conservation measures. The role of the tree component in an agroforestry system is one example (Young, 1988). Soil erodibility or the susceptibility of a soil to erosion is an inherent property that is influenced by a number of soil characteristics including, texture, structure, permeability, organic matter content, clay minerals and chemical composition (Lal, 1990; Shainberg, et al., 1992; Wiersum, 1984). The erodibility defines the ability of the soil to resist detachment and transport (Morgan, 1979). The effects of trees on soils and the benefits of a vegetation cover on or near the soil surface have already been discussed in previous sections. A more extensive review of soil erosion processes and factors is found in Ciccaglione (1998).

2.6.2 Agroforestry for Erosion Control

The potential of agroforestry as a reclamation technique can be examined primarily by its effectiveness in erosion control. Soil erosion results in a loss of soil nutrients, organic matter and consequently, productivity. Forest cover reduces erosion primarily through surface litter and understory vegetation. In an agroforestry system, the tree canopy itself may provide little protection, and measures must be taken to maintain a ground surface layer of vegetation or to use mulch to cover the soil. Trees and shrubs also can be used as effective barriers to soil erosion when planted in distinct patterns, such as hedgerows. Young (1989, p.55; 1986) has written extensively on agroforestry systems for erosion control, and suggests the following points must be considered when planning an agroforestry system:

- The tree canopy is not likely to reduce erosion, and may actually increase it.
- The potential for many agroforestry systems to maintain or improve soil organic matter will help to check erosion, but cannot be expected to reduce it greatly where conditions of climate, slope and soil cover are adverse.
- Barrier hedges substantially reduce runoff and increase infiltration, while their permeability prevents destruction during occasional high intensity storms.
- Maintenance of a ground surface cover of 60% or more throughout the period of erosive rains, formed by any combination of living herbaceous plants, crop residues and tree prunings, has a high potential to reduce erosion, and should be a primary objective in research design.

Direct experimental evidence on the effectiveness of agroforestry for controlling erosion is limited but increasing, and many countries have begun research trials for this purpose. Trees or shrubs that are used specifically to reduce erosion are considered *direct use* (Young, 1989). Their functions are to increase soil cover by litter and prunings; to provide partly permeable hedgerow barriers; to lead to the progressive development of terraces upslope of hedges through soil accumulation; and to increase soil resistance to erosion by maintenance of organic matter (Young, 1989). Other functions are to provide a multistory canopy with three or more levels, composed of the tree canopy, a ground cover of annual crops, and a surface litter layer. The use of stems or surface roots also reduces the water velocity and therefore, the erosivity of surface runoff (MacDicken and Vergara, 1990). Examples of *direct use* agroforestry systems include hedgerow intercropping, multistory tree gardens, plantation crop combinations, windbreaks and shelterbelts, and multiple use forestry. *Supplementary use* is where trees are used as erosion control structures but are not the primary means of reducing erosion (Young, 1989). Trees on erosion-control structures that stabilize the earth structures with their root systems and make productive use of the land are examples of *supplementary use* functions.

Not all agroforestry systems have the potential to control erosion (Wiersum, 1984; Young, 1989, 1986). Agroforestry comprises a large continuum between pure agriculture and pure forestry and therefore, the type of system adapted by the farmer will determine the principal function. Thus, the effectiveness of similar agroforestry practices in controlling erosion will differ based on the design and management of the specific system. Another factor is the length of time that is needed for the trees to become effective. Management techniques are also very important as soil tillage or frequent harvesting may occur in agroforestry systems, and tend to increase erosion rather than control it. There is evidence that trees intercept raindrops and may reduce splash erosion by slightly decreasing the amount of water reaching the soil surface (Wiersum, 1984). However, if the tree canopy is not close to the soil surface, the throughfall raindrops that are intercepted by trees may be more erosive than the rainfall itself, causing more damage to crops below the trees (Box and Bruce, 1996; Wiersum, 1984). Canopy characteristics such as crown architecture, percent coverage, height, size and position of leaves will determine the potential to increase or decrease splash erosion (Bregman, 1993; Wiersum, 1984; Young 1989).

As previously mentioned, an important consideration is the ground cover or leaf litter on the soil surface. A study conducted by Wiersum (1984) found that when the litter and other organic debris was removed, erosion increased by a factor of 10 to 100 percent, whereas removing the tree canopy without disturbing the protective soil cover only increased the erosion rates by a few tenths of a percent. An ideal agroforestry system that is effective for controlling water erosion on sloping land depends on many factors: establishing trees in specific spacings or patterns; removing as little of the ground cover as necessary; enhancing the litter or mulch protection by pruning and limiting the tree height; and employing proper management techniques, such as soil conservation measures.

Soil erosion is a natural process that cannot be eliminated entirely in any ecosystem. Tolerance limits of soil erosion are often based on acceptable levels of sustained crop yields, determined by the maintenance of organic matter and nutrients or soil fertility. The effectiveness of agroforestry systems to accumulate organic matter and recycle nutrients needs to be integrated with their relative losses through erosion, to determine whether a system is stable and sustainable (Young, 1986). Well-established soils in an undisturbed forest display lower erodibility values than cultivated soils, including agroforestry systems. Individual trees in an agroforestry system cannot be expected to influence the landscape as effectively as a stable forest ecosystem. Erosion rates in different agroforestry systems will vary considerably between systems and within phases of a specific system (Wiersum, 1984). Good management practices are the most significant contributor to a successful agroforestry system rather than the presence of trees alone (Wiersum, 1984).

2.7 Agroforestry in St. Vincent

Evidence of established agroforestry systems was observed throughout the island, most commonly in the form of live hedges, and coconut trees mixed with bananas, or bananas mixed with underlying root crops such as dasheens. However, most of these systems were found on large, level or near level areas in the lower and middle basins of many watersheds. Most of the steeply cultivated slopes were covered with monocultural crops, usually bananas. Previous research on the soils and soil erosion processes in St. Vincent have recommended that agroforestry systems should be implemented as a suitable land use alternative to reverse current trends of soil degradation (CCA, 1991; Ciccaglione, 1998; Reid Collins and Associates, 1994; Strand, 1996).

Trevin (1993) discusses the types and locations of agroforestry systems within the Colonarie Watershed in a draft report prepared for the Watershed Management Plan. Agrisilviculture is presently the most common practice in the watershed. Eight types of agroforestry systems were identified in the lower and middle watershed including: live hedges, windbreaks, homegardens, and the use of fruit or other trees irregularly scattered on fields of banana and root crops. There is little evidence of agroforestry in the upper basin area.

Live hedges are utilized most often to maximize land use as fences and boundary markers along roads and property lines. Windbreaks are used to protect crops from the persistent trade winds. However, the layout is often ineffective and there are few local, wind-resistant species (Trevin, 1993). Multipurpose trees on farmland are also widespread on the island, commonly using fruit trees scattered among bananas. Plantation crop combinations or the planting of coconut trees and banana crops occur throughout the island, but are absent in the Colonarie Watershed. The traditional taungya system is found occasionally in former illegally cultivated areas under reclamation in the upper watershed. The Forestry Division allows squatters to harvest crops for several months after the trees are planted to protect the seedlings. Once the trees become well established the area will be reclaimed back to forest cover and the squatters relocated (Trevin, 1993). Lastly, the use of live trellises to support vine crops such as yam and passion fruit is increasing with on-farm trials on different parts of the island.

Most of the agroforestry systems on the island still play a complementary role to commercial banana cultivation. The production of bananas has persisted as the "boom" crop even in the face of fluctuating markets and prices, low productivity, and high inputs of fertilizers, pesticides and labour. There is also little willingness by farmers to use trees for soil conservation or to implement other conservation measures, even though many farmers stated that soil erosion is a problem on their land (Anderson, 1992). Soil conservation measures relate to long-term values that are abandoned primarily because of insecure land titles. However, limitations on arable land, economic needs and financial pressures to modernize are also important factors (Trevin, 1993). Only one-third of the farmers in the Colonarie Watershed own the land they farm (Anderson, 1992).

Within the last few years there has been an increasingly positive trend towards agroforestry systems in the form of live trellises and mixed fruit crop plantations in the Colonarie Watershed. This trend is expected to continue with the implementation of the Colonarie River Watershed Management Plan. The Watershed Management Plan proposed six combinations of agroforestry (AF) practices that correspond to six different zones in the watershed (Reid Collins and Associates, 1994). Table 2.2 presents a summary of the proposed zones where the first three combinations are located in the Upper Basin and the latter three combinations are located in the Middle and Lower Basins.

Zone	Location	Characteristics	Land Use Practices
Zone 0	Upper Basin	Highly erodible soils on steep slopes; very high landslide hazard	No AF to be implemented; maintain in a natural state; strict enforcement of law in response to illegal land use
Zone 1	Upper Basin	Less erodible soils on steep slopes; moderately high landslide hazard	Plantations to be established for protection purposes and for limited commercial use; species selection suitable for wildlife; fast growing species if squatting is a problem

Zone 2	Upper Basin	Moderate slopes and less erodible soils; moderate landslide hazard	Rural forestry and agroforestry where land tenure is certain; favoured AF practices should be mixtures of fruit crops combined with soil conservation measures involving trees such as *Gliricidia sepium*, and grasses
Zone 3	Upper Basin	More gentle slopes and least erodible soils; moderate to low landslide hazard	Favoured AF practices should be mixtures of fruit crops combined with soil conservation measures involving trees and grasses; introduction of MPT trees as windbreaks, hedges and on cropland where land is presently cultivated; soil conservation measures recommended
Zone 4	Middle and Lower Basins	Moderately high soil erosion especially on steeper slopes; landslide hazard present	Local species of trees for windbreaks, live hedges and farmland with gradual introduction of new species; promote mixed fruit trees as an alternative to bananas particularly on steeper slopes; soil conservation measures needed on slopes above 10° (18%)
Zone 5	Middle and Lower Basins	Moderate to low soil erosion; low landslide hazard	Emphasize soil conservation measures; introduce mixed fruit trees and windbreaks; MPTs on croplands and live hedges may be considered where more comprehensive changes cannot be introduced
Zone 6	Middle and Lower Basins	Low soil erosion when managed; low landslide hazard	Plant trees and other woody plants and grasses for general erosion control functions

Table 2.2 Proposed agroforestry zones (Reid Collins and Associates, 1994).

3. CHAPTER THREE: STUDY AREA

3.1 Introduction

St. Vincent and the Grenadines is composed of over 30 islands and cays, and is located within the Eastern Caribbean Windward Isles Archipelago (Reid Collins and Associates, 1994). St. Vincent is the largest island, approximately 344 square kilometres in size with 84 kilometres of coastline. The island is located at 13° 20′ N latitude and 60° 50′ W longitude, with the Atlantic Ocean to the east and the Caribbean Sea to the west.

St. Vincent is a high island with volcanic peaks forming rugged mountains, sharp ridges and deep valleys. The island greatly contrasts the smaller Grenadine Islands with its dense, lush rainforests, numerous rivers, and black sand beaches. A map of St. Vincent and the Grenadines is illustrated in Figure 3.1.

3.2 Biophysical Setting

3.2.1 Geology and Geomorphology

St. Vincent is part of the Lesser Antilles active island arc, located on the eastern boundary of the Caribbean plate. The complete Antillean Arc is actually composed of a double arc that is approximately 850 kilometres in length, stretching from Puerto Rico to eastern Venezuela (Maury and Westercamp, 1990). The two arcs join at the southern end to form a single row of islands that includes Martinique, St. Lucia, St. Vincent and the Grenadines, and Grenada. The arcs diverge north of

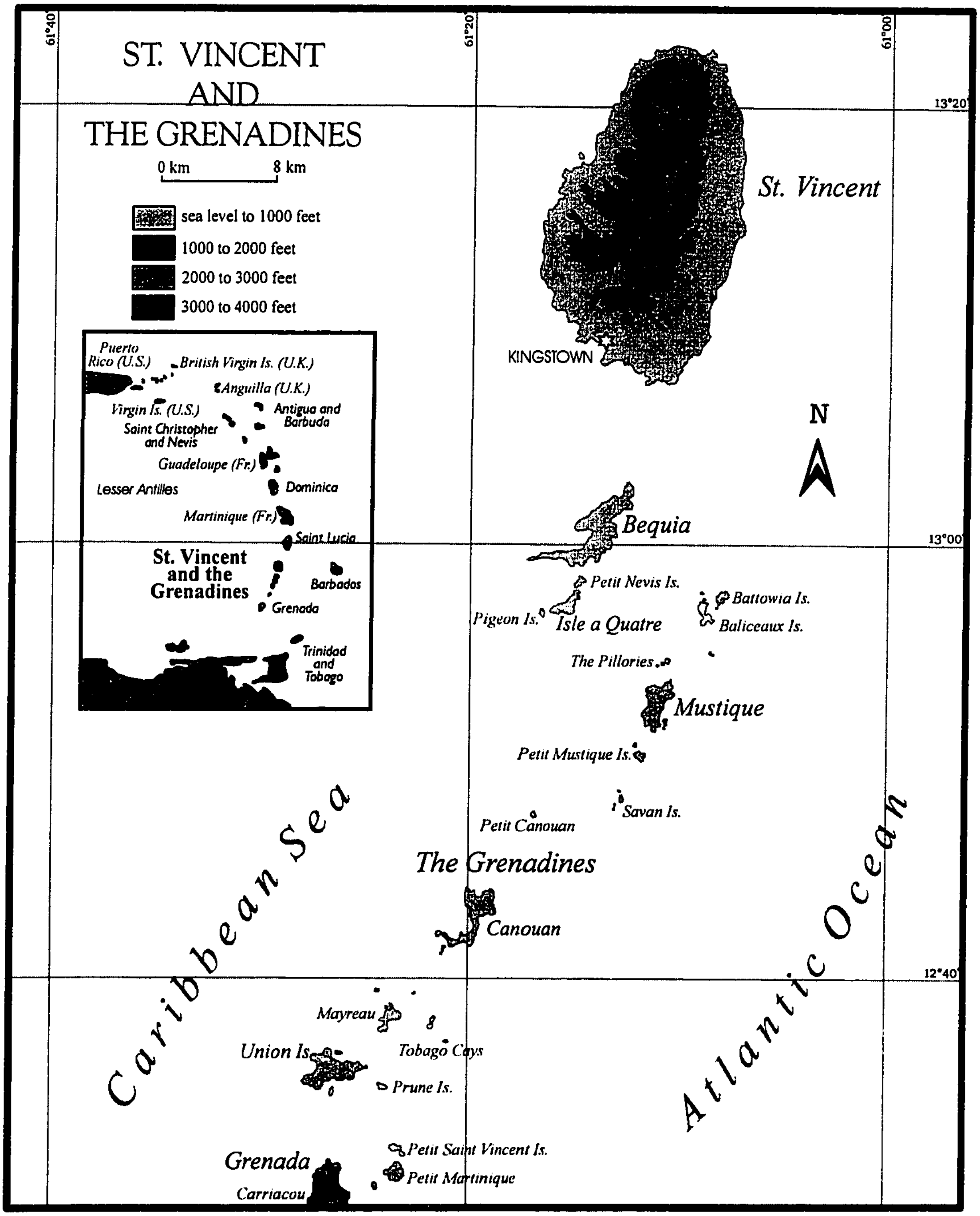

Figure 3.1 St. Vincent and the Grenadines (modified from Ciccaglione, 1998).

Martinique forming a northeastern and northwestern branch of islands (Maury and Westercamp, 1990).

The northeastern arc consists of the low islands of Grande Terre of Guadeloupe, Antigua, Barbuda, St. Bartholomew and St. Martin. The northwestern arc is composed of younger volcanic islands and includes Dominica, Basse Terre of Guadeloupe, Montserrat, Nevis, St. Kitts and Saba. The southern and northwestern branches are characterized by recent or active volcanoes and are called the Volcanic Caribbees.

The formation of the islands of the Antillean arc is a result of the subduction of the Atlantic oceanic plate under the Caribbean plate at its eastern boundary by a rate of two centimetres a year (Maury and Westercamp, 1990). The melting of the oceanic plate creates magma, which rises and erupts on the surface, leading to the mountain building process of volcano formation.

Geologically, the island of St. Vincent is quite young, less than 3.5 Ma, and shows a greater likeness to the more northern Volcanic Caribbees than the surrounding southern islands (Maury and Westercamp, 1990). There is no evidence of sedimentary formations on St. Vincent, nor does the island have the complex geologic histories that are found in the Grenadines. St. Vincent is composed of basaltic or andesitic lavas, and agglomerates with finer pyroclastic materials that have solidified to become *tuffs* or have remained unconsolidated as cinders and ashes (Reid Collins and Associates, 1994). The olivine-pyrite basalts are silica-oversaturated and potassium-poor, but tend to be rich in magnesium, chromium and nickel (Maury and Westercamp, 1990). The surficial geology is formed by either ashes or pyroclastics overlying the lavas, and range in age from Pleistocene to recent (CCA, 1991).

A coastal plain surrounds the perimeter of the island, and marine terraces representing various stages of crustal uplift are found near coastal areas (Reid Collins and Associates, 1994; Watson, et al., 1958). The north to south trending central mountain range is located in the interior of the island and consists of volcanic cones and remnants of cones. More than 50 percent of the island has slopes of 30° or greater, and only 20 percent of the island has slopes less than 20° (Reid Collins and Associates, 1994). The northern end of the island is dominated by the active strato-volcano, La Soufriere, which rises up to 1178 metres. The volcano was formed within the last half million years by the interlayering of lava flows and pyroclastic layers, alternating with violent explosions. Violent and destructive eruptions have occurred in 1718, 1812, 1902, 1971-72 and 1979, causing mudflows, ash falls and gas avalanches called *nuees ardentes* (CCA, 1991; Maury and Westercamp, 1990). The western leeward side of the island is characterized by high, steep coastal cliffs, and deep valleys carved by the many rivers cutting into the unconsolidated ashes, whereas the valleys are wider and flatter on the eastern windward side opening up to a relatively flat coastal plain (CCA, 1991).

3.2.2 Climate

The regional climate of St. Vincent is characterized as humid tropical marine, with little seasonal or diurnal variation (CCA, 1991). Under the Koppen climate system, St. Vincent is classified as a wet-dry tropical climate because of its location between the equator and the Tropic of Cancer (Ahrens, 1994; Strahler and Strahler, 1992). However, the length of the dry and wet seasons varies greatly depending on the location on the island. The climate is greatly influenced by the subtropical anticyclone belt, and the intertropical convergence zone (ITCZ). The winter dry season lasts for a minimum of two months with average monthly rainfall values no greater than six centimetres (Ahrens, 1994). It begins in December and continues until May with average temperatures rising to 27° Celsius (CCA, 1991). During the summer, the rainy season begins with the northward migration of the ITCZ. The rainy season in the coastal areas occurs from June to early December and has an average yearly rainfall of 2000 millimetres and an average temperature of 24° Celsius (Reid Collins and Associates, 1994). Rainfall fluctuates greatly from year to year in this wet-dry climate (Ahrens, 1994; Watson, et al., 1958).

Due to the mountainous interior of the island, a range of microclimates is created that vary by location, elevation and orientation. This causes an orographic effect over the cloud-covered mountains that results in heavy precipitation at higher elevations, especially on the windward side of the island. The effect of orographic precipitation pattern causes the windward side to receive up to ten percent more rainfall than the leeward side (Reid Collins and Associates, 1994). Rainfall decreases concentrically from the mountainous interior to the coast with no marked dry season at the higher elevations (Reid Collins and Associates, 1993). Precipitation in the mountains occurs year-round with an average yearly range of 600 millimetres in the valleys and up to 3800 millimetres at higher elevations, and yearly annual temperature ranging from 18° to 20° Celsius (Reid Collins and Associates, 1994).

A belt of surface trade winds from the northeast also influences St. Vincent's climate. This brings a strong and steady wind to the windward coast, as the surface winds are deflected northeasterly from the horse latitudes to the equator by the Coriolis effect (Ahrens, 1994). This is evident on the windward side by the appearance of windblown vegetation, coastal erosion features and greater wave action, whereas the leeward side appears calmer with noticeably less wind and wave action.

3.2.3 Soils

The soils on the island of St. Vincent are relatively young and immature, and are generally derived from volcanic ash and rock fragments (CCA, 1991). Volcanic soils are commonly acidic, unconsolidated, friable, deeply weathered and leached, and therefore are highly erodible. The Food and Agricultural Organization (FAO) of the United Nations describes these soils as Andosols, also named Andisols in the U.S. Soil Taxonomy System. Simonson et al. (1984, p.12) defined Andosols as:

> "Mineral soils in which the active fraction is dominated by amorphous materials (minimum 50 percent). These soils have a high sorptive capacity, a relatively friable A horizon, are high in organic matter (up to 30 percent), have a low bulk density and a low stickiness. They may have a B horizon and do not show significant clay movement. These soils occur under humid and subhumid conditions."

Andisols were formerly classified as Inceptisols and Entisols in the U.S. Soil Taxonomy System until 1990, when a new soil order with seven sub-orders was created (Tan, 1984). These soils are unique because they are rejuvenated by subsequent volcanic eruptions, and their spatial distribution throughout the world is quite small (Christopherson, 1997).

Allophane is a noncrystalline clay (lacking an ordered three-dimensional crystalline structure) which is a product of the weathering of volcanic glass (Tan, 1984). Allophane gives Andisols their distinctive properties, such as the high organic matter content, good permeability and porosity, and a high phosphate fixation capacity. The clay structure is dominated by Si-O-Al bonds and has a high specific surface area, resulting in a high capacity to adsorb cations and anions (Brady, 1990).

Allophane also displays a thixotrophic quality that causes the clay colloids to weaken when they are disturbed (Limbird, 1992). With repeated wetting and drying, the clays expand and contract, leading to aggregate instability (Limbird, 1992). This instability may lead to slope failures, such as slumping and landslides if they develop on steep slopes (Ciccaglione, 1998).

The soils of St. Vincent have been classified into six main groups: Alluvial soils, Shoal soils, Recent Volcanic Ash soils, High-Level Yellow Earth soils, Low-Level Yellow Earth soils, and Central Mountain Soils. Their distribution on the island is shown in Figure 3.2.

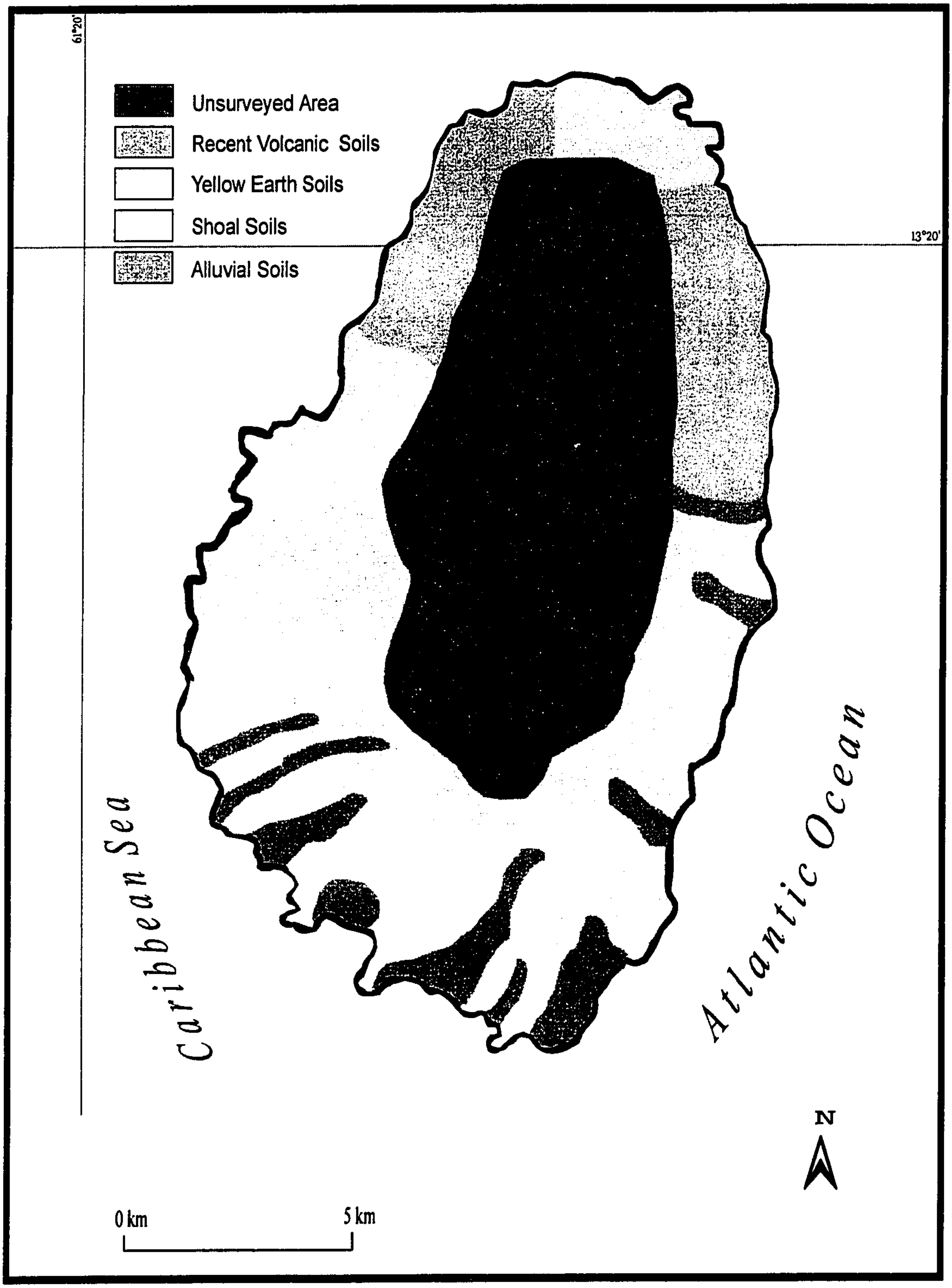

Figure 3.2 Soils of St. Vincent (modified from Ciccaglione, 1998).

Alluvial Soils

The Alluvial soils are mature soils that occupy valley bottoms and are found primarily on the southwest side of the island (CCA, 1991). The parent material originated from the High-Level and Low-Level Yellow Earth soils that have been transported by streams and deposited along the river channels (Limbird, 1992). These soils are considered to be the most productive and fertile soils on the island.

Shoal Soils

The Shoal soils are found on coastal areas in the south and western parts of the island. They are mature soils that are shallow and bouldery with a fine textured, dark surface horizon (Limbird, 1992). These soils developed from the parent material of remnant volcanic cones that was firmly cemented and therefore has impeded drainage (Limbird, 1992; Reid Collins and Associates, 1994; Watson, et al., 1958). The Shoal soils are moderately fertile but become sticky when wet, hard and cemented when dry, and are difficult to cultivate (CCA, 1991; Reid Collins and Associates, 1994).

Recent Volcanic Ash Soils

The Recent Volcanic Ash soils are immature soils that are unconsolidated, coarse textured, porous, and grayish in colour (CCA, 1991; Reid Collins and Associates, 1994). They cover the slopes of the Soufriere volcano as well as the northern third of the island. The parent material was rejuvenated in part from the 1902 volcanic eruption, and exhibits a weakly developed soil profile and horizonation (Limbird, 1992). These soils have a good potential fertility but are highly susceptible to erosion (CCA, 1991).

Central Mountain Soils

The Central Mountain soils occur over approximately 20 percent of the island in high rainfall areas under forest cover. These soils are only slightly acidic with very little leaching, and have a high surface organic matter content (Limbird, 1992). They are found on steep slopes, and thus are generally shallow and are the most vulnerable to erosion (CCA, 1991).

Yellow Earth Soils

The Yellow Earth soils are classified on the basis of elevation, soil texture, origin and age of parent material, and on their position on the landscape (Reid Collins and Associates, 1994). They are distinguished by their yellow-brown colour and exhibit excellent physical properties such as a high infiltration capacity, high permeability and water retention, and an extremely stable soil structure (Limbird, 1992).

The High-Level Yellow Earth soils are located in higher rainfall areas above 200 metres elevation (Reid Collins and Associates, 1994). They are *zonal* soils with impeded drainage and were earlier thought to be deeply weathered, leached and highly acidic (CCA, 1991). However, more recent studies have found that these soils are only slightly acidic and have not been leached, due to the periodic rejuvenation from ashfalls of recent volcanic eruptions (Limbird, 1992). This addition of calcium, magnesium and potassium to the soils has lowered the acidity to more neutral pH levels (Limbird, 1992). The Yellow Earth soils are considered to be the oldest soils on the island.

The Low-Level Yellow Earth or Brown Earth soils are found mainly below 200 metres elevation, and are *intrazonal* soils that have better drainage and less leaching (CCA, 1991). These brownish soils are found on gentler slopes and have been transported by colluvial processes from higher elevations. They are more fertile than the High-Level soils because they are rich in kaolinite and halloysite clays (Limbird, 1992). However, they have a lower water holding capacity and water availability than the upper level soils (Limbird, 1992). These soils have been intensely cultivated because they are found at lower, more accessible elevations.

The latter two soils described, as well as the alluvial soils, are the dominating soil types in the Colonarie River Watershed. There is also the possibility that the recent volcanic ash soils may be found at the highest elevations of the watershed; however, this area has not yet been surveyed (Limbird, 1992).

3.2.4 Vegetation

The description of the natural vegetation of the island of St. Vincent is based on Beard's (1949) classification. The Primary Rainforest has shown no evidence of disturbance and represents the climax vegetation community on the island. Only five percent of the total land area and thirteen percent of forested land is characterized as rainforest, which is found in the central mountains at elevations from 305 to 488 metres (CCA, 1991).

The Palm Brake forest is found in the central mountains above 488 metres, and is considered sub-climax due to disturbances such as landslides and intense storms (CCA, 1991). Disturbed areas are initially stabilized by the growth of moss, followed by a stand of small tree ferns (CCA, 1991). Elfin Woodlands are found within the Palm Brake on exposed ridges. Strong winds and cooler temperatures result in vegetation characterized by mosses, epiphytes and vines. Exposed trees appear gnarled, twisted and stunted (CCA, 1991). The Palm Brake Forest and the Elfin Woodlands are quite extensive, comprising 21 percent of forested land and 8 percent of the total land area (CCA, 1991).

The Secondary Rainforest (second growth forest) creates a buffer zone between the permanently cultivated land and the primary rainforest. Past disturbances have been caused by natural events or human activities. It ranges from areas under natural successional processes to plantation forests and agricultural production, including agroforestry. The general vegetation patterns of the island are shown in Figure 3.3.

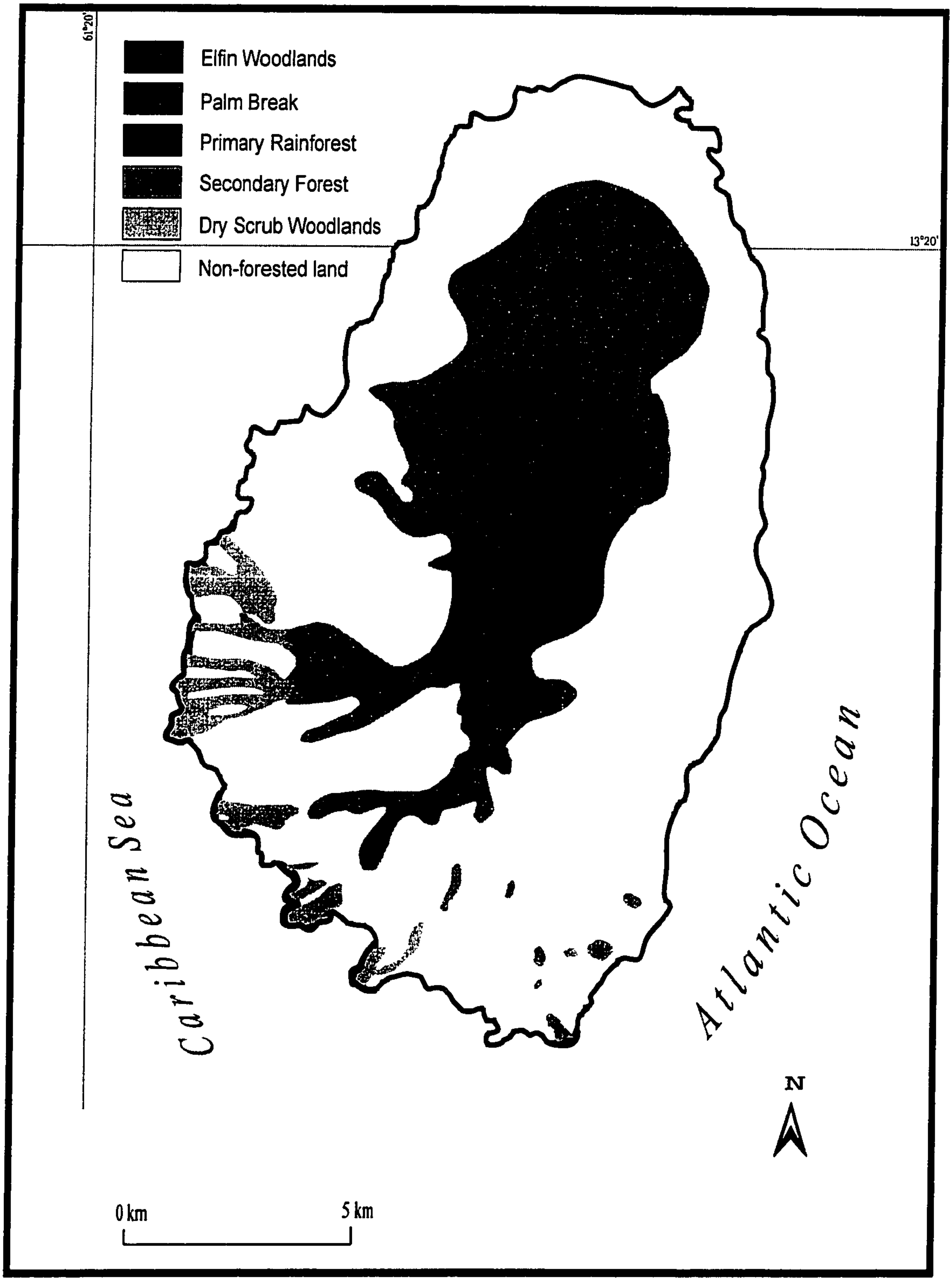

Figure 3.3 Vegetation of St. Vincent (modified from Ciccaglione, 1998).

3.3 Lauders Region

The Lauders region is located on the windward side of the island in the Union Watershed, approximately five kilometres inland from the coast. The region borders the southern edge of the upper basin of the larger Colonarie River Watershed, and is northwest of the village of Greiggs (see Figure 3.4). Small tributaries feed into the Union River that meanders northeasterly toward the coast. The topography of the area is mountainous with deep valleys, and elevation ranges from 305 to 518 metres. Due to its proximity to the windward coast, a marked dry season and the northeast trade winds influence the climate of the area.

Figure 3.4 Northwest view of the ridge boundary between the Colonarie and Union Watersheds: vegetation layers in foreground composed of *Gliricidia sepium* trees, mixed fruit trees (citrus, mango, breadfruit) and coconut palms.

Most of the land area appears to be under permanent cultivation in bananas, plantains, fruit trees (coconut, mango, breadfruit), root crops (dasheen, yam, sweet potato) and livestock farming (CCA, 1991) (see Figure 3.5). Access from the coastal Windward Highway is by a secondary road that travels west through the villages of Lowmans, Lauders and Greiggs. Vehicle access roads are limited in the upper reaches of the watershed but narrow banana roads do exist. Many of the farmers commute by walking, carpooling or by donkey.

Figure 3.5 Northeast view from the study area: coconut palms intermixed with bananas (in foreground).

A road extends from Greiggs to the edge of the upper basin in the Colonarie Watershed, to give access to farmers from the surrounding area who work in the Colonarie Basin (Reid Collins and Associates, 1993). Because of its close proximity and shared boundary with the Colonarie Watershed, the Lauders region is within the management jurisdiction of the neighboring watershed. The study area is illustrated in Figure 3.6.

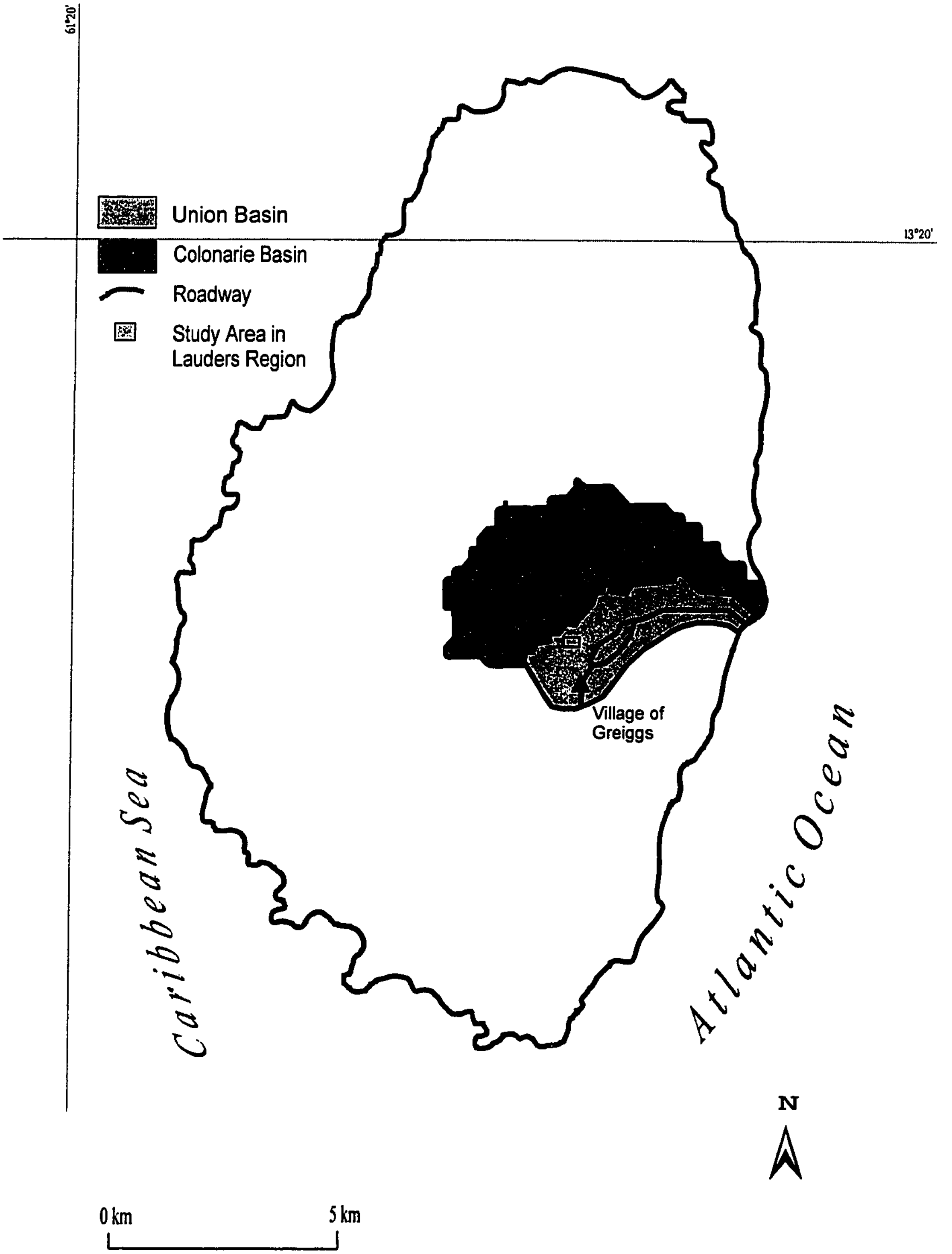

Figure 3.6 The Study Area within the Union Basin (modified from Ciccaglione, 1998).

4. CHAPTER FOUR: METHODOLOGY

4.1 Introduction

The research study consisted of fieldwork, laboratory analysis of the soil and sediment samples, and statistical analysis of the collected data. The fieldwork was carried out over a thirteen-week period beginning on May 27, 1997 and continuing until August 20, 1997. Data on water runoff, sediment loss, and precipitation values were collected weekly for each site. Soil profile samples also were taken including a topsoil sample (Ap horizon) from each site. Laboratory work was conducted on all sediment loss samples and soil profile samples at the University of Calgary. Statistical analysis was performed on the data using SPSS® for Windows 6.1.

4.2 Field Methodology

4.2.1 Site Selection

The location of the study area was based on a number of factors including: identifying established agroforestry systems on sloping lands that utilized alternatives to bananas, and obtaining the permission and cooperation of the farmer to set up the study and collect data. Relatively good access to the area by walking and driving was also important, especially when setting up and removing the equipment used in the field. Due to the short duration of the field season agroforestry systems employing a spatial as opposed to a rotational (temporal) arrangement were chosen.

The study area was located on private farmland in the Lauders region of the Union River Watershed, within the management zone of the Colonarie River Watershed. Four study sites were chosen in close proximity to each other based on similar characteristics of elevation, slope angle, length, aspect and soil type. Erosion plots were nested within larger vegetation plots to reflect any variation within the site. The size of each erosion plot was 5.0 metres in width and 12.0 metres in length (60 metres^2), and 7.0 metres by 14.0 metres (98 metres^2) for the vegetation plots, respectively. Small-scale runoff plots are suitable for a comparative analysis of different cropping practices and productivity losses (Hudson, 1993). The design of the agroforestry plots consisted of overlapping the tree and crop components to determine the erosional effects at the tree/crop interface.

4.2.2 Data Collection

The *Gerlach* trough method was used to quantitatively measure runoff water and sediment yield from erosion processes. This method is suitable for studying hillslope erosion at the micoscale level to evaluate soil erosion processes in relation to soil type, rainfall characteristics and overland flow (Lal, 1990). It involves the installation of troughs or traps placed at a slight downslope angle in a shallow trench along contours to intercept and collect eroded sediments and runoff (Lal, 1990). The trough units were constructed with plastic eavestroughing one metre in length and capped at each end. Metal flashing was attached to one side of the trap forming a lip that could be inserted easily into the soil. A thin plywood cover prevented rainfall and leaf litter or other debris from entering the trough. The eroded soil material was collected using a five-gallon bucket that was connected to the sediment trap through a six centimetre circular opening at the bottom of one end of the trough. The buckets were covered with plastic lids or duct tape and plastic sheeting. Wooden stakes were placed on all sides to secure each trough and to prop up the cover slightly. An example of the modified Gerlach trough is illustrated in Figure 4.1.

Three trough units were placed side by side and one metre apart along the lower boundary in each erosion plot (see Figure 4.2). The yam plots were bounded at the upslope edge using metal flashing because of their midslope position. Once the traps were put into place there was a two-week stabilization period to monitor any disturbance that may have occurred. Data on water runoff and sediment losses were collected weekly for thirteen weeks. Sediment loss samples were collected in labeled, plastic zip lock bags that were air dried for weighing and laboratory analysis. Water runoff volumes were measured and recorded on site using a graduated cylinder and a one-litre Nalgene bottle.

Data collection also involved completing a soil profile analysis representative of the soil type of the area. An eroded gully wall in close proximity to the study area was used to complete the soil field description and to collect soil samples from each horizon. This minimized the disturbance to the farmer's land and provided a clear view of the depth and horizonation of the soil. Information about the vegetation characteristics such as the composition and structure, percent canopy cover, height and diameter breast height of the tree species, and an estimation of the mass/square metre of leaf litter and mulch were collected in each plot using 0.25 x 0.25 metre quadrats.

Figure 4.1 A sediment and runoff collection trough at the yam study site.

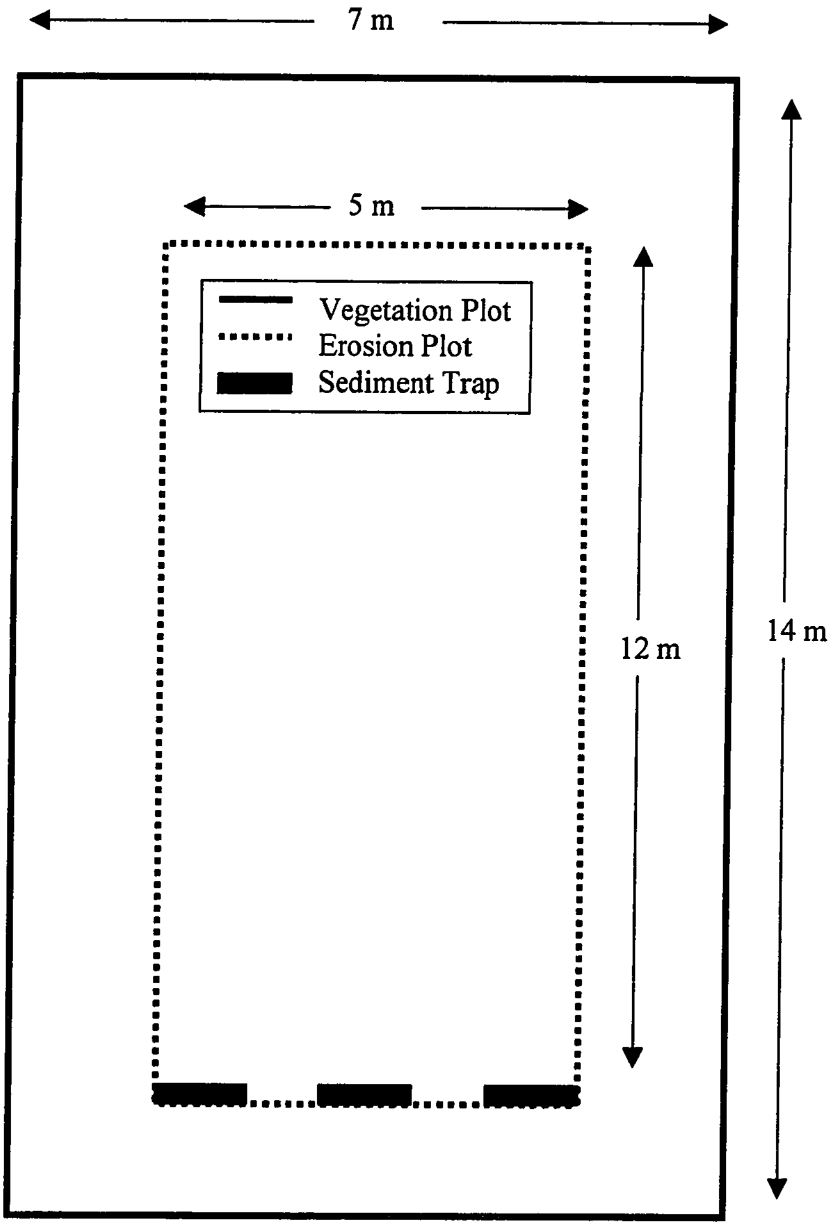

Figure 4.2 Schematic of soil erosion and vegetation plots.

Precipitation values were recorded weekly using a Belfort Universal Dual Traverse Weighing Bucket Recording Rain Gauge and a non-recording Rainwise Tipping Bucket Rain Gauge. Precipitation values are important in determining the variability of rainfall and possible effects on erosion processes. Data was collected for total precipitation, rainfall intensity, and the number and duration of rainfall events from the recording rain gauge, whereas the non-recording gauge was used as a check on total weekly precipitation.

The consent and cooperation of the farmer, Edmond Francis, was essential to conduct this research study. Background information about the establishment, maintenance and management practices was gathered for the study area whenever possible. The transfer of knowledge to farmers, ie. soil conservation measures, was discussed with forestry officers to determine how effectively information is spread to the local population.

4.3 Laboratory Analysis

Before undertaking the laboratory analysis the sediment samples and soil profile samples were air dried, and a portion of the sample was sieved through a 2mm screen. The sediment samples were weighed prior to sieving to determine the total sediment loss that occurred at each study site. Sediment samples collected from the three troughs in each study site were combined to give a representative weekly total of sediment loss. In addition, the weekly samples were combined into three time periods (*seasons*) for laboratory testing due to the small quantities of sediment collected. The time periods consisted of *Early* (weeks 1-5), *Middle* (weeks 6-9), and *Late* (weeks 10-13). These time divisions also were used to show any existing variability in the amount of sediment loss occurring throughout the field season.

The laboratory analysis consisted of a number of tests that were performed on both the sediment loss samples and the soil profile samples. The chemical analysis included pH, electrical conductivity, organic matter, extractable phosphorous, allophane, exchangeable cations and cation exchange capacity. Physical analysis consisted of particle size distribution (texture analysis). All procedures except extractable phosphorous were based on McKeague's (1976) "Manual of Soil Sampling and Methods of Analysis."

4.3.1 pH

The measurement of soil pH was conducted using a 2:1 solution/soil ratio whereby 20ml of distilled water (DI) was added to 10g of soil. The solution was stirred several times within one hour before any readings were taken. The measurements then were taken with a Fisher Scientific pH meter by immersing the electrode into the supernatant without touching the settled sediment. pH values of soils in distilled water are slightly higher (~ 0.5) than using 0.01*M* $CaCl_2$, but the results are highly correlated between the two methods (Limbird, 1997; Van Lierop, 1990). Electrical conductivity readings also were taken on the same sample with the DI water method.

4.3.2 Electrical Conductivity

Electrical conductivity is the ability of the charged ions within a soil to conduct an electrical current. Conductivity represents the presence of soluble salts, which occur by the weathering of rocks and minerals, rainfall and groundwater. Samples were prepared using the 2:1 ratio of distilled water/soil. Following the pH readings, the samples were centrifuged for 10 minutes to allow any soluble salts to dissolve. Then readings were taken using a Fisher Scientific Accumet meter and recorded in micro-Siemens/centimetre (μS^{-1}).

4.3.3 Organic Matter

The percentage of organic matter was determined using a modification of the Walkely-Black Wet Oxidation method. The samples were prepared by adding 10ml of potassium dichromate ($K_2Cr_2O_7$) and 20ml of concentrated sulfuric acid (H_2SO_4) to 1g of soil. After cooling for 20 minutes, 70ml of distilled water was added and the solution was filtered through a Whatman #2 filter paper into a cuvette. The cuvette was placed in the Perkin-Elmer Lambda 3 UV/VIS Spectrophotometer to determine an estimated transmission value, which corresponds to a percentage of organic matter in the standard table (available in the Department of Geography Soil Laboratory) .

4.3.4 Extractable Phosphorous

Available phosphorous was determined by using a solution of acid ammonium/sulfuric acid extract (Technicon, 1976). In this procedure, 25ml of the

Modified Medium Bray extract (0.03N NH_4 in 0.03N H_2SO_4) was added to 5g of soil and 1tsp of charcoal, and mechanically shaken for 2 minutes. The solution was then filtered with a #42 Whatman filter paper into a cuvette. The cuvette samples were analyzed in the Lambda 3 Colourimeter and graphically displayed. The length of the peaks (in centimetres) were then graphed to determine the concentration of available phosphorous (PO_4^-P) in mg/g.

4.3.5 Allophane

A spot test was used to determine if allophane was present in the sediment and soil profile samples (Wada and Kakuto, 1985). The test involved adding 0.4ml of 0.02% toluidine blue solution ($C_{15}H_{16}N_3SCl$) to 0.1g of soil in a white spot plate, and mixing for 15 seconds. Allophane is present in the sample if the supernatant remains blue. If the supernatant becomes colourless and the soil colour changes to purple/purplish red, then negatively charged humus and/or silicate layers are present.

4.3.6 Exchangeable Cations / Cation Exchange Capacity

Nutrient analysis consisted of testing for the exchangeable cations: Ca, Mg, Na, K, Al, Fe, and Mn. The method involved the addition of 30ml of 0.1*M* barium chloride extracting solution ($BaCl_2$) to a flask containing 1g of soil. The flasks were mechanically shaken for 2 hours, and then filtered through a Whatman #42 filter paper into a polyethylene vial. The extracts were analyzed with the Unicam 939 Atomic Absorption Spectrophotometer. Initial results were expressed as mg/L and were then converted into milliequivalents (meq) per 100 grams. The cation exchange capacity (CEC) is the total number of chemical reactions that occur on the soil particle surface by the various cations. The CEC is calculated by summing the totals of the exchangeable cations, and is also expressed as meq/100g.

4.3.7 Particle Size / Texture Analysis

Both the hydrometer method and the dry sieving method were used to determine the percentage of clay, silt and sand in the soil. The hydrometer method measures the specific density of soil particles suspended in water at various times of settling (McKeague, 1976). This method involved pretreating 40g soil samples with 20ml of hydrogen peroxide to oxidize the excess organic matter. Then the samples were mixed with 100ml of 50g/L calgon solution and 300ml of distilled water, and left to soak for a minimum of 12 hours. The samples were mechanically mixed for 5 minutes and poured into 1L cylinders and topped with distilled water. The suspended solution was inverted repeatedly for 10 seconds and hydrometer readings were taken at 30sec, 60sec, 3min, 10min, 30min, 90min, 4.5hrs and 18hrs. Particle diameters in microns (μm) were determined by comparing the readings obtained with standard tables posted in the Department of Geography Soil Laboratory.

The dry sieving method consisted of filtering the dry soil sample through a series of metal sieves of decreasing mesh size in the Tyler Ro-Tap Testing Sieve Shaker for approximately 5 minutes. The mesh sizes varied from 1700μm down to 120μm. After the sample was shaken, the amount of soil left in each sieve was weighed and a cumulative total was determined for each decreasing mesh size. The weights (in grams) were converted into percentages representing the " % Coarser by Weight," and graphed against the particle size (in microns) to determine the textural composition of the sample.

4.4 Statistical Analysis

The use of statistical methods in geography are important tools to present relationships and patterns based on empirical data (Silk, 1979). One simple method of describing the highlights or trends within the data is through descriptive statistics. Descriptive statistics including the weekly and season totals, and the average mean values were used to summarize and compare the data collected for sediment loss, water runoff and nutrient losses between each site. A one-way analysis of variance (ANOVA) was performed at a 5% significance level for examining variable means to determine if there were any statistical differences between each of the sites. Multivariate analysis was used to determine more complex relationships within the data. More specifically, a multivariate analysis of variance was used to analyze the differences within and between each of the study sites. Linear regressions were also performed on precipitation and runoff data for the Yam/Agroforestry and Dasheen sites, based on strong correlation values obtained between the two variables for these two sites.

4.4.1 Analysis of Variance / Multivariate Analysis of Variance

The one-way ANOVA evaluates the differences among means through two estimates of variance: differences within each group and differences between group means. The multivariate analysis of variance (MANOVA) analyzes the differences among means for a set of dependent variables when there are two or more levels of independent variables (Tabachnick and Fidell, 1996). The ANOVA tests whether mean differences among groups on a single dependent variable occurred by chance, whereas, the MANOVA tests whether the mean differences among groups on a combination of dependent variables occurred by chance (Tabachnick and Fidell, 1996). The "chance fluctuation" is determined by the spread (or variance) of observed values within each sample (Wonnacott and Wonnacott, 1984).

The statistical test for the null hypothesis (that the population means are equal) is based on a ratio termed the F statistic. It is calculated by dividing the between-groups mean square by the within-groups mean square. If the null hypothesis is true the ratio should be close to 1.0 (Norusis, 1993). The second step involves comparing the calculated F value to the F distribution (the distribution of the F value when the null hypothesis is true) to determine the observed significance level, called the *significance of F* (Norusis, 1993). If the significance level is less than 0.05 or 95% the null hypothesis is rejected (Fung, Pers. comm., 1999).

A two-way MANOVA was used to determine if observed differences in the dependent variables, sediment loss and runoff, among the four study sites came from the same population (natural variability) or from populations with different means (treatment effects). The two levels of independent variables used in the analysis were site and season (specified time divisions). The variability in sediment loss and runoff was analyzed by seasonal effects within and between each site, and by the interaction effect of site and season.

The MANOVA and the ANOVA both require the following assumptions: each of the groups is an independent random sample from a normal population, and the variances of the groups must be equal (Norusis, 1993). It is also necessary to have more cases than dependent variables in every cell (Tabachnick and Fidell, 1996). The significance tests for MANOVA are based on the multivariate normal distribution. Frequencies and box plots were performed to ensure a normal sampling distribution of the dependent variables. A greater limitation of the MANOVA is its sensitivity to outliers, which can produce either a Type I or Type II error (Tabachnick and Fidell, 1996). The presence and handling of outliers is discussed in Chapter 5.

4.4.2 Linear Regression

Although the main emphasis of this study was to examine differences in runoff, sediment and nutrient losses among the four sites, correlation matrices indicated a significant relationship between total rainfall and runoff in the Yam/Agroforestry and Dasheen sites. A simple regression analysis was performed for each of these sites to determine the influence of rainfall on runoff. A regression analysis is an expression of the relationship between an independent variable and the dependent variable. The degree of change in the dependent variable, Y, for a given change in the independent variable, X, is indicated by the parameters of the regression equation (Johnston, 1978):

$$Y = a + bX + E$$

Where, Y = predicted value on the dependent variable
a = y intercept (constant)
b = slope
X = independent variable
E = error term

The regression line or line of *best fit* is a straight line between the two variables that describes the trend in the scatterplot of points. The "fit" of the line is determined through the means of X and Y and minimizes the sum of the least squared residuals (the squared distances between the data points and the line), termed the least squares method (Tabachnick and Fidell, 1996; Harnett and Murphy, 1986). This method completes the regression equation by solving for the *a* and *b* values.

The regression model may be used as either a descriptive or predictive measure of a relationship depending on the type of study (Harnett and Murphy, 1986). If the values of X are randomly assigned and result in an increase in Y, then the likelihood of causation is greater than when the relation of Y to X occurs in an uncontrolled observational study where extraneous variables also may be significant (Wonnacott and Wonnacott, 1984).

4.4.3 Missing Data

Equipment problems in the field led to missing precipitation data. Missing values for weekly rainfall totals were estimated by determining the total amount of rainfall recorded, divided by the number of hours the rain gauge was operational. This average value was then multiplied by the total number of hours in a week to provide an average total rainfall value for the individual week (Fung, Pers. comm., 1999). The substituted values provide a general description of total rainfall patterns, but are likely to underestimate the actual rainfall that did occur. Average weekly intensity values were calculated only for the available data, as individual storm intensities could not be extrapolated from unrecorded data. This limits the number of outliers or extreme storm events that were recorded and consequently, would tend to underestimate the importance of rainfall intensity.

5. CHAPTER FIVE: RESULTS

5.1 Introduction

This chapter presents the results of the field, laboratory and statistical analyses. The results consists of descriptions of the study sites, data collected from the soil profile and surface horizon properties, sediment and runoff losses, and the statistical analyses. The interpretation of the results is presented in Chapter 6.

5.2 Study Site Descriptions

The yam sites were located side-by-side on the middle of the slope. The dasheen sites were located on the upper slope, adjacent to the yam/agroforestry site. The erosion plots were 60 metres^2 in size, within the 98 metres^2 vegetation plots. There was no evidence of fertilizer or pesticide use in any of the sites during the field season. The yams were planted four months prior to the start of the study and the dasheens were planted five months prior to the start of the study. Harvesting for both crops was expected to occur in September, following the completion of the study.

5.2.1 Yam Agroforestry Site (Y)

Site Y was a spatially zoned agroforestry system composed of yam vines (*Dioscoreales alata*) growing on live trellises, also called posts (*Gliricidia sepium*). The live posts were planted 1.5 metres apart between slope contours. The yams were planted on mounds (similar to discontinuous contours across the slope) that were 0.6 metres wide and 1.5 metres apart and acted as a soil conservation measure.

The slope angle was 16° (28%) with a straight, regular shape, facing southeast (see Figure 5.1).

Fertilizer was applied immediately after planting, but not during the field season. The site had a total of 21 *Gliricidia* trees in the vegetation plot (16 trees in the erosion plot) averaging 2.0-2.5 metres in height and a diameter breast height (DBH) of 15 centimetres. Canopy cover ranged from 20% at the beginning of the study to approximately 40% at the end of the study. Ground cover varied greatly throughout the plot and during the field season. At the beginning of the study, the ground cover was composed of *Gliricidia* cuttings, weeds and grasses, ranging from 25-30% towards the upper plot boundary to approximately 40-50% near the lower plot boundary. During the fourth week the ground cover was cleared and the live posts were pruned, leaving the *Gliricidia* cuttings on the soil surface. The ground cover increased to approximately 60% by the eighth week and increased weekly until the area was partially cleared by weeding during the final week of the study.

Figure 5.1 Yam study area: yam vines (*Dioscorea alata*) trailing on soil surface in foreground with live posts (*Gliricidia sepium*) in background.

5.2.2 Yam/Citrus Agroforestry Site (Y/AF)

Site Y/AF was a combination of a spatially zoned and mixed agroforestry system composed of yam vines (*D. alata*) growing on live trellises (*G. sepium*) intermixed with two Washington navel orange trees (*Citrus sinensis*). The orange trees were approximately 7.5 years of age and 5.0 metres tall with an average DBH of 25 centimetres. The planting pattern of the live posts (1.5 metres apart between mounds) and yams were similar to site Y. The slope angle was 15° (26%) with a straight, regular shape, facing southeast (see Figure 5.2). There were 25 *Gliricidia* trees in the vegetation plot (12 in the erosion plot) averaging 2.5 metres in height and 15 centimetres in width. The canopy cover varied from 30-35% at the beginning of the study to approximately 50% at the end of the study. The ground cover remained at 90 to 100% below the orange trees throughout the study, and differed greatly between the *Gliricidia* posts. Overall ground cover between the live posts was 20-25% at the beginning of the study, composed of *Gliricidia* cuttings, grasses and weeds. During the fourth week the live posts were pruned and the surrounding ground cover was cleared, but no cuttings were left on the soil surface. There also appeared to be some weeding around the perimeter of continuous ground below the citrus trees. The ground cover increased throughout the field season reaching 75% coverage by the eleventh week.

Figure 5.2 Yam/Agroforestry study area: yam vines (*D. alata*) twining around live posts (*G. sepium*) with an orange tree (*C. sinensis*) in right foreground.

5.2.3 Dasheen/Citrus Agroforestry Site (D/AF)

Site D/AF was a spatially mixed agroforestry system with one Washington navel orange tree (*C. sinensis*) intermixed with dasheen plants (*Colocasia esculenta*). Dasheens were densely planted approximately 0.5 metres apart. The orange tree was eight years of age and approximately 5.5 metres tall. Slope angles ranged from 15° (26%) on the upper slope to 17° (30%) on the lower slope with a slightly convex shape that faced south to southeast (see Figure 5.3).

The orange tree was located toward the bottom of the plot, providing 25% canopy cover. The understory and ground cover vegetation ranged from 80-90% near the top of the plot with larger dasheen plants and grasses, a ground cover of 100% underlying the tree, and only 10-15% understory composed of smaller dasheen plants towards the bottom of the plot. The ground cover was cleared during the fifth week of the study upslope from the tree, however, an understory coverage of 60% or greater was maintained throughout the season by the dasheen plants.

Figure 5.3 Dasheen/Agroforestry study area: dasheen plants (*Colocasia esculenta*) in foreground and orange trees (*Citrus sinensis*) in background.

5.2.4 Dasheen Agriculture Site (D)

Site D was a monoculture root crop of densely planted dasheens (*C. esculenta*). Dasheens were planted in holes 10.0 centimetres in diameter and 10.0-20.0 centimetres deep. Slope angles varied from 19° (34%) on the upper slope to 17° (30%) on the lower slope with a concave shape that faced southeast (see Figure 5.4).

The dasheen plants were slightly larger in size than in the D/AF site. An understory and ground cover layer composed of primarily dasheen plants with some grasses and weeds led to an overall coverage of 75% at the beginning of the study. The cover increased weekly until the tenth week when the area was fully weeded.

Figure 5.4 Dasheen study area: dasheen plants (*C. esculenta*) in foreground with an emerging ground cover composed of weeds and grasses.

5.3 Physical Properties of Soil Profile and Surface Horizons

5.3.1 Characteristics of Soil Profile Horizons

A soil profile analysis, representing the general soil type for the area was conducted on an exposed eroded gully wall adjacent to the four study sites. The description of the soil profile and soil chemistry results are found in Appendices A and B, respectively.

The profile was representative of the High-Level Yellow Earth soils developed from deep volcanic ash and found above 200 metres elevation. The soil also shares many common properties with a new soil series described by Limbird (1992) in the

Colonarie Watershed, called the Gabe Field Series. Similarities included: moderate organic matter content that decreased with depth; pH levels greater than 6.0 (ranging from 6.8 to 7.2); low phosphorous levels; relatively high levels of potassium and calcium; and a high base saturation (>80%). Other common properties are moderately rapid infiltration and moderate to rapid permeability, increasing with increasing particle size (Limbird, 1992). The solum depth (total depth of the A and B horizons) was 166 centimetres and was generally well-drained. The soil colour ranged from dark brown (10YR) to strong brown (7.5YR) with relatively high chromas, indicative of good aeration and oxidation in the soil. Clear, smooth boundaries marked each horizon.

The results of the standard tests used for texture analysis in the lab were misleading in comparison to the field method. The laboratory results indicated that the dominating texture within the soil profile was sand to loamy sand, whereas field textures ranged from clay loam to sandy loam. One explanation for these differences is the tendency of silt and clay particles to encrust sand and silt sized aggregates in volcanic ash soils (Limbird, Pers. comm., 1999; Spycher, et al., 1986). This process of interstitial sedimentation or cementation occurs naturally when water drains from the soil (Spycher, et al., 1986). Air-drying the samples also causes cementation of the finer particles, resulting in a decrease in the measured clay and silt content (Maeda, et al., 1984). When standard particle size analysis procedures are used the large aggregates resist dispersion, forming "artificially" coarse textures (Lal, 1979a; Limbird, Pers. comm., 1999). The discussion of the soil profile and surface horizons are therefore, based on the field texture results.

The surface horizons (A and B1) formed the cultivation mixing zone with a depth of 56 centimetres, and exhibited granular (A) to sub-angular blocky (B1) structure and a silty loam texture, consistent with the surface horizons of the Gabe Field soils. The A horizon had the lowest pH (6.8) and CEC (2.91meq/100g) of the horizons but higher levels of organic matter (3.5%) and soluble salts (85.9mS^{-1}). The percentage of organic matter (4.0%) was only higher in B1. The loamy textured B2 horizon was an *agric* horizon resembling a compact plow pan resulting from years of cultivation. Evidence of an *argillic* horizon (enriched with clay from above) was found in B4, with the appearance of clay nodules. This horizon was characterized as a clay loam with the highest CEC and the strongest concentration of the mineral nutrients Ca, Mg, and Na, but lower levels of organic matter (2.8%). The most distinguishing feature of the soil profile was the presence of two coarse sand layers in the subsoil, characteristic of the Gabe Field Series. The B3 and C1 horizons represent coarser ashfalls dating back to the Pleistocene (Limbird, 1992). These horizons had a sandy loam texture and the lowest percentages of organic matter (2.6% and 2.5%, respectively). However, the CEC of B3 was quite high relative to the other horizons (5.23meq/100g) and exhibited the highest concentration of Fe (0.21meq/100g) in the profile. The unconformity of these coarse layers make the soil more vulnerable to severe erosion on steeper slopes (>43°), and may lead to slumping and sliding activity, especially by undercutting the slope (Limbird, 1992).

5.3.2 Characteristics of Surface Horizons

Overall, the surface horizons sampled at each site displayed a higher CEC, percent base saturation and greater levels of organic matter than the A profile horizon. There was also evidence of available phosphorous although the values are low. The Dasheen/Agroforestry site was characterized with the highest CEC, K concentration, and percent organic matter, and the lowest conductivity value (soluble salts). All of the surface horizons had a silt loam texture and granular structure.

5.4 Soil Chemistry of Surface Horizons

Soil erosion processes result in the loss of nutrients and organic matter from the surface horizons. Therefore, an examination of the chemical properties of the surface horizons is important as the source of the eroded material. The results of the chemical analysis for the surface horizons are shown in Appendix B.

5.4.1 Cation Exchange Capacity

Overall, the CEC based on the exchangeable cations was quite low for all of the sites (<10.0meq/100g). However, when the contribution of organic matter is factored in, the total CEC is similar to the average CEC of the Gabe Field soils (15.0-20.0meq/100g). The total CEC ranged from fair (10.0-15.0meq/100g) to good (15.0-20.0meq/100g) among the surface horizons (Limbird, 1992). The Dasheen/Agroforestry site had the highest CEC (18.18meq/100g), followed by the Yam site (16.17meq/100g). The lower values were similar in the Yam/Agroforestry and Dasheen sites (14.10meq/100g and 14.95meq/100g, respectively). The highest cation exchange capacity excluding organic matter was also found in site D/AF (6.58meq/100g) and the lowest value was in site Y/AF (4.7meq/100g). The CEC based on exchangeable cations and the total CEC for the surface horizons at each site are presented in Figure 5.5.

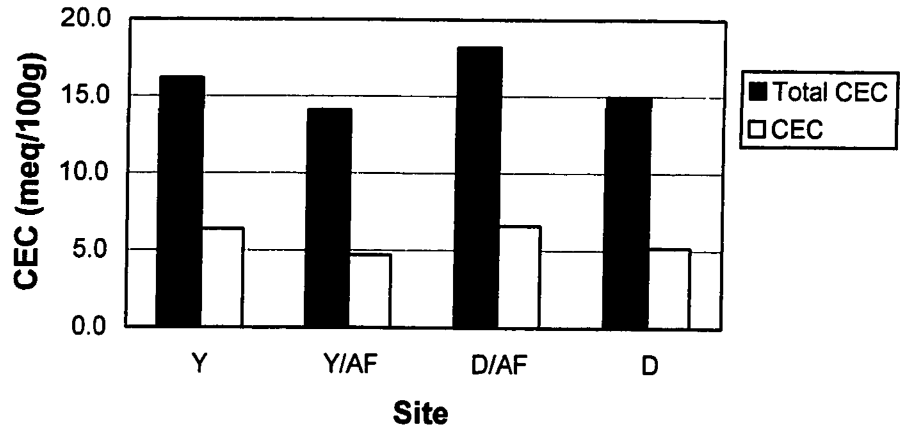

Figure 5.5 CEC for the surface horizons at the study sites.

5.4.2 Organic Matter

The percentages of organic matter in the surface horizons are shown in Figure 5.6. Overall, the organic matter content is similar among the four sites and is considered very good relative to other St. Vincent soils (Limbird, 1992). The greatest percentage of organic matter (5.8%) was found in the Dasheen/Agroforestry site. An organic matter content of 5.5% or more is considered excellent (Limbird, 1992). The percentages were similar for the remaining sites, varying from 4.7% in the Yam/Agroforestry site to 4.9% in the Yam and Dasheen sites.

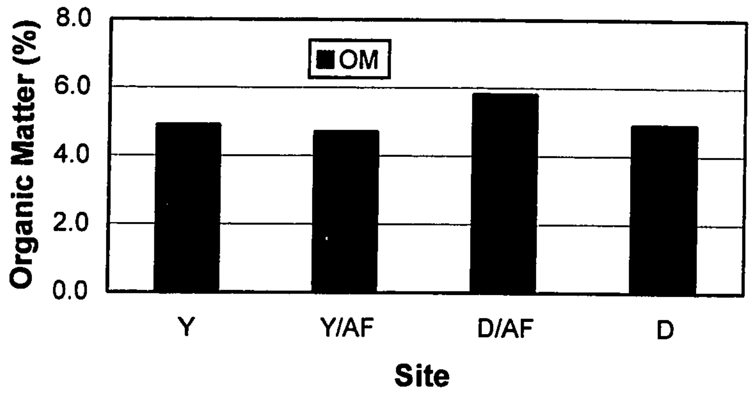

Figure 5.6 Percent organic matter for the surface horizons at the study sites.

5.4.3 pH

The pH levels for the surface horizon at each study site are presented in Figure 5.7. The pH levels ranged from slightly acidic to neutral, with the lowest pH in the Yam/Agroforestry site (6.4) and the highest pH at the Yam site (7.0).

A pH level greater than 6.3 is considered excellent, indicating a high nutrient availability for plants (Limbird, 1992).

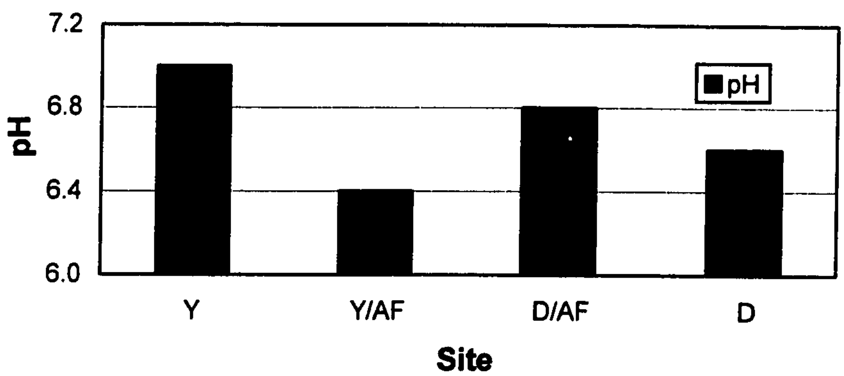

Figure 5.7 pH levels for the surface horizons at the study sites.

5.4.4 Base Saturation

The base saturation is the percentage of a soil's total cation adsorption (exchange) capacity represented by the proportion of the base-forming cations, Ca, Mg, K and Na (Brady, 1990). The percent base saturation is calculated by dividing the exchangeable base-forming cations by the total CEC of the soil. The surface horizons have extremely high base saturation percentages (>90%) with the highest value in the Yam site (99.2%). A percent base saturation of 70% or greater is considered excellent (Limbird, 1992). The percentage base saturation for the surface horizons is presented in Figure 5.8.

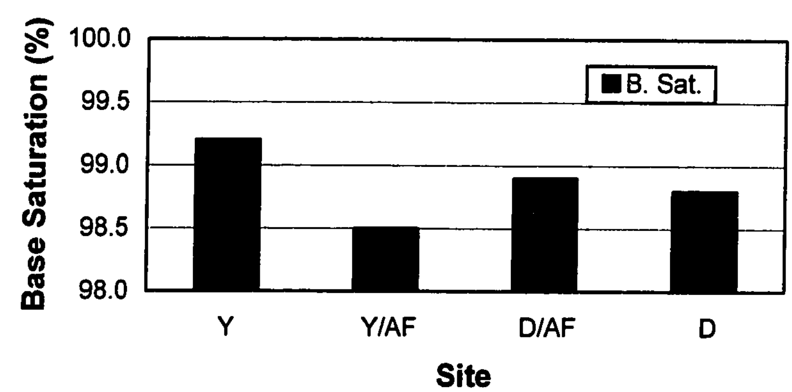

Figure 5.8 Base saturation for the surface horizons at the study sites.

The largest proportion of the CEC is the base-forming cation calcium. The percentage calcium saturation accounts for approximately 60% or higher of the total percentage base saturation. The highest percentage of calcium ions is located in the Yam/Agroforestry site, followed by the Dasheen, Yam and Dasheen/Agroforestry sites (70.8%, 69.5%, 66.7%, and 59.7%, respectively).

5.4.5 Electrical Conductivity

Electrical conductivity readings for the surface horizons are presented in Figure 5.9. Conductivity exhibited the greatest range of all the chemical properties among the four sites. The presence of soluble salts was greatest in the Yam site (118.0μS^{-1}) followed by the Yam/Agroforestry site (103.0μS^{-1}). The conductivity values were similar in both the Dasheen/Agroforestry and Dasheen sites (77.5μS^{-1} and 79.2μS^{-1}, respectively).

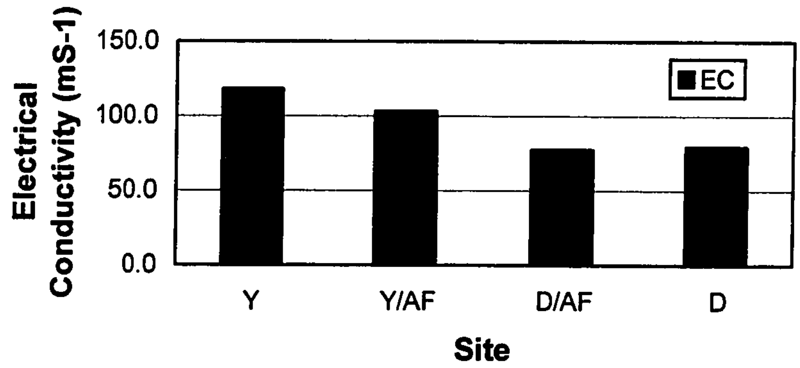

Figure 5.9 Electrical conductivity for the surface horizons at the study sites.

5.4.6 Allophane and Extractable Phosphorous

Laboratory analysis indicated that no allophane was present in any of the surface or profile horizons. There are two possible explanations for this occurrence. The lack of allophane may be indicative of older soils due to the weathering of silicate clays (Limbird, 1992). Alternatively, young soils that have not undergone sufficient weathering of the silt and fine sand fractions (containing volcanic glass) will contain little or no allophane (Leamy, et al., 1984).

Available (extractable) phosphorous was only found in trace quantities in the surface horizons. The highest concentration (0.004mg/g) occurred in the Dasheen/Agroforestry and Yam sites. Low extractable phosphorous levels are common in most soils, particularly in volcanic ash soils due to the binding of phosphorous compounds (termed phosphorous fixation) by the soil solids in a form that is unavailable to plants (Brady, 1990; Visser, 1989).

5.5 Sediment and Runoff Analysis

5.5.1 Total Sediment Loss and Runoff

Total runoff and sediment losses are summarized in Table 5.1. Total sediment loss values were calculated by site (g/60m^2 or 0.006ha) and by an indexed value (kg/ha). Runoff values also were calculated by site (L/60m^2) and by an indexed value (L/m^2). Overall, total sediment loss does not appear to differ greatly between the four sites. Sediment losses were only 1.4 times greater in the Dasheen/Agroforestry site (143.3g/site) compared to the Yam/Agroforestry site (102.5g/site). The variability decreased slightly between different crop types. Sediment loss was 1.2 times greater or 124% in the Yam site relative to the Yam/Agroforestry site, whereas, the Dasheen/Agroforestry site had only 1.1 times or 114% more sediment loss than the Dasheen site.

Site	Sediment Loss (g/site) / kg/ha	Runoff (L/site) / L/m^2
Yam	*(123.0g/site)* / **21.0kg/ha**	*(42.6L/site)* / **0.71L/m^2**
Yam/Agroforestry	*(102.5g/site)* / **17.0kg/ha**	*(27.7L/site)* / **0.46L/m^2**
Dasheen/Agroforestry	*(143.3g/site)* / **24.0kg/ha**	*(16.9L/site)* / **0.28L/m^2**
Dasheen	*(122.9g/site)* / **21.0kg/ha**	*(12.3L/site)* / **0.21L/m^2**

Table 5.1 Sediment and runoff losses for the study sites.

Differences in runoff values were more significant. The highest runoff value recorded in the Yam site (42.6L/site) was 3.4 times (338%) greater than the lowest runoff value recorded in the Dasheen site (12.3L/site). Runoff at the Yam site was 1.5 times or 154% greater than at the Yam/Agroforestry site, and 1.3 times or 133% greater at the Dasheen/Agroforestry site compared to the Dasheen site.

5.5.2 Seasonal Runoff and Sediment Losses

Seasonal runoff and sediment losses are presented in Figures 5.10 and 5.11, respectively. The seasonal or time divisions were denoted earlier (section 4.3) as *Early* (weeks 1-5), *Middle* (weeks 6-9) and *Late* (weeks 10-13). Runoff increased over the field season at all sites, but seasonal patterns differed between each site (see Appendix C). The highest runoff values were recorded during the *Late* season in the Yam and Dasheen/Agroforestry sites. The largest increase in runoff at the Yam/Agroforestry and Dasheen sites occurred during the *Middle* season. Runoff decreased by over 50% from the *Middle* to *Late* seasons in the Yam/Agroforestry site.

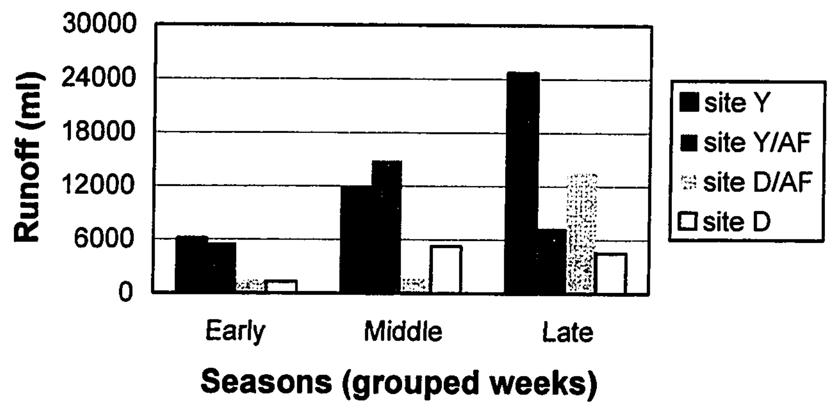

Figure 5.10 Seasonal runoff losses for individual study sites.

Sediment loss increased similarly for all sites throughout the field season, however, seasonal patterns differed from the observed runoff patterns. Sediment losses were highest during the *Late* season in the Yam/Agroforestry, Dasheen/Agroforestry and Dasheen sites. The greatest sediment loss occurred in the Yam site during the *Middle* season. The anticipated pattern of increased runoff resulting in increased sediment loss was evident only in the Dasheen/Agroforestry site. Weekly and seasonal values collected for runoff, sediment loss and rainfall are shown in Appendix C.

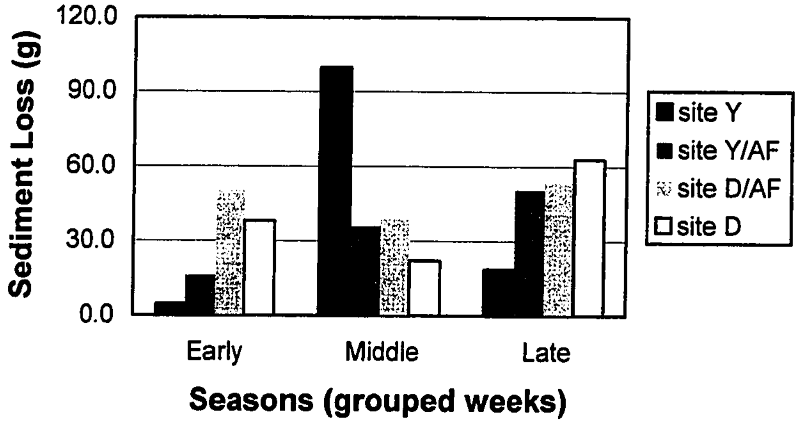

Figure 5.11 Seasonal sediment loss for individual study sites.

5.6 Soil Chemistry of Eroded Sediments

The soil chemistry of the eroded sediments is presented in Appendix B. This section presents a summary of the results for each study site by season. An ANOVA was performed for each variable to determine whether differences were statistically significant.

5.6.1 CEC and Exchangeable Nutrients

CEC: Total loss in CEC of exchangeable cations in the Dasheen/Agroforestry site was 1.69 times greater (169%) than in the Yam/Agroforestry site. These sites represented the highest (20.76meq/100g) and the lowest (12.31meq/100g) total losses in CEC, respectively. The largest overall seasonal loss of CEC was during the *Late* period (weeks 10 to 13), with a total loss of 26.72meq/100g and an average loss per site of 6.68meq/100g. Average seasonal losses in CEC were greatest in the Dasheen/Agroforestry site (6.92meq/100g), followed by the Dasheen

(4.90meq/100g), Yam (4.51meq/100g), and Yam/Agroforestry (4.10meq/100g) sites (see Appendix B). A one-way ANOVA indicated that there was no statistical difference between average seasonal losses in CEC between sites. Seasonal loss results are presented in Figure 5.12.

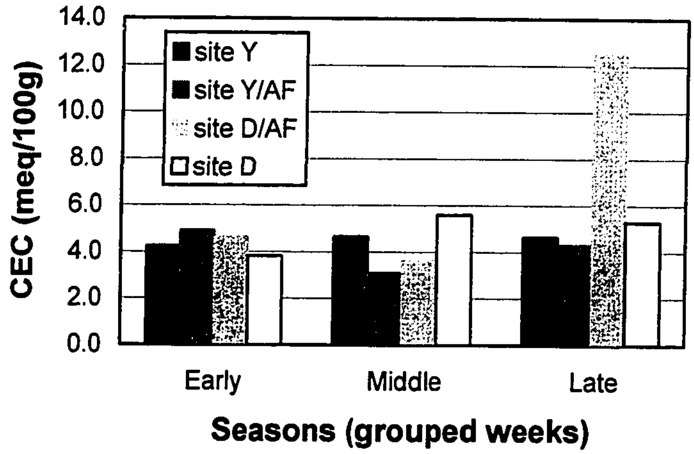

Figure 5.12 CEC for sediment loss samples by season.

Individual Nutrients: Nutrient losses also were determined for all sediment loss samples. Nutrient analysis included Ca, Mg, Na, K, Mn, Fe, and Al. Table 5.2 compares the mean seasonal loss value for each nutrient between the sites. One-way ANOVA tests performed for each individual nutrient indicated that the mean seasonal nutrient losses between sites were not statistically significant.

Nutrient	Site Y (meq/100g)	Site Y/AF (meq/100g)	Site D/AF (meq/100g)	Site D (meq/100g)	Statistical Difference
Ca	2.56	2.28	4.31	2.31	**no**
Mg	0.93	0.81	0.99	0.93	**no**
Na	0.49	0.43	0.55	0.61	**no**
K	0.36	0.42	0.86	0.88	**no**
Mn	0.12	0.11	0.16	0.10	**no**
Fe	0.02	0.01	0.02	0.02	**no**
Al	0.03	0.04	0.04	0.04	**no**

Table 5.2 Comparison of average seasonal loss values for individual nutrients.

The total loss of each nutrient per site is another important measure of site comparison. Table 5.3 compares the total loss of each nutrient for each site. The greatest difference (expressed in magnitude) between the **highest** and ***lowest*** values are given with the site reporting the greatest loss of the individual nutrient. The individual nutrients are expressed as g/kg/site (or g/site).

Nutrient	Site Y g/site	Site Y/AF g/site	Site D/AF g/site	Site D g/site	Greatest Loss Site (x times)
Ca	15.36	***13.71***	**25.88**	13.89	Site D/AF (1.9 times)
Mg	3.41	***2.96***	**3.59**	3.39	Site D/AF (1.2 times)
Na	3.82	3.39	***2.96***	**4.22**	Site D (1.4 times)
K	9.99	***4.23***	4.86	**10.30**	Site D (2.4 times)
Mn	1.01	0.92	**1.34**	***0.79***	Site D/AF (1.7 times)
Fe	0.12	***0.09***	**0.18**	0.15	Site D/AF (2.0 times)
Al	***0.09***	0.11	0.10	**0.12**	Site D (1.3 times)

Table 5.3 Comparison of total individual nutrient losses.

The greatest loss of nutrients occurred in the Dasheen/Agroforestry site and the Dasheen site. The loss of potassium (K) was 2.4 times greater in the Dasheen site than in the Yam/Agroforestry site, representing the largest difference between sites. For other nutrients, the magnitude of losses varied from 1.2 times (Mg) to 2.0 times (Fe) between sites.

5.6.2 Organic Matter

The loss of organic matter by season is shown in Figure 5.13. The total loss of organic matter was 1.3 times greater in the Dasheen site (21.50g) than in the Dasheen /Agroforestry site (16.76g). Losses were also high in the Yam site (20.54g) and relatively lower in the Yam /Agroforestry site (13.73g). The average seasonal loss of organic matter ranged from 4.58g in the Yam/Agroforestry site to 7.17g in the Dasheen site. The *Late* season (weeks 10-13) had the highest overall average loss among all of the sites (6.57g), followed by the *Middle* (5.79g) and *Early* (5.78g) seasons. A one-way ANOVA indicated that there was a statistically significant difference in the average seasonal loss of organic matter between sites.

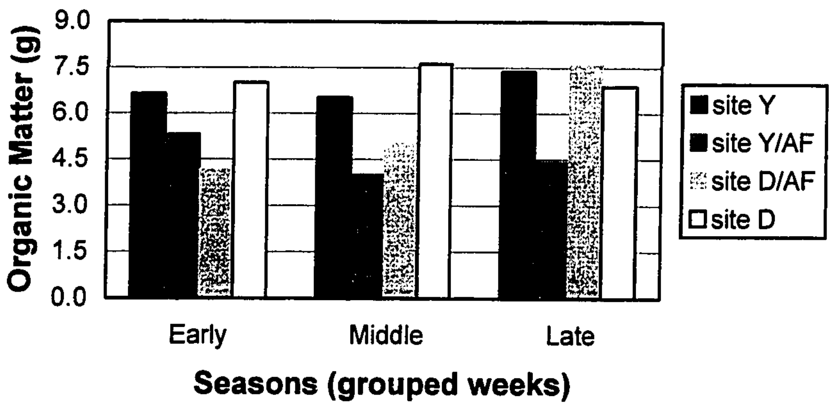

Figure 5.13 Organic matter values for sediment loss samples by season.

5.6.3 pH

Average pH values of the eroded sediments ranged from 6.6 in the Yam/Agroforestry site to 7.0 in the Yam site. The average pH in the Dasheen/Agroforestry and Dasheen sites was 6.8 and 6.7, respectively. The pH decreased over time in the two yam sites becoming slightly more acidic, whereas, the pH values decreased by one/tenth in the *Middle* season and then increased by two/tenths (to the original recorded value) in the *Late* season in both of the Dasheen sites. An ANOVA found no statistically significant differences in average seasonal pH values among the sites. The seasonal pH values for the eroded sediments are shown in Figure 5.14.

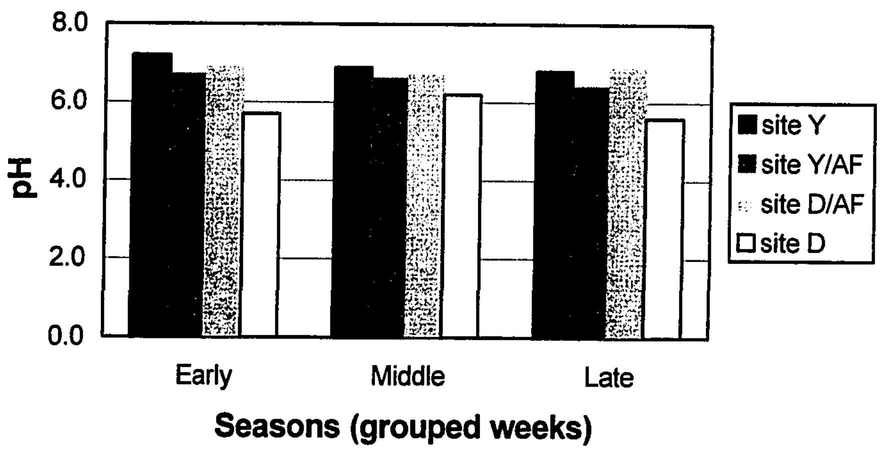

Figure 5.14 pH values for sediment loss samples by season.

5.6.4 Electrical Conductivity

Seasonal averages for electrical conductivity were similar among the sites with the exception of the Dasheen site (see Figure 5.15). The average conductivity values for the first three sites were 362.0μS^{-1}, 321.0μS^{-1} and 387.0μS^{-1}, respectively. The Dasheen site had an average seasonal conductivity value of 678.3μS^{-1}. Soluble salt levels increased throughout the field season in the eroded sediments at the Yam and Dasheen/Agroforestry sites, but fluctuated greatly in the Yam/Agroforestry and Dasheen sites. The conductivity levels at site D increased sharply in the *Middle* season, but decreased in the *Late* season. The reverse occurred at the Yam/Agroforestry site, where the conductivity levels decreased during the *Middle* season and increased towards the end of the study. Average seasonal electrical conductivity losses were not statistically significant between the four study sites.

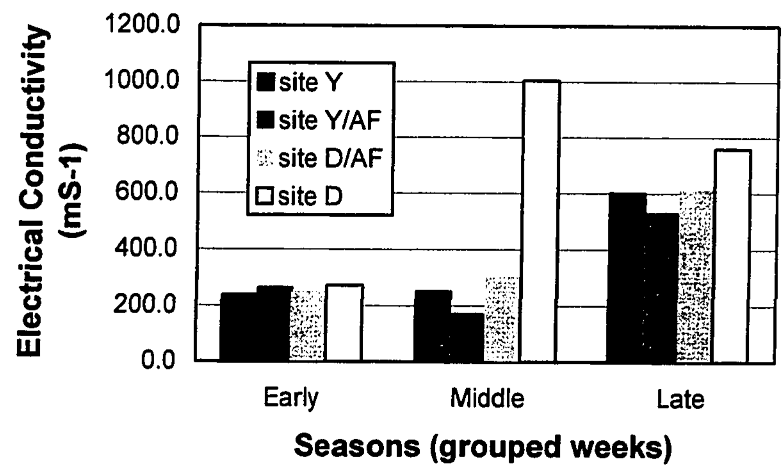

Figure 5.15 Electrical conductivity for sediment loss samples by season.

5.6.5 Allophane and Extractable Phosphorous

No allophane was present in the eroded sediments, as anticipated. Trace amounts of extractable phosphorous were determined, and differences between sites were insignificant. Total losses of extractable phosphorous by site were Y (0.016mg/g), Y/AF (0.013mg/g), D/AF (0.023mg/g), and D (0.020mg/g), respectively.

5.7 Multivariate Analysis of Variance

A two-way multivariate analysis of variance (MANOVA) was performed to determine if the observed losses of runoff and eroded sediments were statistically different both within each site (seasonal variation) and between each site. The

MANOVA also calculates whether an interaction effect between the two independent variables, site and season, is significant.

Before the analysis was undertaken the data values were checked to ensure a normal sampling distribution using frequency tables and boxplots (see Appendix D). Boxplots were created for each of the dependent variables runoff, sediment loss and rainfall (used in regression analysis). The horizontal line within the box represents the median value, whereas the lower and upper boundaries of the box are the calculated 25th and 75th percentiles, respectively (Norussis, 1993). Outlying values are classified in the following ways. Values that are within 1.5 to 3.0 box lengths from the upper or lower edge are classified as outliers and characterized by a circle. These values are included in the study but must be explained during the interpretation. Values that are more than 3.0 box lengths away, are defined as extreme values, and must be omitted or modified for the analysis (Fung, Pers. comm., 1999; Norusis, 1993).

The boxplot of the runoff variable exhibited two extreme values (represented by a star), and one outlier. The boxplot created for sediment loss had two extreme values and two outliers. Because the MANOVA works with pairwise data, three cases were omitted from the analysis (case number 6 was extreme in both variables). Case number 6 represented a sharp increase in both runoff and sediment values in the Yam site during week 6, as a result of the plastic cover falling into the collection bucket. The other extreme value omitted from the runoff variable may have resulted from a potential leak (unsecured cover) at the Yam site (week 12). A large increase in sediment loss at the Dasheen site in week 10 was the second extreme value in the sediment loss variable, and was attributed to the clearing of the understory within that week.

5.7.1 MANOVA for Sediment Loss

The first component of the MANOVA analyzed the means and standard deviations of the eroded sediments collected for each site by season. Fifty cases were analyzed including the two outliers. The sum of squares and the mean sum of squares (dividing each sum of squares by its degrees of freedom) were calculated from the means and standard deviations. This generated an *F* value and the *significance of F*. The significance of *F* compares the calculated *F* value to the *F* distribution, and accepts the null hypothesis if it is greater than 0.05. The significance of *F* for sediment loss by site was 0.191 and 0.576 for sediment loss by season, respectively. The interaction effect had a significant *F* of 0.651. These results indicate that the population means were not statistically different and the null hypothesis was accepted. Therefore, the observed differences in seasonal sediment loss patterns within a site and the total loss of sediment between the four sites was not statistically significant.

5.7.2 MANOVA for Runoff

The MANOVA for runoff also analyzed fifty cases including one outlier value. Following the same calculations, the significance of *F* values were generated. The significance of F for runoff by site and by season was 0.312 and 0.032, respectively. The interaction effect between site and season had a significant F of 0.096. These results show that site effects and the interaction effect were not statistically different and the null hypothesis was accepted. However, the seasonal effect of runoff was statistically significant among the four sites. An examination of the means suggest great fluctuations in runoff by season between the sites. These trends were observed in the recorded data (see section 5.5.2). The Dasheen/Agroforestry site was the only site where runoff progressively increased throughout the field season. In the Y/AF and D sites, runoff increased considerably between the *Early* and *Middle* seasons, but decreased in the *Late* season. Site Y had a decrease in runoff from the *Early* to the *Middle* seasons and a large increase in the *Late* season.

One limitation of the analysis was the small number of cases (Fung, Pers. comm., 1999). A small sample size reduces the effectiveness of the analysis because it does not reflect a true representative sample of the population. This was observed in the large standard deviations calculated in this analysis. Although the minimum requirement of cases per dependent variable for each cell was met, the power of the analysis was lowered because of reduced degrees of freedom for error (Tabachnick and Fidell, 1996).

5.8 Linear Regression

Correlation matrices indicated a strong correlation (>0.5) between total rainfall and runoff in two of the four sites (see Appendix E). The rainfall–runoff relationship was reflected in the Yam/Agroforestry site with a correlation of 0.5722 and in the Dasheen site with a correlation of 0.6945. An examination of the scatterplots infers a positive linear relationship between the two variables, thereby suggesting that an increase in rainfall would cause an increase in runoff (see Appendix E). A simple regression was performed for each of these sites to determine the strength of the linearity of the relationship. Regression analyses were not performed for the Yam and Dasheen/Agroforestry sites due to the low correlation values obtained between the rainfall and runoff variables. The correlation values were 0.2089 for the Yam site and 0.1533 for the Dasheen/Agroforestry site, indicating a weak relationship between rainfall and runoff.

Boxplots (see section 5.7) were created for both of the variables to ensure normality and homogeneity (Appendix D). The two extreme values in the runoff boxplot also were omitted from the regression analyses. The boxplot for total rainfall exhibited no outliers (within 1.5 to 3.0 box lengths) or extreme values (>3.0 box lengths). However, total rainfall values are likely to be underestimated due to problems with missing data. The substituted rainfall values represent mean values based on the individual week's precipitation patterns (Appendix C).

5.8.1 Yam/Agroforestry Site

The correlation coefficient between the independent variable, rainfall, and the dependent variable, runoff, was 0.5722. The regression analysis generated an R^2 value of 0.327 and an adjusted R^2 value of 0.266. The R^2 value is the total variance of the dependent variable explained by the regression equation. The adjusted R^2 value is the total variance corrected for sample size (Tabachnick and Fidell, 1996). The results indicate that rainfall explained approximately 33% of the variance in runoff (adjusted R^2 = 27%). The strength of the relationship between rainfall and runoff at the Yam/Agroforestry site was expressed by the following regression equation:

$$\textbf{Runoff} = \mathbf{670.178 + 21.959\ (X_{n1}) + 1709.230}$$

The explanation for runoff is stated in the equation as the constant (670.178), plus the predicted value for rainfall (the regression coefficient b_1 = 21.959), multiplied by the observed value for runoff (X_{n1}), plus the standard error of estimate (1709.230).

The overall explanatory power of the regression equation was quite low for a number of reasons. The predictive power of rainfall may have been underrepresented because of missing data. The predictive power also may have been influenced by the presence of an outlier recorded on the scatterplot during week 8 (6,620ml) that is inconsistent with the linear pattern exhibited in the data.

The value was included in the analysis because it wasn't considered an extreme value. In addition, the outlier would have contributed to the large standard error (1709.23). The standard error describes how far the dependent variable departs from its predicted value (Achen, 1982). Finally, other factors such as rainfall intensity may also have been as or more influential in causing runoff, but accurate data was not available for analysis.

5.8.2 Dasheen Site

The Dasheen site had a relatively strong correlation (0.6945) between the rainfall and runoff variables. The regression analysis resulted in an R^2 value of 0.4823 and an adjusted R^2 value of 0.4305. Therefore, the variance of runoff explained by rainfall was 48% (adjusted R^2 = 43%). The strength of the relationship between rainfall and runoff at the Dasheen site was expressed by the following regression equation:

$$\textbf{Runoff} = -152.944 + 13.563\,(X_{n1}) + 711.462$$

The runoff equation was expressed as the constant (–152.944), plus the predicted value for rainfall (13.563) multiplied by the observed value for rainfall (X_{n1}), plus the standard error of estimate (711.461).

The overall explanatory power of the regression analysis for the Dasheen site was much higher than in the Yam/Agroforestry site. The standard error was also much lower (711.461) indicating a decrease in variance between the observed and predictive values for the dependent variable. As previously stated in the first regression analysis, the predictive power of rainfall may have been underestimated, and the influence of other variables was not examined.

The greatest limiting factor of the regression analyses was the sample size. A *significance of F* value close to 1.0 characterizes a representative sample of the population. The *significant F* values for the Yam/Agroforestry and Dasheen sites were 0.0122 and 0.0410, respectively. These values indicate that the sample size was too small to accurately represent a population sample. Therefore, the results of the regression analyses are simply a descriptive measure rather than predictive.

6. CHAPTER SIX: DISCUSSION

6.1 Introduction

This chapter presents a discussion of the results outlined in Chapter Five. An assessment of the study sites is based on a comparison of vegetation characteristics, soil properties (texture, organic matter, CEC, pH, electrical conductivity), nutrient losses (exchangeable cations) and soil fertility levels at each of the sites. This assessment is followed by an examination of the sediment and runoff loss patterns. Lastly, the use of agroforestry systems as a reclamation technique is discussed.

6.2 Vegetation Characteristics and Soil Properties

6.2.1 Vegetation Characteristics

The characteristics of the different vegetation types provided a unique contribution toward the productive and/or protective roles in each of the study areas. The characteristics of the dominant vegetation types: yams, live posts, orange trees and dasheens, are discussed individually to examine their role(s) at each site.

Yams (Dioscorea alata)

The dominant forms of vegetation in the Y and Y/AF sites were yam vines and live posts. Commonly called the "water yam" or "greater yam," *D. alata* is considered to be a demanding crop because of its high nutrient requirements, particularly for potassium and magnesium, and a low tolerance of waterlogging and salinity (Degras, 1993; Landon, 1984). Yams require approximately seven to nine months from planting to harvesting, with a relatively long rainfall season. They are often planted during the dry season (two or three months before the rains) because of their moderate tolerance to dry conditions (Onwueme, 1978). The "sett" (a whole or piece of a tuber) may lie dormant for two or three months without moisture and may even sprout before the rainy season begins. Planting yams on mounds or hills is the most common planting practice. The mounds are approximately 30 to 50 centimetres in height and are composed of fertile topsoil collected from the area that is rich in organic matter and contains most of the yam roots. The loose soil also provides unimpeded penetration for tuber growth, facilitates harvesting, and enables roots to remain above a high water table (Onwueme, 1978). In addition, the mounds act as soil conservation measures by channeling runoff horizontally and vertically along the modified slope contours.

Yams require medium-coarse textured soils (loamy soils) that are relatively fertile and have a high organic matter content. Optimum soil pH levels range from 5.5 to 6.5. Good drainage is essential to avoid waterlogging. Sandy soils with low water and nutrient holding capacities are unsuitable, as well as heavy clay soils with limited aeration of the roots and tubers (Onwueme, 1978). Fertilizers with nitrogen, potassium and phosphorous are often needed to maintain soil productivity. The water yam has two types of roots: one or more thicker coronal roots with an approximate depth of 1.0 metre, and a fibrous root system composed of numerous, very fine roots that remain mostly within the upper 30 centimetres of the soil surface (Degras, 1993; Onwueme, 1978). The "rope-like" stem may grow up to 15 metres in length (Kay, 1973). The stem, unable to hold its own weight, climbs by twining onto the live post, supported by "wings" attached to its petioles (Coursey, 1967). The leaves are relatively large, ovate and opposite in arrangement. The tuber is generally cylindrical in shape with white, pink or purplish flesh and a loose, watery texture (Coursey, 1967). For optimum yields, 100-150 centimetres of rainfall distributed evenly over six or seven months is needed (Kay, 1973). In addition, high light intensity and daylengths less than 12 hours favour tuber formation and growth (Kay, 1973; Onwueme, 1978). The yam vegetation is primarily for the production of food, yet the planting methods and amount of foliage produced may also provide some soil protection.

Live Posts (Gliricidia sepium)

Gliricidia sepium is a multipurpose tree legume that is easily established, fast-growing, and nitrogen-fixing (Otu and Agboola, 1994). It is adaptable to a wide range of climates (60-300cm rainfall) and soil types (including saline soils), and may grow up to 10 metres tall (Nair, 1993). *Gliricidia* trees are commonly used for shade, fuelwood, fodder (for cattle), green manure, wood for furniture and fence posts, live fences and as support trees (Nair, 1993; Otu and Agboola, 1994). Once established, *Gliricidia* produce suitable support stems in one to two years and can be used as a permanent stake. Regular pruning of *Gliricidia* upgrades the soil nutrient status through decomposition, conserves or increases soil moisture content, regulates surface temperatures, decreases weed growth, and eliminates shading of yam vines (Otu and Agboola, 1994). One research study found that yam productivity increased when intercropped with *Gliricidia* trees due to its open architecture, sparse foliage and uncongested root system, which is generally deep and localized (Degras, p. 198, 1993). Rapid decomposition of prunings increases soil organic matter content resulting in a higher water holding capacity, as well as releasing plant nutrients into the soil, especially nitrogen. In Mexico, estimates of nitrogen fixation based on nodule biomass and rate of decomposition were approximately 13 kg/ha/yr (Dommergues, 1987). A disadvantage of rapid decomposition rates is its reduced effectiveness as a mulch cover. Therefore, it has been suggested that *G. sepium* trees should be grown in combination with other legume trees, and/or prunings should be mixed with grasses or other prunings (Otu and Agboola, 1994).

Orange Trees (Citrus sinensis)

The Washington navel orange trees in the Y/AF and D/AF sites have a growing period of 240 to 365 days with a low tolerance of strong winds and waterlogging, and a moderate tolerance of drought (Landon, 1984). Nutrient requirements are moderate with higher requirements for nitrogen and potassium. Production begins after 3 to 4 years and peaks at 12 to 15 years (ILACO, 1981). An average rainfall of 90 to 120 centimetres and mild, warm temperatures (~ 25°C) are needed for satisfactory yields. Deep, well-drained, light to medium textured soils (sandy loam) with an optimal pH range of 5.5 to 6.5 (will tolerate pH levels from 5.0 to 8.0) are preferred for good growth conditions. The rooting systems of orange trees have three components: larger taproots that reach depths of 1.0 to 2.0 metres, providing stability to the tree; the main nutrient/water uptake roots that vary from 1.2 to 1.6 metres in depth; and the shallow fibrous roots (~ 60%) that are found mostly in the upper 50 centimetres of the soil surface (Landon, 1984). Well-aerated soils are essential because of the high oxygen requirements of roots. Citrus trees also are sensitive to salinity, and are susceptible to magnesium deficiency, especially when excessive amounts of calcium or potassium are found in the soil (Landon, 1984; Nunez-Moreno and Valdez-Gascon, 1994; Weir, 1971). The production of fruits is the primary productive role, yet environmental factors such as providing shade, moderating ground temperatures, improving soil properties and protection from wind and rainfall are also important functions.

Dasheens (Colocasia esculenta)

The vegetation characteristics of dasheen plants, also known as "old cocoyams" and "taro" are quite distinct from the other vegetation types. High density planting of this perennial herb results in greater yields but smaller plants and corms, and provides more protection of the soil surface and better weed suppression (Onwueme, 1978; Safo-Kantanka, et al., 1994). The growing season is eight to nine months, but may increase to twelve months in high rainfall areas. Shoot and leaf growth increases rapidly for the first six months after planting but then declines, resulting in a reduction of leaf number and area and a decrease in height caused by the shortened leaf petiole (Onwueme, 1978). The shoots, cormels and roots grow from the cylindrical shaped "corm" which represents the main stem of the plant.

The corm is planted in holes approximately 10 centimetres in diameter and 10 to 20 centimetres deep. Root systems are dense, fibrous and shallow.

Dasheen plants have a high requirement for moisture, needing over 200 centimetres of rainfall per year and hot (21° to 27°C) humid conditions for high yields (Kay, 1973; Onwueme, 1978). They can tolerate flooding and waterlogging conditions, and favour deep, fine to medium textured soils with a high water holding capacity (Onwueme, 1978). Drainage conditions may range from well-drained to poorly-drained soils (Kay, 1973; Landon, 1984; Onwueme, 1978). Optimal soil pH levels range from 5.5 to 6.5 and nutrient requirements are high, especially for potassium and magnesium (Landon, 1984; Onwueme, 1978). Dasheens are tolerant of shade and salinity but have a low drought resistance (Landon, 1984). Water stress occurs frequently because of high rainfall variability, low soil water holding capacity, rapid drainage or uneven topography (Manrique, 1993). The large, thick, heart-shaped leaves have large transpiration surfaces requiring ample water throughout the growing season (Onwueme, 1978). Weed control is important during the early growth period (3-4 months) and the maturation period when starch accumulation occurs (6-7 months). Dasheens have both a productive and a protective role, providing a dense understory cover with their large leaves.

6.2.2 Characterization of Soil Profile and Surface Horizon Properties

Table 6.1 presents a summary of the physical and chemical properties of the surface horizons including the A horizon of the soil profile. The CEC and individual cations (nutrients) are examined in section 6.3.

Soil Property	Soil Profile A Horizon	Site Y Ap Hor.	Site Y/AF Ap Hor.	Site D/AF Ap Hor.	Site D Ap Hor.
Texture	silt loam	silt loam	silt loam	silt loam	silt loam
Structure	granular	granular	granular	granular	granular
%OM	3.5	4.9	4.7	5.8	4.9
pH	6.8	7.0	6.4	6.8	6.6
EC (mS^{-1})	85.9	118.0	103.0	77.5	79.2

Table 6.1 Soil properties of the surface horizons.

A silty loam texture and granular structure characterized the surface horizons of the soil profile (A and B1) and the study sites (Ap). The friable A horizons have a high silt content due to the wind-borne ash source from earlier eruptions (Limbird, 1992). Granular structure is often associated with coarser textures or larger aggregates that increase infiltration, drainage and aeration in the soil because of the larger (macro) pore spaces. However, they often have a low water holding capacity, which may cause drought-like conditions (Naeth, et al., 1991). In addition, soils with a high silt content are more susceptible to surface disaggregation that may result in lower infiltration rates, surface crusting and/or increased erosion (Evans, 1996). There was no evidence of crusting during the field season due to the resistance of the artificially coarse aggregates to dispersion (see section 5.3.1). Generally, cultivation leads to a decline in structural stability over time whereas plant roots and organic matter tend to improve soil structure. Soils with a higher organic matter content are structurally more stable (Evans, 1996; Lal, 1979a; Tan, 1984). Aggregation is predominantly a function of decomposition of soil binding materials and microbial populations, where organic macromolecules (humic substances and polysaccharides) act as binding agents between organic molecules and mineral surfaces upon drying and contraction in surface horizons (Evans, 1996; Naeth, et al., 1991).

Organic matter content was high for cultivated soils with approximately 5% in all but the surface horizon of the soil profile. The rapid decomposition of cuttings left on the soil surface, especially in the yam sites, and the increase in ground cover among all of the sites at various times during the field season increased the organic matter content of the soil. However, orange trees contribute less litterfall to the surface because they are not deciduous. The higher percentage of organic matter in the Dasheen/Agroforestry site (5.8%) may be explained in part by the presence of a continuous ground cover for most of the field season, and by the constant addition of organic matter through dead and decaying roots from the orange trees (Nair, 1984). The presence of organic matter modifies soil texture, thereby improving the water holding capacity of the coarse soils. Increased organic matter also moderates nutrient availability and release patterns (Lundgren and Nair, 1985). Crops depend on the decomposition of organic matter as a source of available phosphorous, as 60 to 80% of the total phosphorous in the soil is organic phosphorous (Limbird, 1992).

The pH of the surface horizons ranged from slightly acidic (6.4) to neutral (7.0). Generally, pH levels close to 7.0 have a greater supply of base-forming cations (nutrients) which have not been leached out of the soil by rainfall (Van Lierop, 1990). In addition, pH levels tend to decrease with increasing organic matter or clay content in the soil. This is indicated by an increase in pH levels with decreasing depth (and organic matter) in the soil profile. The pH values for all of the sites were near to or within the optimal range for each vegetation type. Most minerals also tend to be more soluble in acidic soils than in neutral or slightly basic soils, thereby increasing the nutrient availability for plants (Miller and Donahue, 1990).

Electrical conductivity levels were higher in the surface horizons and decreased with depth. Soluble salts are formed from cations and anions of weathered minerals (Miller and Donahue, 1990). Conductivity represents a measure of the soluble nutrients available for plants (Limbird, 1992). The addition of fertilizers increases the salt content of soils, primarily in the surface horizons (Brubaker, et al., 1993). Low precipitation and high evaporation also leads to an accumulation of salts in the soil that are not removed by leaching (insoluble salts). Conductivity levels were highest in the yam sites, however the base saturation of exchangeable sodium was only five percent. The relatively low conductivity values and an exchangeable sodium ratio well below 15% throughout the profile signified that the level of soluble salts in the soil was not detrimental to plant growth, especially for the saline-sensitive orange trees (Brady, 1990; Miller and Donahue, 1990).

The subsurface textures ranged from sandy loam (coarse sand layers in B3 and C1) to clay loam (B4). The predominant soil structure of the profile was fine, weak to moderate granular, developing into subangular blocky in the compacted (B2) and clay loam horizons. Aeration and drainage was moderately good to rapid throughout the profile, with the exception of the clay loam horizon. This was indicated by the high chromas and absence of mottles in the strong brown to dark brown horizons. Fine roots were concentrated in the surface horizons to a depth of 50 centimetres, consistent with the rooting patterns of the dasheen plants.

There is a greater potential for slumping in this soil because of the presence of unconformities caused by the coarse sand horizons (B3 and C1). The tendency for water to concentrate in these coarse layers and move laterally (parallel to the slope) rather than vertically, may contribute to slope instability and increased erosion (Limbird, 1992). Undercutting of the overlying soil horizons will result if the coarse layer becomes exposed at the surface and begins to erode (Limbird, 1992). This potential increases on steeper slopes because of increased shear stress.

Soil development was characterized by moderate leaching in the soil profile with the eluviation of the base-forming cations from the A horizon to the B horizons. Profile development also was apparent by the horizonation, the clear smooth boundaries between horizons, the total depth of the soil (>180cm) and the colour change from the surface horizons (10YR) to the subsoil horizons (7.5YR). In addition, evidence of weathering was represented by the accumulation of clay and improved structure in the B4 horizon. However, near neutral pH levels, a relatively thick A horizon (28cm), a high base saturation throughout the profile, and an absence of allophane (clays) indicated that the soil was not highly weathered. The lack of weathering may be attributed to a number of factors. Foremost, are climatic influences such as rainfall variability and wind that are described more thoroughly in section 6.4. Another explanation is the midslope position of the study sites, commonly called the erosion zone, where runoff is likely to exceed infiltration (Brubaker, et al., 1993). Thirdly, the presence of a compact but uncemented horizon (B2) below the cultivation mixing zone may reduce the downward movement of water. Perennial crops with deep root systems, such as *G. sepium* and tree species may help to break up this compact horizon and improve percolation through the soil (Pellek, 1992). And lastly, the deposition of subsequent ash falls would mask the true age of the soil by rejuvenating the soil's nutrient supply and retarding soil development.

The presence of vitric or glassy material (in the silt fraction), combined with neutral pH values and high base saturation percentages suggest that the soil was rejuvenated by a recent ashfall (following soil formation) and therefore appears "younger" and less developed than anticipated. This contradicts earlier thinking that the last major ashfall had extended only as far as the southern ridge boundary of the Colonarie River Watershed (Limbird, Pers. comm., 1999).

Surface horizon properties were not significantly different among the four study sites, with the exception of the larger percentage of organic matter in the Dasheen/Agroforestry site. Also, a high concentration of iron relative to the other horizons was found in the B3 horizon of the soil profile (0.21meq/100g). This may have resulted from the layering of materials with varying mineralogical composition during a number of ash fall events prior to soil formation (Limbird, Pers. comm., 1999). Subsurface lateral flow of iron-rich water from upslope is another possible explanation (Limbird, Pers. comm., 1999). The soil properties are favourable for the growth of yams, live posts and orange trees. Near drought conditions and the lack of irrigation water caused slight moisture stress conditions during the early season for the dasheen plants, yet the plants remained hardy for the duration of the field season (Francis, Pers. comm., 1997).

6.3 Nutrient Loss and Soil Fertility

6.3.1 Nutrient Loss (Exchangeable Cations)

Losses of individual nutrients were analyzed by comparing the chemical properties of the eroded sediments and the surface horizons. The comparison of chemical concentrations of the eroded sediments and the original source soil is defined as the Enrichment Ratio (ER) (Ciccaglione, 1998). The Enrichment Ratio was calculated for each nutrient, CEC, organic matter, pH and EC to determine the total and seasonal losses that occurred (see Appendix B). Table 6.2 presents a summary of the nutrient composition and CEC of the surface horizons and the eroded sediments. The nutrient concentration of the eroded sediments is represented by *Sed.* Individual nutrient concentrations present in the surface horizons are labeled (A hor.). E.R. is the Enrichment Ratio.

Nutrients meq/100g	**Site Y** *Sed.* **(A hor.) E.R.**	**Site Y/AF** *Sed.* **(A hor.) E.R.**	**Site D/AF** *Sed.* **(A hor.) E.R.**	**Site D** *Sed.* **(A hor.) E.R.**
Ca	***7.67*** (4.25) **1.8:1**	***6.84*** (3.33) **2.1:1**	***12.92*** (3.93) **3.3:1**	***6.94*** (3.58) **1.9:1**
Mg	***2.80*** (1.66) **1.7:1**	***2.44*** (0.83) **2.9:1**	***2.96*** (1.20) **2.5:1**	***2.80*** (0.81) **3.5:1**
Na	***1.46*** (0.28) **5.2:1**	***1.29*** (0.27) **4.7:1**	***1.66*** (0.33) **5.0:1**	***1.84*** (0.30) **6.1:1**
K	***1.08*** (0.13) **7.7:1**	***1.25*** (0.20) **6.3:1**	***2.57*** (1.05) **2.4:1**	***2.64*** (0.40) **6.6:1**
Mn	***0.36*** (0.02) **18.0:1**	***0.33*** (0.03) **11.0:1**	***0.49*** (0.02) **24.5:1**	***0.31*** (0.02) **15.5:1**
Fe	***0.05*** (0.01) **5.1:1**	***0.03*** (0.01) **3.1:1**	***0.06*** (0.01) **6.0:1**	***0.05*** (0.01) **5.1:1**
Al	***0.10*** (0.03) **3.3:1**	***0.12*** (0.04) **3.0:1**	***0.12*** (0.03) **4.0:1**	***0.12*** (0.04) **3.0:1**
CEC	***13.52*** (6.37) **2.1:1**	***12.31*** (4.70) **2.6:1**	***20.76*** (6.58) **3.2:1**	***14.70*** (5.15) **2.9:1**
%OM	***16.70*** (4.90) **3.4:1**	***13.40*** (4.70) **2.9:1**	***11.70*** (5.80) **2.0:1**	***17.50*** (4.90) **3.6:1**

Table 6.2 Comparison of nutrients, CEC and OM of the surface horizons and eroded sediments.

Concentrations of individual nutrients, CEC and soluble salts were greater in the eroded sediments than in the surface horizon from which they originated in all of the sites. This may be explained by the artificially coarse aggregates that are not dispersed by erosional processes. The resistance of the macro-aggregates in combination with the increased surface area from the clay and silt coatings attracts and holds the positively-charged cations to their negatively-charged sites.

Overall individual total nutrient losses were not explained by the patterns of sediment loss. However, the highest loss in CEC and the greatest sediment loss occurred in the Dasheen/Agroforestry site and the lowest CEC and sediment loss values were recorded in the Yam/Agroforestry site. There was no correlation between the amount of runoff and the CEC of the eroded sediments. Cations found in trace amounts in the surface horizons, such as Fe, Al, and Mn had the highest losses relative to their original concentration. The largest loss of nutrients (Ca, Fe, Mn, Al) occurred in the Dasheen/Agroforestry site, as expected with the highest loss in CEC. The Dasheen site recorded the highest losses in Mg and Na, and the Yam site had the largest loss in K. Seasonal nutrient losses were highest in the early season followed by the late and middle seasons. The concentration of nutrients lost in solution (runoff water) was not determined.

6.3.2 Soil Fertility

The Gabe Field soils on moderate slopes are characterized as having moderate fertility levels (Limbird, 1992). Soil fertility determines the productive potential or the capacity of a soil to support plant growth on a sustained basis (Young, 1989). The fertility of the soil is determined by the maintenance of soil organic matter, physical properties and nutrient status. An important indicator of potential soil fertility is the degree of chemical activity in the soil water solution. The cation exchange capacity is the capacity of a given quantity of soil to adsorb and exchange cations with hydrogen ions. Nutrients are released through cation exchange into the soil water where they become available for plants (Thompson, and Troeh, 1973). Soil pH influences the solubility, the rate of nutrient release by weathering, and the amount of ions stored on the cation exchange sites (Thompson and Troeh, 1973). Higher pH values (slightly acidic to moderately basic) tend to permit the exchangeable base-forming cations to remain in the soil, thus increasing the CEC (Brady, 1990).

Silt particles contribute to the fertility of the soil because of their moderate physical properties. Silts have a much lower CEC than clays and organic matter, but are good agricultural soils because of their favourable water retention and drainage properties, and moderate nutrient availability. Thus, the surface horizons containing a moderate silt content are favourable to plant growth. Clay particles have a high surface area that increases the rate of chemical activity, thereby increasing the CEC. For a given mass, the capacity of the humus colloids (decomposed organic matter) to hold water and nutrient ions greatly exceeds that of clay (Brady, 1990). Although humus particles have greater water and nutrient holding capacities, clay is usually present in larger amounts in the soil. However, soils with a high clay content have poor drainage and subsequently, poor aeration when saturated with water, and hold cations tightly when the soil is too dry. An accurate measure of clay content in the soil profile and surface horizons was not determined due to the macro-aggregation of the clay-sized particles (section 5.3.1). Recorded clay percentages were relatively low, ranging from 2.0 to 5.0% in the laboratory analysis.

The cation exchange capacity of the surface horizons was not significantly different among the four sites (in meq/100g): 6.37 (site Y), 4.70 (site Y/AF), 6.58 (site D/AF) and 5.15 (site D). The CEC values of the eroded sediments follow a similar pattern in the Y (13.52), Y/AF (12.31) and D (14.70) sites, but is significantly higher in the D/AF site (20.76meq/100g). The loss in potential cation exchange capacity was evident both through soil erosion and leaching. Leaching of cations through the soil profile was indicated by an increase in CEC values with increasing depth (see Appendix B). CEC increased from 2.91meq/100g in the A horizon to 7.39 meq/100g in the B4 (clay loam) horizon. Soil erosion had a greater influence in the loss of CEC and individual nutrients, than did leaching. This is significant as the soil's nutrient reserves are often concentrated in the thin surface horizon in tropical soils (Lal, 1985). However, the use of fertilizers can compensate for most losses of topsoil in soils with an edaphically favourable subsoil, like Andisols (Lal, 1985).

CEC values do not differentiate between the amounts of different cations in the soil and may not be totally representative of actual soil fertility (Ewaschuk, 1995). Therefore, the level of plant growth can be no greater than that allowed by the most limiting of the essential plant growth factors. Another consideration is the amount of exchangeable-sodium (Na) in the soil, which is toxic to plants at high levels. High sodium levels overestimate the potential fertility of the soil by increasing the value of the total CEC. However, a high base saturation dominated by Ca and Mg, and a low exchangeable-sodium (<6%) was found in all of the surface horizons (see section 6.2.2).

The total loss of organic matter from the surface horizon at each site was significant. The percentages of organic matter found in the eroded sediments ranged from 2.0 (site D/AF) to 4.0 (site D) times greater than in the surface horizons. The loss in organic matter results in an increased erodibility of the soil and a loss of nutrient cations. A decrease in organic matter also could result in a large decrease in water content (water holding capacity), thereby exacerbating drought-like conditions (Tan, 1984). Additional changes may include a reduction in infiltration rates and aeration, loss of granular or crumb structure in the topsoil, lower cation exchange capacity, lower total porosity, increased leaching and possible changes in base saturation and pH (Wiersum, 1988c). The loss in organic matter from the surface horizons reflects the need for greater protection of the soil surface at all of the sites.

High soil temperatures can influence the plant nutrient status and uptake directly by affecting root growth, and indirectly by influencing nutrient availability, especially when there is little to no protection of the soil surface (Lal, 1979b). Often the input of organic matter in the soil decreases during the cropping period, whereas mineralization of the existing humus in the soil increases due to the high temperatures of the exposed soil (Wiersum, 1988c). Solar radiation and constant winds like the northeast trade winds, increase evaporation at the soil surface and reduce the soil moisture level in the surface horizon. The process of evapotranspiration, whereby moisture is lost through evaporation from the soil and by transpiration by plants, also increases in these climatic conditions. Therefore, higher moisture requirements are needed for good growth especially with the large leaves of the dasheen plants.

The greatest limiting factor in soil fertility was the loss of organic matter from the surface horizons. Better protection of the soil surface against water erosion, high temperatures and the effects of wind is essential to maintain the soil physical properties, nutrient status and organic matter content. Even the dense understory of dasheen plants in the D/AF and D sites did not sufficiently reduce soil losses. The replacement of plant nutrients by fertilizers can maintain productivity levels in the short term, but continual losses of the surface soil may lead to the irreversible degradation of the soil physical characteristics (Lal, 1979b).

6.4 Runoff and Sediment Loss

6.4.1. Statistical Summary of Runoff and Sediment Losses

Based on the Land Suitability Evaluation for the Colonarie Watershed, soils belonging to the Gabe Field Series on moderate slopes have a moderate erosion potential that increases with a decrease in the vegetation cover (Limbird, 1992). A summary of the slope characteristics, and the total sediment and runoff losses for each site are presented in Table 6.3.

Site Characteristics	Site Y	Site Y/AF	Site D/AF	Site D
Slope Angle	16° (28%)	15° (26%)	15° (26%) upper slope, 17° (30%) lower slope	19° (34%) upper slope, 17° (30%) lower slope
Slope Form	straight, regular	straight, regular	convex	concave
Slope Aspect	SE	SE	S/SE	SE
Sediment Loss (kg/site)	0.12	0.10	0.14	0.12
Runoff (L/site)	42.6	27.7	16.9	12.3

Table 6.3 Site comparison of slope characteristics and erosion rates.

Sediment Loss: Total sediment losses indicate that soil erosion was relatively low in all of the sites. The agroforestry sites with trees accounted for the highest (site D/AF) and lowest (site Y/AF) values of sediment loss. However, the total values are quite similar across the four sites. These observations were supported by the results of the MANOVA for sediment loss. No statistically significant differences were found in the total sediment loss between the four sites.

Overall seasonal sediment losses increased over the field season, but patterns of seasonal loss varied greatly between the four sites. Sediment loss was substantially higher in the Yam site during the *Middle* season relative to the *Early* and *Late* seasons. The other sites exhibited the greatest sediment loss during the *Late* season. Sediment loss decreased in the Dasheen site during the *Middle* season and almost tripled in the *Late* season. These results were not supported by the MANOVA, which found no significant seasonal difference within each site. This may be explained by the omission of three extreme values in the analysis, which would decrease the variability in the data set. Therefore, large seasonal increases in sediment loss were not reflected in the statistical analysis.

Runoff: Total runoff values exhibited much greater variability than sediment loss between the four sites. Runoff at the Yam site was over two times greater than the Dasheen sites. This variability was not reflected in the MANOVA because of the omission of the extreme values. Therefore, the observed differences in runoff between the sites were not statistically significant. High seasonal variation in runoff also was observed. Large increases in runoff occurred in the Yam and Dasheen/Agroforestry sites during the *Late* season. The highest runoff values in the Yam/Agroforestry and Dasheen sites were recorded in the *Middle* season. The results of the MANOVA confirmed that seasonal differences in runoff within the sites were statistically significant.

6.4.2 Erosional Characterization

A number of factors influenced the amount of sediment and runoff loss that occurred at each site. Factors include: vegetation characteristics (the presence or absence of vegetation cover, vegetation type, planting methods), slope characteristics, soil properties (of surface horizons), rainfall, runoff and equipment problems. The vegetation characteristics, especially the presence or absence of a vegetation cover appeared to be the most influential factor in controlling runoff and sediment loss. The importance of maintaining a ground cover is illustrated by a number of site examples. Increases in runoff and sediment loss were noted in both of the yam sites in two consecutive weeks following the removal of the ground cover in week 4. In addition, the yam sites had a much lower percentage of ground cover throughout the field season and recorded the largest total runoff losses. Ground cover remained below 60% for the first eight weeks in the Yam site, and reached 75% in the Yam/Agroforestry site towards the end of the study. The clearing of the ground cover in the Dasheen site in week 10 also resulted in a large increase in sediment loss. Alternatively, the low sediment loss in the Yam/Agroforestry site may be partly explained by the presence of a permanent ground cover comprised of weeds and grasses underneath the orange tree.

The structure of the vegetation was also an important factor in controlling soil erosion. This was evidenced by the low total runoff values in both dasheen sites. The large leaves and high density planting of the dasheen plants protected the soil from erosive raindrops by acting as an umbrella (Ciccaglione, 1998). The small leaves, open architecture, and canopy height of the orange trees in the Y/AF and D/AF sites did not appear to have a great effect in either decreasing or increasing erosion. Raindrops intercepted by the canopy did not increase erosion on the ground surface directly below the tree. The permanent ground cover below the orange trees reduced sediment loss and runoff by acting as an island barrier in the surrounding exposed soil. This was observed by the lack of sediment and runoff in the trough unit nearest to the tree in both of the sites. The beneficial effects of trees, such as the maintenance or improvement of soil physical properties, organic matter, increased nitrogen fixation, and the moderation of ground temperatures were not measured in this study and are not examined.

The absence of a vegetation cover exposes the soil to the erosive power of raindrops and leads to increased runoff and soil loss. In addition, intense rainstorms following a prolonged dry period cause severe erosion, especially if the soil is unprotected (Lal, 1990). A continuous ground cover functions as a blanket and increases soil infiltration, maintains soil properties and organic matter content, and helps to stabilize the soil through its root systems. The vegetation cover also dissipates raindrop impact and protects the soil from rainsplash by altering the volume, drop size distribution, impact velocity and kinetic energy of rainfall reaching the ground surface (Lal, 1990). A study of soil erosion and sediment yield in forest and agroforestry areas in Java, Indonesia concluded that cover management was the most important factor in minimizing erosion (Kusumandari and Mitchell, 1997). Other research studies on soil erosion in the humid tropics recommend that a ground surface cover of 60% or more composed of living plant cover, crop residues and tree prunings must be maintained throughout the period of erosive rains (Nair, 1993; Wiersum, 1984; Young, 1986, 1988, 1989). The blanket effect of a continuous ground cover in the Dasheen/Agroforestry site is illustrated in Figure 6.1.

Planting methods had a significant impact on the low total values of sediment loss. The formation of contour mounds in the yam sites resembling semi-permeable hedgerows are commonly used as soil conservation measures (Konig, 1992; Nair, 1993; Pellek, 1992; Wiersum, 1984; Young, 1989).

Figure 6.1 Importance of ground cover vegetation: the large, broad-leaves of the dasheen plants in combination with weeds and grasses form a continuous ground cover in the Dasheen/Agroforestry site, with an orange tree in the foreground.

The definition of soil conservation includes the control of erosion and the maintenance of soil fertility (Young, 1988). The mounds acted as effective filters for entrained soil, dissipated the force of runoff by spreading it laterally and decreased the slope length (Pellek, 1992; Young, 1988). Thus, infiltration was increased and on-site soil loss was reduced as evidenced by the low sediment losses in the yam sites. In addition, the discontinuous nature of the mounds allowed runoff to pass through during heavy storms without damage to the yam plants. Research on erosion control methods in Rwanda by Konig (1992, p.173) suggested that "semi-permeable biological protection measures (hedgerows) can reduce runoff to tolerable limits and will remain functional and stable even during exceptional rainstorms." Konig (1992) also concluded that a reduction in soil loss is much more significant than a reduction in runoff, particularly in high rainfall areas. The planting method for dasheens also led to lower total sediment losses. The dasheens in sites D/AF and D were planted in holes that acted as sediment traps. Throughout the course of the field season the holes began to fill in with sediment, aided by the large number of plants and the growth of grasses and weeds around the holes.

Slope characteristics were similar among the four sites except for the form (shape) and angle of the slope in the dasheen sites. Slopes direct the flow of surface water under the influence of gravity (Strahler and Strahler, 1992). The shape or form of the slope affects soil erosion by influencing the amount and velocity of overland flow (Lal, 1990). The slope increased from 26% on the upper slope to 30% on the lower slope in the Dasheen/Agroforestry site forming a slightly convex shape.

Increased erosion often occurs on convex slopes due to the increased velocity of overland flow that results in a greater detaching and transport capacity (Lal, 1990). This may help to explain the higher loss of sediment recorded in the D/AF site. The concave shaped slope in the Dasheen site decreased from the top (34%) of the plot to the bottom (30%), thereby decreasing the velocity of runoff. Although sediment loss was lower in site D than in the D/AF site, the slope characteristics were not the most influential factors in controlling erosion.

The soil properties of the surface horizons, discussed in section 6.2.2, were similar in structure, texture, and organic matter content. The combination of these properties decreased erosion by maintaining good infiltration, good permeability and good aggregate stability, as larger aggregates are more resistant to erosion (Lal, 1990). Strong aggregate stability was indicated by the low level of sediment loss with varying levels of runoff. In addition, the importance of organic matter in improving the soil's structure and resistance to erosion was a significant factor in decreasing sediment loss.

The impact of rainfall on sediment loss and especially runoff, was reflected in the statistical analysis and through site observations. A strong correlation between rainfall and runoff in the Y/AF and D sites indicated that there was a cause and effect relationship between the two variables. To determine the strength of this relationship a regression analysis was performed for each site. The results of the regression for the Yam/Agroforestry site generated an R^2 value of 0.327. This suggested that rainfall accounted for approximately one-third (33%) of the variance in runoff. The relationship between rainfall and runoff appeared to be stronger in the Dasheen site because of a higher observed correlation value. The regression resulted in an R^2 value of 0.4823, indicating that rainfall accounted for approximately half of the variation in runoff (48%). The explanatory power of the regression analyses was reduced because of the lack of actual rainfall data. In addition, the relationship between rainfall intensity, runoff and sediment loss was not examined because of incomplete precipitation data. Other erosion studies in St. Vincent determined that both total rainfall and rainfall intensity were influential factors in runoff and/or sediment loss (Ciccaglione, 1998; Hackman, 1998; Strand, 1996).

The importance of rainfall and rainfall intensity in both runoff and sediment loss was also exemplified in site observations. The lack of rainfall in the *Early* season also had a significant impact on crop growth. The total rainfall measured over the duration of the field season was 86.59 cm. Recorded rainfall for the first four weeks of the study was only 11.1 cm. The prolonged dry season caused great concern for many farmers as drought conditions damaged many crops, particularly bananas (Francis, Pers. comm., 1997). The highest recorded rainfall occurred in the *Middle* season (weeks 6-9). However, the rainfall value measured in the *Late* season may have greatly underestimated the actual rainfall because of the amount of missing precipitation data, and was likely to have exceeded the total value recorded for the *Middle* season.

Soil erosion is affected by both the amount and intensity of rainfall (Lal, 1990). Tropical storms are often intense, localized and short in duration (Lal, 1990). The same amount of rain falling over a short time causes more erosion than a rain of low intensity distributed over a relatively long period of time (Lal, 1990). Intense storms have a relatively higher proportion of larger drops that lead to increased rainfall erosivity (Lal, 1990). Although the impact of rainfall intensity on runoff and sediment loss could not be fully examined, a number of examples from the available data were characteristic of intense tropical storms. Rainfall intensities ranged from 0.75 to 100.0 mm/hr. The higher intensities recorded were associated with short duration events, ranging from 10 to 30 minutes in length.

Intensity is generally considered to be the most significant rainfall characteristic in causing erosion by overland flow and rills (Morgan, 1979). Evidence of rilling between the contour mounds in the Yam/Agroforestry site was observed in week 10. The rills were approximately 7.0 cm in width and 2.0-3.0 cm deep. Rill erosion is caused mainly by concentrated overland flow and often results in greater soil loss (Gray and Leiser, 1982; Meyer, 1985). This may explain the increased sediment loss in the Yam/Agroforestry site during week 11. Rill erosion also is indicative of increased runoff velocities that entrain larger soil aggregates (Meyer, 1985).

The final factor that influenced the total values of runoff and sediment loss was equipment problems. This was due to human error and the curiosity of the local population. The plastic cover falling into the collection bucket during week 5 in the

Yam site allowed rainfall and any accumulated sediment on the cover to be included in the sediment and runoff measurements. This led to a large recorded increase in sediment and runoff loss in week 6. The second example also occurred in the Yam site during week 11, where an unsecured cover led to a large recorded increase in runoff during week 12. These examples may help to explain the significant increase in runoff in the Yam site relative to the other runoff values.

6.4.3 Levels of Tolerable Erosion

The factors that had the greatest influence on limiting runoff and sediment loss were vegetation cover and structure, the methods of planting, soil properties of the surface horizons and rainfall. Less significant factors included: runoff, slope characteristics and equipment problems. The natural process of soil erosion cannot be entirely reduced in any ecosystem (Young, 1986). Recorded losses in sediment and runoff (extrapolated to a yearly basis) were far below the limit set by the U.S. Soil Conservation Service for tolerable erosion, which ranges from 2.2-11.2 t/ha/yr (Nair, 1993). Tolerable erosion levels are based on the loss of soil volume (thickness) and sustainable crop yields, including the maintenance of organic matter and nutrients. The sediment losses found in this study do not include the period of greatest rainfall and therefore, greatest erosivity, and are likely to be underestimated in a yearly projection. Additionally, the loss of nutrients and organic matter from all of the sites indicates that greater protective measures are needed to sustain productivity over a long period of time.

The low levels of sediment and runoff losses appear more significant when compared with a similar study of banana plants on sloping lands in the Colonarie River Watershed. Soil erosion was examined on two sites where banana plants dominated the vegetation. The moderately sloped site (MD) was characterized by 21° slope, sandy loam soil, and a high canopy and ground cover density (Ciccaglione, 1998). The steeply sloped site (ST) was characterized by a 45° slope, clay loam soil, and a low canopy and ground cover density (Ciccaglione, 1998). A comparative summary of the runoff and sediment losses is presented in Table 6.4.

	Site Y	Site Y/AF	Site D/AF	Site D	MD Site	ST Site
Sediment Loss (kg/site)	0.44	0.36	0.50	0.44	6.3	34.0
Runoff (L/site)	149.1	97.0	59.2	38.9	248.0	1358.0

Table 6.4 Total sediment and runoff losses compared to Ciccaglione (1998).

The results indicate that sediment and runoff loss in the agroforestry and dasheen sites were considerably lower than in the banana sites. Given that the studies occurred at different times, locations and under different conditions, any comparison must be interpreted loosely. However, the low levels of erosion exhibited in the four sites holds potential for the greater agricultural community in St. Vincent.

6.5 Agroforestry Systems for Reclamation

6.5.1 Environmental Factors

The results of this study indicate that the monocrop system and the agroforestry systems were equally effective in controlling soil erosion. More importantly, the presence of a continuous ground cover and the use of soil conservation measures were the most significant factors in reducing runoff and sediment loss. The effectiveness of agroforestry systems as a reclamation technique depends on a number of factors including: the type of system, vegetation structure and arrangement, soil properties, slope characteristics, and management practices. Agroforestry systems combined with soil conservation measures are suitable in areas with gentle to moderate slopes, and where there is a low to moderate soil erodibility and landslide potential. Agroforestry systems are not recommended on steep slopes where the potential for landslides and the erodibility of the soil is high.

The integration of trees in the Yam/Agroforestry and Dasheen/Agroforestry sites could neither prevent runoff nor reduce sediment beyond their perimeter. Individual scattered trees cannot be expected to have such noticeable beneficial effects as a well-functioning, undisturbed forest ecosystem (Wiersum, 1984). However, the role of fruit trees in improving soil properties such as the addition of organic matter, and in producing a nutritive and economically valuable product is equally important (Nair, 1984).

The effectiveness of the semi-permeable mounds in both Yam sites was reflected in the low levels of sediment loss. The mounds, in combination with the role of the *Gliricidia* trees reduced runoff and soil loss, increased infiltration, and provided some protection of the soil surface through litter and prunings. The potential of this system in reducing erosion could be enhanced with the addition of other legume tree species and a better protection of the soil surface composed of living plant cover, prunings and leaf litter (Young, 1986).

6.5.2 Socio-Economic Factors

The effectiveness of agroforestry systems in diversifying and increasing productivity is well-documented (Konig, 1992; Nair, 1990b, 1993; Vergara, 1987; Young, 1986, 1989). Productivity levels in a monocrop system have slightly higher yields than in a mixed cropping system, but the total productivity level from the equivalent unit area increases in the agroforestry system (Nair, 1984). The need for a sustainable and economically productive alternative to bananas is essential in St. Vincent. Bananas require high inputs of labour, fertilizers (every 2 to 3 months) and herbicides (every 6 weeks) (Francis, Pers. comm., 1997). In addition, the export prices set by the St. Vincent Government and the Banana Growers Association to the UK are decreasing, ranging from 0.18-0.23¢/lb for a 46 pound box (Francis, Pers. comm., 1997).

Another challenge facing the St. Vincent government is the size of the family farm. Most land holdings are too small to be economically viable. Ninety-seven percent of family farms are less than ten acres, and fifty percent of those are less than one acre in size (CCA, 1991). Also, the lack of secure tenure is the greatest impediment in the adoption of soil conservation measures (Anderson, 1992; CCA, 1991). For resource poor farmers, agroforestry is the most suitable approach to land management where both food and wood products can be produced from the same piece of land at the same time without causing deterioration of the ecosystem (Nair, 1984).

"It is a truism that the success or failure of any innovation in farming systems depends on the skill of its management. It is one thing to elucidate the scientific merits and advantages of a new and innovative technology; to make it acceptable and adoptable by the farming community is yet another" (Nair, 1984, p.57). Management encompasses all aspects of site preparation, species selection, planting pattern and density, pruning, thinning, and so forth (Nair, 1984; Young, 1989). Good management practices are evident all over the Francis farm in the Lauders region. Favourable management practices included the use of live fences, wind breaks, vegetated drainage gullies (live drains), various planting methods and arrangements, and a number of crop and tree species, such as dasheens, yams, bananas, plantains, tomatoes, cucumbers, sugarcane, and orange, guava, coconut, mango, *Gliricidia sepium* and *Leucaena leucocephala* trees. The ideas and spirit of Edmond Francis cannot be overemphasized. This motivation has led to the development of a sustainable agricultural system that may be unique to St. Vincent.

7. CHAPTER SEVEN: CONCLUSIONS

7.1 Conclusions

The principal objective of this research study was to assess the potential of agroforestry systems in reducing soil erosion on sloping lands. More specifically, runoff and sediment losses were examined under three different types of agroforestry systems and one monoculture system. The agroforestry systems were composed of: (1) a spatially zoned system where yam vines were grown on live posts (*Gliricidia sepium*); (2) a spatially mixed system of yam vines growing on live posts intermixed with two orange trees; and (3) a spatially mixed system with densely planted dasheens intermixed with an orange tree. The fourth site was a monoculture system of densely planted dasheens.

The data collected was examined for differences between sites (treatment effects) and within sites (seasonal effects). The results of this study indicated that there were no significant differences in runoff and sediment loss between the sites. Seasonal differences were observed within sites but were statistically significant only for losses in runoff.

Although sediment losses were relatively low, the loss of nutrients and organic matter were comparatively high, especially in the Dasheen/Agroforestry and Dasheen sites, respectively. This was attributed to the absence of a continuous vegetation cover protecting the soil surface. Examples of how the clearing and weeding of the understory were directly related to an increase in sediment loss during the following week were discussed. The yam sites recorded the highest runoff losses but the lowest loss of sediment. This was due to the use of discontinuous contour mounds that resembled the semi-permeable hedgerows often used as a soil conservation measure. The contour mounds protected the yam plants from runoff and reduced soil erosion by filtering entrained sediment. The mounds also dissipated the force of runoff and decreased the effective length of the slope by spreading runoff laterally between the contours.

Other important factors that determined the amount of runoff and sediment loss at each site were total rainfall and rainfall intensity, properties of the surface soil, runoff, and vegetation cover and structure. The factors that decreased erosion were the presence of a continuous ground cover, the structure of the vegetation (leaf size and low height of dasheens), and the surface horizon properties (aggregate stability, soil structure, texture, and organic matter content). The factors that increased erosion were rainfall intensity (short duration, high intensity storms), total rainfall (rainsplash) and runoff (rilling, overland flow).

The use of agroforestry systems was proposed as a reclamation measure in the middle and upper basins of the Colonarie Watershed to reverse the trend of illegal clearing and cultivation (Reid Collins and Associates, 1994). Proper management and appropriate land use practices are necessary to reduce soil degradation and protect the remaining primary and secondary rainforests. Agroforestry systems were chosen as a transitional land use because of their potential effectiveness for soil conservation, erosion control and slope stability. The results of this comparative research study suggest that agroforestry systems in combination with soil conservation measures have the potential to reduce soil erosion on sloping lands, and are therefore a suitable reclamation technique in St. Vincent.

7.2 Recommendations

Site Recommendations:

(i) Maintain a ground surface cover of 60% or more throughout the period of erosive rains (May to December) composed of living plant matter, crop residues and tree prunings.

(ii) Maintain the use of semi-permeable contour ridges on moderate slopes with *Gliricidia sepium* trees combined with other legume trees to provide an effective mulch cover of the soil surface.

(iii) Increase the density and use of fruit trees in combination with cover crops, such as dasheens, to increase the beneficial effects of trees and diversify food production.

Recommendations for the Government of St. Vincent:

(i) Recognition of the Francis farm as a "model" for agroforestry systems, and hold on-site workshops and information meetings for local farmers regarding the advantages and disadvantages of agroforestry systems, and the use of soil conservation measures.

(ii) Assist farmers in converting existing banana plantations to agroforestry systems on tenured lands; and help relocated-farmers establish agroforestry systems by providing information on spatial arrangements, species selection, maintenance, sustainable management practices, and free tree seedlings (if economically feasible).

7.3 Additional Work

The results of this study reflect the measurement of hillslope erosion at the micro-scale or individual farm level. This scale was appropriate for evaluating the processes of soil erosion in relation to soil properties, rainfall characteristics, vegetation characteristics and runoff (Lal, 1990). Further research is needed to evaluate different combinations of agroforestry systems in various locations on the island, over a longer time period to account for the yearly variability of rainfall (minimum of three years). The potential of agroforestry systems in controlling soil erosion on sloping lands was demonstrated in this study and more research in agroforestry will provide greater alternatives for sustainable farming in St. Vincent.

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APPENDIX A:

Soil Profile Description

REPRESENTATIVE SOIL PROFILE OF STUDY AREA

Soil Classification: Alfic haplustand / hapludand
Parent Material: Volcanic Ash
Elevation: 366m
Average Slope: 16° (28%) / Moderate
Aspect: East facing
Drainage: Well drained
Vegetation: Dasheen and orange trees
Land Use: Cropland agriculture (agroforestry)
Erosion Hazard: Moderate, if understory vegetation is removed
Landslide Hazard: Moderate, due to coarse sand layers in subsoil

Soil Profile

Profile Description

Horizon	Depth (cm)	Colour	Description
A	0-28	10YR 3/3	very fine, moderate granular structure, abundant roots, clear and smooth boundary, loamy sand (silty loam)
B1	28-56	10YR 3/6	medium, weak granular to fine, weak subangular blocky structure, some fine roots, clear and smooth boundary, sandy texture (silty loam)
B2	56-93	10YR 4/6	fine, strong subangular blocky to granular structure, compact horizon resembling plow pan (agric horizon), some small stones, no roots, clear and smooth boundary, sandy texture (loam)
B3	93-122	7.5YR 4/6	fine, weak granular structure, many small stones, gritty, no roots, clear and smooth boundary, loamy sand (sandy loam)
B4	122-142	7.5YR 4/4	fine, moderate subangular blocky structure, greasy with some clay nodules (argillic horizon), no roots, clear and smooth boundary, loamy sand (clay loam)
B5	142-166	7.5YR 4/6	fine, moderate granular structure, gritty with a few rotted stones and harder aggregates, no roots, clear and smooth boundary, sandy texture (loam)
C1	166-180	7.5YR 4/6	fine, weak granular structure, gritty with some larger stones, no roots, clear and smooth boundary, sandy texture (sandy loam)
C2	>180	7.5YR 4/3	fine, moderate granular structure, gritty with some small stones, no roots, sandy texture (loam)

* Field measure of soil textures shown in (brackets)

APPENDIX B:

Soil Chemistry Analysis

SOIL CHEMISTRY OF SOIL PROFILE SAMPLES

HORIZON	Ca	Mg	Na	K	Al	Fe	Mn	CEC	Total CEC	%BS	%OM	pH	EC mS-1	PO4-P	Texture	Allophane
A	1.95	0.45	0.31	0.13	0.03	0.01	0.02	2.91	9.91	97.6	3.5	6.8	85.9	0	loamy sand	no
B1	2.59	0.50	0.28	0.12	0.03	0.01	0.00	3.56	11.56	98.0	4.0	6.9	60.9	0	sand	no
B2	2.39	0.48	0.44	0.20	0.04	0.02	0.02	3.58	9.38	98.0	2.9	7.2	51.6	0	sand	no
B3	3.60	0.55	0.63	0.17	0.05	0.21	0.02	5.23	10.43	94.6	2.6	7.2	38.9	0	loamy sand	no
B4	5.76	0.71	0.64	0.19	0.04	0.02	0.02	7.39	12.99	98.8	2.8	7.1	47.4	0	loamy sand	no
B5	3.68	0.57	0.64	0.13	0.05	0.02	0.02	5.11	10.91	98.2	2.9	7.0	40.6	0	sand	no
C1	2.10	0.46	0.37	0.15	0.03	0.01	0.01	3.15	8.15	97.8	2.5	7.0	44.3	0	sand	no
C2	2.67	0.51	0.35	0.18	0.03	0.00	0.02	3.76	9.16	98.7	2.7	7.1	37.3	0	sand	no
Ap1	4.25	1.66	0.28	0.13	0.03	0.01	0.02	6.37	16.17	99.2	4.9	7.0	118.0	0.004	loamy sand	no
Ap2	3.33	0.83	0.27	0.20	0.04	0.01	0.03	4.70	14.10	98.5	4.7	6.4	103.0	0.003	loamy sand	no
Ap3	3.93	1.20	0.33	1.05	0.03	0.01	0.02	6.58	18.18	98.9	5.8	6.8	77.5	0.004	loamy sand	no
Ap4	3.58	0.81	0.30	0.40	0.04	0.01	0.02	5.15	14.95	98.8	4.9	6.6	79.2	0.002	sand	no

Note: Ap1-Ap4 represent surface horizon for each study site
Elements expressed in meq/100g
Extractable phosphorous (PO4-P) expressed in mg/g
% Base Saturation for Ca, Mg, Na and K
Total CEC = [CEC + (2 x %OM)] expressed in meq/100g

SOIL CHEMISTRY OF SEDIMENT LOSS SAMPLES

SITE	Time Period	Ca	Mg	Na	K	Al	Fe	Mn	CEC	%OM	OM (g)	Total CEC	pH	EC mS-1	PO4-P	Texture
Y	Early	2.30	0.80	0.37	0.44	0.04	0.02	0.26	4.24	5.4	6.64	15.04	7.2	237.0	0.002	
	Middle	2.90	1.05	0.39	0.23	0.04	0.01	0.04	4.65	5.3	6.52	15.25	6.9	250.0	0.006	
	Late	2.47	0.95	0.70	0.41	0.02	0.02	0.06	4.63	6.0	7.38	16.63	6.8	599.0	0.008	
	Average	**2.56**	**0.93**	**0.49**	**0.36**	**0.03**	**0.02**	**0.12**	**4.51**	**5.6**	**6.85**	**15.64**	**7.0**	**362.0**	**0.005**	loamy sand
	Total	***7.67***	***2.80***	***1.46***	***1.08***	***0.10***	***0.05***	***0.36***	***13.52***	***16.7***	***20.54***	***46.92***		***1086.0***	***0.016***	
Y/AF	Early	2.96	0.81	0.37	0.49	0.05	0.01	0.22	4.91	5.2	5.33	15.31	6.7	264.0	0.004	
	Middle	1.44	0.69	0.45	0.38	0.04	0.01	0.07	3.09	3.9	4.00	10.89	6.6	171.0	0.004	
	Late	2.44	0.94	0.47	0.38	0.03	0.01	0.04	4.31	4.3	4.41	12.91	6.4	528.0	0.005	
	Average	**2.28**	**0.81**	**0.43**	**0.42**	**0.04**	**0.01**	**0.11**	**4.10**	**4.5**	**4.58**	**13.04**	**6.6**	**321.0**	**0.004**	loamy sand
	Total	***6.84***	***2.44***	***1.29***	***1.25***	***0.12***	***0.03***	***0.33***	***12.31***	***13.4***	***13.73***	***39.11***		***963.0***	***0.013***	
D/AF	Early	2.10	0.79	0.42	0.95	0.03	0.04	0.31	4.63	2.9	4.16	10.43	6.9	248.0	0.006	
	Middle	1.50	0.76	0.54	0.67	0.05	0.01	0.10	3.63	3.5	5.02	10.63	6.7	303.0	0.008	
	Late	9.32	1.41	0.70	0.95	0.04	0.01	0.08	12.5	5.3	7.59	23.10	6.9	610.0	0.009	
	Average	**4.31**	**0.99**	**0.55**	**0.86**	**0.04**	**0.02**	**0.16**	**6.92**	**3.9**	**5.59**	**14.72**	**6.8**	**387.0**	**0.008**	loamy sand
	Total	***12.92***	***2.96***	***1.66***	***2.57***	***0.12***	***0.06***	***0.49***	***20.76***	***11.7***	***16.76***	***44.16***		***1161.0***	***0.023***	
D	Early	2.04	0.71	0.40	0.43	0.03	0.02	0.20	3.83	5.7	7.00	15.23	6.8	272.0	0.005	
	Middle	2.10	1.01	0.92	1.43	0.05	0.02	0.06	5.59	6.2	7.62	17.99	6.6	1004.0	0.007	
	Late	2.80	1.08	0.52	0.78	0.04	0.01	0.05	5.28	5.6	6.88	16.48	6.8	759.0	0.008	
	Average	**2.31**	**0.93**	**0.61**	**0.88**	**0.04**	**0.02**	**0.10**	**4.90**	**5.8**	**7.17**	**16.57**	**6.7**	**678.3**	**0.006**	loamy sand
	Total	***6.94***	***2.80***	***1.84***	***2.64***	***0.12***	***0.05***	***0.31***	***14.70***	***17.5***	***21.50***	***49.70***		***2035.0***	***0.020***	

Note: Elements expressed in meq/100g
Extractable phosphorous (PO4-P) expressed in mg/g
Early (weeks 1-5), Middle (weeks 6-9), Late (weeks 10-13)
Total CEC = [CEC + (2 x %OM)] expressed in meq/100g

ENRICHMENT RATIOS OF SURFACE HORIZONS AND ERODED SEDIMENTS

	Ca	Mg	Na	K	Mn	Fe	Al	CEC	%OM	pH	ECmS-1
Site Y	4.25	1.66	0.28	0.13	0.02	0.01	0.03	6.37	4.9	7.0	118.0
Sed. Loss	7.67	2.80	1.46	1.08	0.36	0.05	0.10	13.52	16.7	6.8	1086.0
Total E.R.	***1.8:1***	***1.7:1***	***5.2:1***	***7.7:1***	***18.0:1***	***5.1:1***	***3.3:1***	***2.1:1***	***3.4:1***	***1.0:1***	***9.2:1***
(E)	**0.5:1**	**0.2:1**	**1.3:1**	**3.4:1**	**13.0:1**	**2.0:1**	**1.3:1**	**0.7:1**	**1.1:1**		**2.0:1**
(M)	**0.7:1**	**0.2:1**	**1.4:1**	**1.8:1**	**2.0:1**	**1.0:1**	**1.3:1**	**0.7:1**	**1.1:1**		**2.1:1**
(L)	**0.6:1**	**0.4:1**	**2.5:1**	**3.2:1**	**3.0:1**	**2.0:1**	**0.7:1**	**0.7:1**	**1.2:1**		**5.1:1**
Site Y/AF	3.33	0.83	0.27	0.20	0.03	0.00	0.04	4.70	4.7	6.4	103.0
Sed. Loss	6.84	2.44	1.29	1.25	0.33	0.01	0.12	12.31	13.4	6.4	963.0
Total E.R.	***2.1:1***	***2.9:1***	***4.7:1***	***6.3:1***	***11.0:1***	***3.1:1***	***3.0:1***	***2.6:1***	***2.9:1***	***1.0:1***	***9.3:1***
(E)	**0.9:1**	**0.4:1**	**1.4:1**	**2.5:1**	**7.3:1**	**1.0:1**	**1.3:1**	**1.0:1**	**1.1:1**		**2.6:1**
(M)	**0.4:1**	**0.5:1**	**1.7:1**	**1.9:1**	**2.3:1**	**1.0:1**	**1.0:1**	**0.7:1**	**0.8:1**		**1.7:1**
(L)	**0.7:1**	**0.6:1**	**1.7:1**	**1.9:1**	**1.3:1**	**1.0:1**	**0.8:1**	**0.9:1**	**0.9:1**		**5.1:1**
Site D/AF	3.93	1.20	0.33	1.05	0.02	0.01	0.03	6.58	5.8	6.8	77.5
Sed. Loss	12.92	2.96	1.66	2.57	0.49	0.06	0.12	20.76	11.7	6.9	1161.0
Total E.R.	***3.3:1***	***2.5:1***	***5.0:1***	***2.4:1***	***24.5:1***	***6.0:1***	***4.0:1***	***3.2:1***	***2.0:1***	***1.0:1***	***15.0:1***
(E)	**0.5:1**	**0.4:1**	**1.2:1**	**0.9:1**	**15.5:1**	**4.0:1**	**1.0:1**	**0.7:1**	**0.5:1**		**3.2:1**
(M)	**0.4:1**	**0.5:1**	**1.6:1**	**0.6:1**	**5.0:1**	**1.0:1**	**1.7:1**	**0.6:1**	**0.6:1**		**3.9:1**
(L)	**2.4:1**	**0.6:1**	**2.1:1**	**0.9:1**	**4.0:1**	**1.0:1**	**1.3:1**	**1.9:1**	**0.9:1**		**7.9:1**
Site D	3.58	0.81	0.30	0.40	0.02	0.01	0.04	5.15	4.9	6.6	79.2
Sed. Loss	6.94	2.80	1.84	2.64	0.31	0.05	0.12	14.70	17.5	6.8	2035.0
Total E.R.	***1.9:1***	***3.5:1***	***6.1:1***	***6.6:1***	***15.5:1***	***5.1:1***	***3.0:1***	***2.9:1***	***3.6:1***	***1.0:1***	***25.7:1***
(E)	**0.6:1**	**0.5:1**	**1.3:1**	**1.1:1**	**10.0:1**	**2.0:1**	**0.8:1**	**0.7:1**	**1.2:1**		**3.4:1**
(M)	**0.6:1**	**1.1:1**	**3.1:1**	**3.6:1**	**3.0:1**	**2.0:1**	**1.3:1**	**1.1:1**	**1.3:1**		**12.7:1**
(L)	**0.8:1**	**0.6:1**	**1.7:1**	**2.0:1**	**2.5:1**	**1.0:1**	**1.0:1**	**1.0:1**	**1.1:1**		**9.6:1**

Note: Elements and CEC expressed in meq/100g
Study site represents surface horizon properties
Enrichment Ratio (E.R.) for Early (E), Middle (M), and Late (L) Seasons

APPENDIX C:

Runoff, Sediment Loss and Precipitation Data

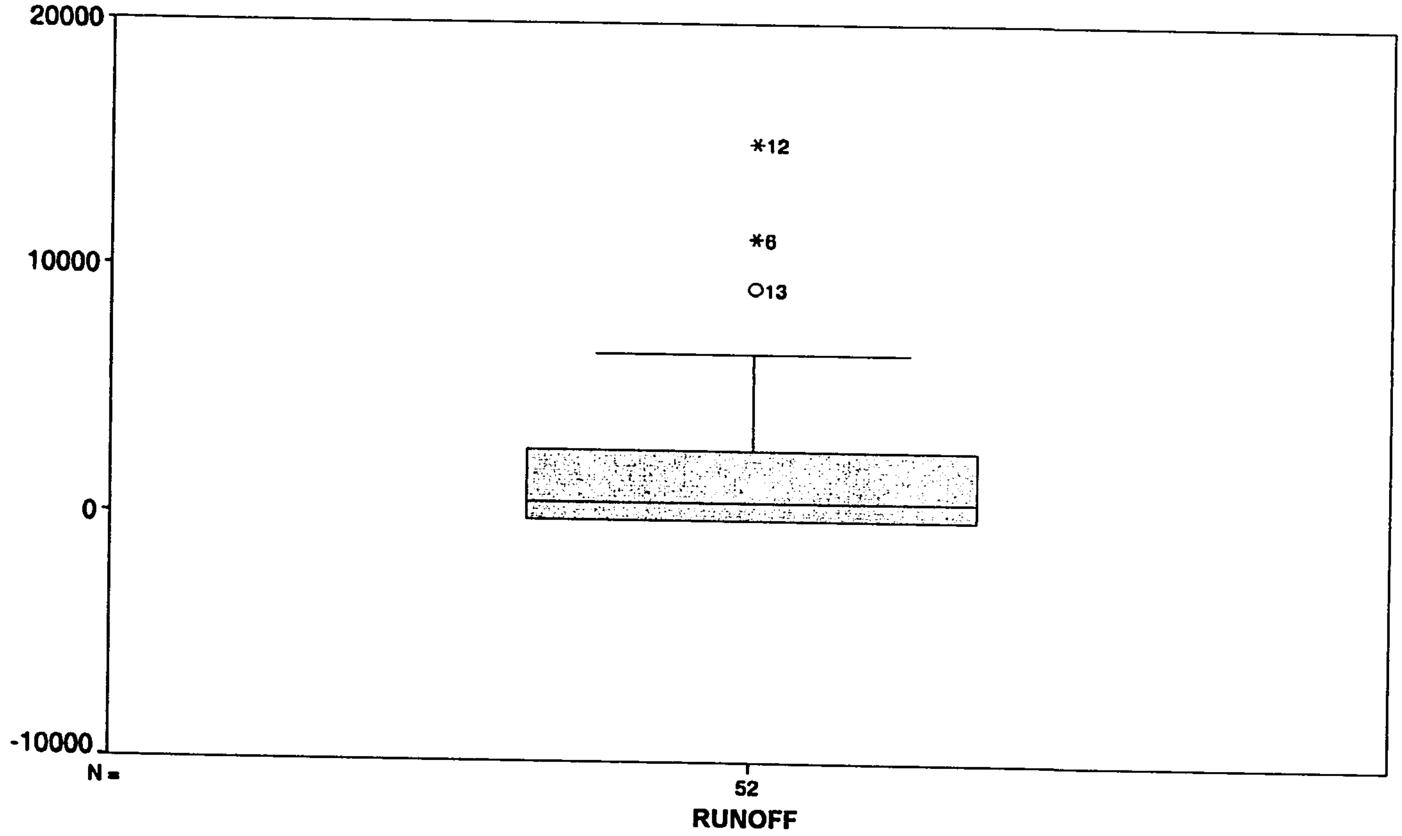
TOTAL WEEKLY SED. LOSS/ RUNOFF/ PRECIPITATION

	EARLY					MIDDLE				LATE				
Weeks	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
	29-May	*5-Jun*	*12-Jun*	*19-Jun*	*26-Jun*	*3-Jul*	*10-Jul*	*17-Jul*	*24-Jul*	*31-Jul*	*7-Aug*	*14-Aug*	*21-Aug*	*Totals*
Site Y														
Total Wkly Sed Loss (g)	0	2.09	0	0	2.51	77.04	0	20.83	1.84	7.72	0	9.7	1.28	***123.01g***
				Total	***4.6g***			***Total***	***99.71g***			***Total***	***18.7g***	
Total Wkly Runoff (ml)	645	126	993	0	4400	11350	0	357	54	86	0	15275	9315	***42,601ml***
				Total	***6,164ml***			***Total***	***11,761ml***			***Total***	***24,676ml***	
Site Y/AF														
Total Wkly Sed Loss (g)	4.4	0.2	0	0	11.53	3.11	18.27	8.32	6.1	9.6	34.31	6.62	0	***102.46g***
				Total	***16.13g***			***Total***	***35.8g***			***Total***	***50.53g***	
Total Wkly Runoff (ml)	55	450	1307	0	3775	1270	2127	6620	4813	3179	2265	365	1500	***27,726ml***
				Total	***5,587ml***			***Total***	***14,830ml***			***Total***	***7,309ml***	
Site D/AF														
Total Wkly Sed Loss (g)	22.79	17.55	7.06	0	2.84	12.64	9.61	14.34	2.42	35.63	11.28	4.06	3.06	***143.28g***
				Total	***50.24g***			***Total***	***39.01g***			***Total***	***54.03g***	
Total Wkly Runoff (ml)	415	150	47	110	805	30	570	370	700	3845	4065	2825	2925	***16,857ml***
				Total	***1,527ml***			***Total***	***1,670ml***			***Total***	***13,660ml***	
Site D														
Total Wkly Sed Loss (g)	7.4	3.11	20.68	0	6.83	6.08	12.37	0.96	2.67	57.52	0	2.36	2.87	***122.85g***
				Total	***38.02g***			***Total***	***22.08g***			***Total***	***62.75g***	
Total Wkly Runoff (ml)	0	725	525	0	0	20	2550	120	2605	3155	615	40	730	***11,085ml***
				Total	***1,250ml***			***Total***	***5,295ml***			***Total***	***4,540ml***	
Total Wkly Rainfall (mm)	11.5	41.5	49	9	128.1*	42.57*	127.79*	52.5*	133.41*	145.85*	33.83*	N/A	90.81*	***865.86mm***
				Total	***239.1mm***			***Total***	***356.5mm***			***Total***	***270.5mm***	
Average Wkly Intensity (mm/hr)	3.2	5.6	7.8	2.2	6.8	5.8	7.6	7.8	19.6	15.1	6.7	N/A	7.3	***8.0mm/hr***

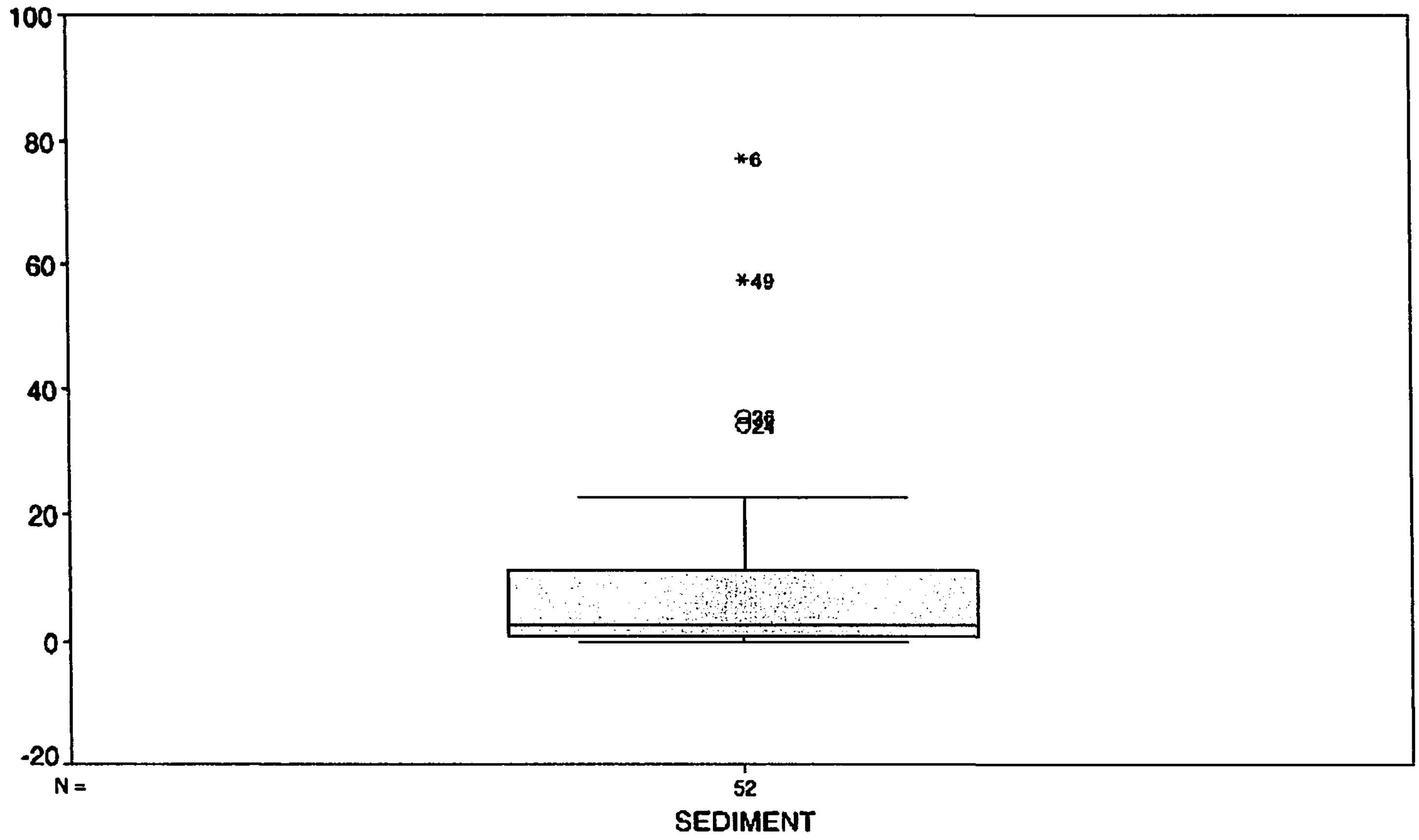
*Denotes estimated data

APPENDIX D:

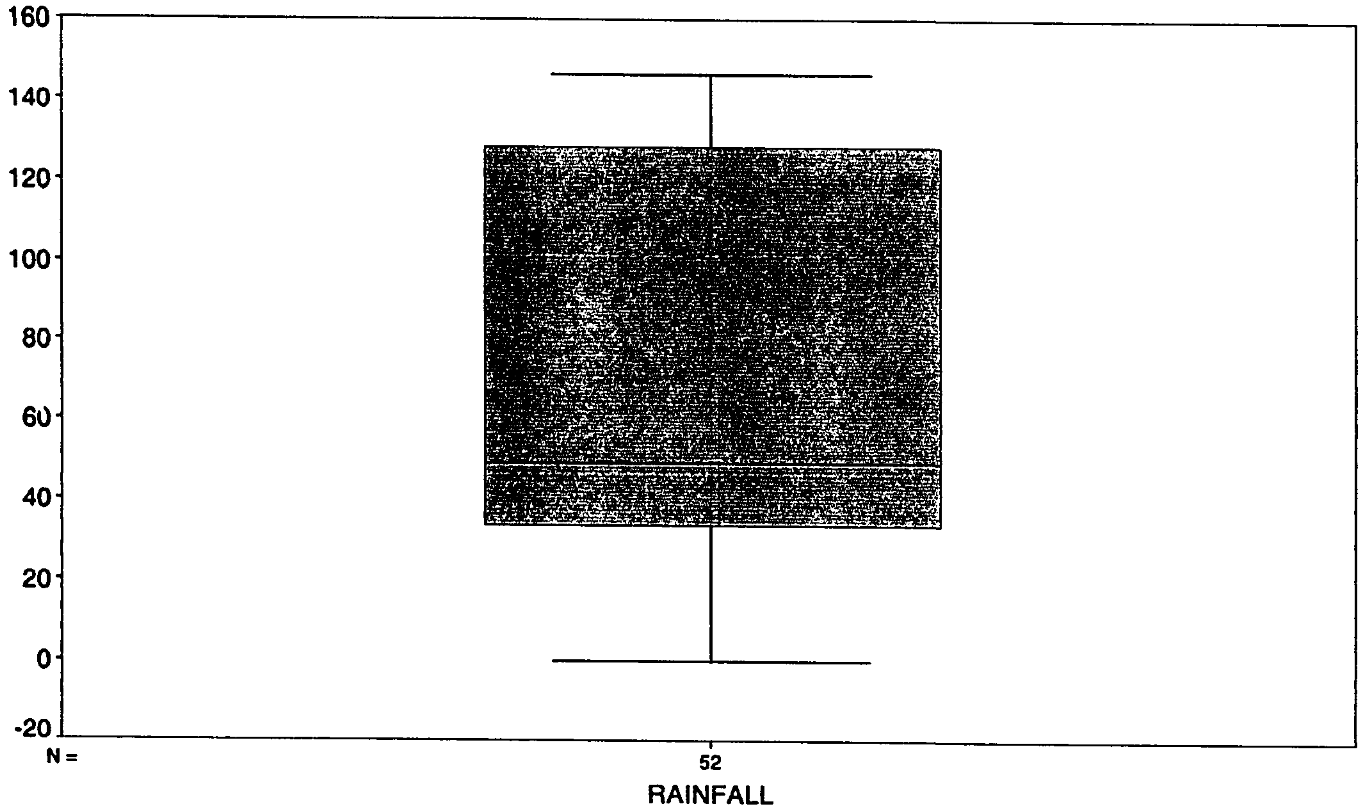
Box Plots



Boxplot 1: Runoff Data [(*) denotes extreme values by case number; (o) denotes outlier values by case number]



Boxplot 2: Sediment Loss Data [(*) denotes extreme values by case number; (o) denotes outlier values by case number]



Boxplot 3: Rainfall Data

APPENDIX E:

Correlation Matrices and Scatterplots

Correlation Matrix 1: Yam/Agroforestry Site

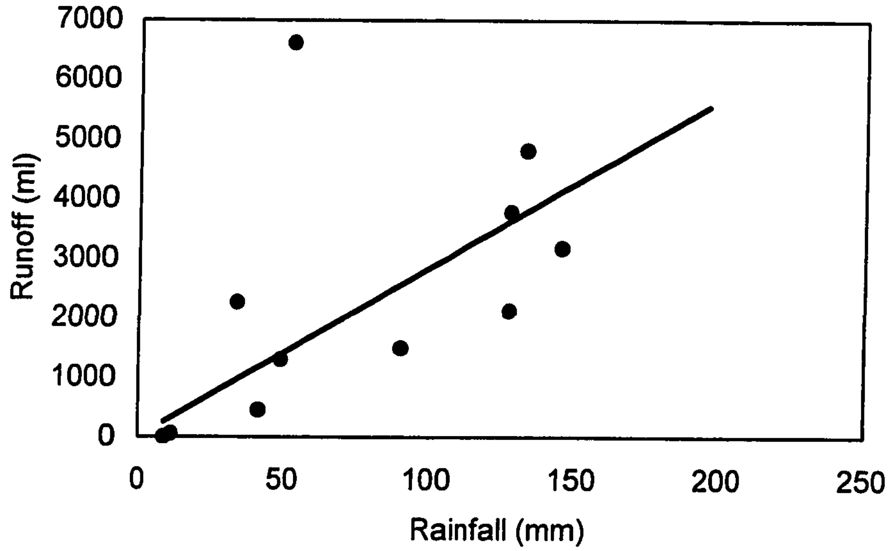
	Sediment Loss	Rainfall	Runoff
Sediment Loss	**1.0000**	**0.1652**	**0.2748**
Rainfall	**0.1652**	**1.0000**	**0.5722**
Runoff	**0.2748**	**0.5722**	**1.0000**

Correlation Matrix 2: Dasheen Site

	Sediment Loss	Rainfall	Runoff
Sediment Loss	**1.0000**	**0.2167**	**0.1748**
Rainfall	**0.2167**	**1.0000**	**0.6945**
Runoff	**0.1748**	**0.6945**	**1.0000**

Scatterplot 1: Yam/Agroforestry Site

Runoff vs Rainfall



Scatterplot 2: Dasheen Site

Runoff vs Rainfall