DFID Forestry Research Project R6290

On-farm research for the development and promotion of improved agroforestry systems for steeplands in the Caribbean

School of Agricultural and Forest Sciences

University of Wales, Bangor

Final report

1 April 1995 - 31 March 1998

ON-FARM RESEARCH FOR THE DEVELOPMENT AND PROMOTION OF IMPROVED AGROFORESTRY SYSTEMS FOR STEEPLANDS IN THE CARIBBEAN

1. EXECUTIVE SUMMARY

Project number: R6290

Title: On-farm research for the development and promotion of improved agroforestry systems for steeplands in the Caribbean

Reporting period: 1 April 1995 - 31 March 1998

Staff involved:

Principal investigators: Dr John R Healey, University of Wales, Bangor;
Dr Morag A McDonald, University of Wales, Bangor;
Dr P V Devi Prasad, University of West Indies, Mona, Jamaica.

Local collaborators: Dr David Smith, Director, Jamaica Conservation Development Trust;
Dr D Lee, Protected Areas Resources Conservation Project, Jamaica.

Research collaborators: Mr Paul A Stevens, Institute of Terrestrial Ecology, Bangor;
Mr Tom Goodland, Dr Fergus Sinclair, Mr Geoff Bright, UWB;
Dr Edmund Tanner, University of Cambridge;
Dr Adrian Newton, University of Edinburgh;
Mr Rafi Ahmad, University of West Indies, Jamaica;
Dr Joseph Lindsay, Caribbean Agric. Research and Development Inst.;
Mr Keith Porter, Dept of Forestry, Min. of Agriculture, Jamaica;
Dr Peter Vogel, Dr Jane Cohen, Dept Life Sciences, UWI, Jamaica;
Alan Pottinger, Duncan McQueen and Joanne Chamberlain, OFI;
Dr L A Bruijnzeel, Mr R Hafkenscheid, Free University, Amsterdam;
Mrs Anna Hofny-Collins, Henry Doubleday Research Association.

Research associates: Mr Kurt McLaren, University of Wales, Bangor
Ms Donna Lowe, Ms Thera Edwards, Ms Lois Morgan , University of the West Indies

Research technician: Ms Jo Hughes, University of Wales, Bangor.

Development collaborators: Jaap Plantenga, FAO Portland Project, Jamaica;
Ms Joy Douglas, Socio-economist, UWI, Jamaica.

The project had five major purposes:

- To elucidate the role of trees on soil processes and physical and chemical properties.
- To develop management regimes for different local tree species to optimise tree and crop production using low-cost methods of controlling soil erosion.
- To prepare an inventory of locally suitable species for contour hedgerow systems, and produce propagation guidelines for each.
- To increase the awareness of local community and extension officers towards the benefits of trees in farming systems and appropriate agroforestry techniques.
- To disseminate outputs throughout the Caribbean region.

To meet these the project carried out the following field-work in Jamaica:

1. A participatory on-farm experiment which provided good evidence that:
   a) the disturbed, buffer-zone of secondary forest on steep hillslopes provides good protection against surface water runoff (consistently less than 0.2% of rainfall) and erosion losses (less than 500 kg ha^{-1} yr^{-1});

b) where farming is carried out on steep hillslopes (24 - 32º) there is a five- to ten-fold increase in water run-off and a twenty- to thirty-fold increase in soil erosion. However, low input agroforestry contour tree hedgerow technology is effective in conservation of soil (erosion reduced by 55%) and water (2.5 times reduction in runoff), and enhancement of agricultural productivity (maize cob and grain weights up to 45% and 63% higher per plant respectively). Despite the loss in land available for crops, yield per area was not significantly reduced by the introduction of hedgerows. These results have great significance for the design of contour hedgerow techniques;
c) the mechanisms of these effects through the physical and chemical properties of the plot soils (determined through laboratory analyses and a bioassay) and the rate of nitrogen mineralisation are very complex, therefore caution must be expressed in extrapolating these results to other environments.

2. Survey of farmer's indigenous knowledge of the ecology and utilisation of native trees and "market-information" on farmer selection of distributed tree seedlings, indicate the importance of farmers' perception of the value of the wide range of products and benefits that trees can provide, rather than just erosion control, in their decisions on selection of species and associated on-farm tree management techniques. It is critical that rural development projects recognise and incorporate the level of existing knowledge held by rural communities.

3. Assessment of the suitability of undomesticated native tree species for farm forestry by analysis of existing ecological data, and on-farm experimentation (with 25 species) has indicated the wide range in characteristics of co-existing tree species including significant variation in establishment success not predicted from their within-forest ecology. The local tree flora provides a range of species with considerable potential for farm forestry/afforestation for a wide range of purposes and environmental conditions. Until existing knowledge is greatly improved, on-farm trials are essential for farmers to establish which species best meet their needs. A wide range in performance was also found in a trial of eight provenances of the naturalised multipurpose tree species *Calliandra calothyrsus*, with similar conclusions.

4. Nursery experimentation lead to incremental improvements in knowledge about the optimal methods for vegetative propagation of selected native tree species. However, the time and resources required for this indicates the importance of the existence of remaining areas of natural forest which can act as a source of wilding seedlings or seeds for an initial phase of farm-forestry with native species (until the planted trees themselves set seed).

The project has demonstrated the appropriateness of contour agroforestry hedgerow techniques for physical and socio-economic conditions that occur frequently within the Caribbean and it has contributed high quality data to meet the internationally-identified need for improved results on the effect of contour hedgerow agroforestry on steep hillslopes.

Dissemination of results in the Caribbean region was a major component of this adaptive project and was carried out successfully via extension leaflets, a widely distributed manual and via numerous other means. Considerable uptake of the project's outputs has already occurred amongst the resource-poor farming community in the area of field-work (this has involved a major change from previous practices) and amongst NGOs, the private sector, government agencies and regional institutions throughout the Caribbean. In at least four of these it has left a significant legacy of: trained personnel, sections of management plans, higher education curricula and plans for a new MSc, a cohort of active research students, infrastructure and transferred established field-experiments.

The project has, and will have, a significant impact on the reduction of poverty of a number of impoverished social groups.
a) Amongst marginalised hillside farmers it has demonstrated, tested and disseminated a technology that is enabling them to increase the productive capacity of their farm-land on a socially, economically and environmentally sustainable basis.
b) A consequence of this is improved quality and quantity of water supply for those involved in fishing and irrigated agriculture, and the urban poor - a major contribution to poverty reduction. It also has importance for both terrestrial and marine ecotourism, and increasingly important source of employment in the Caribbean.

2. BACKGROUND

This project addresses several development needs:

- to arrest productivity declines as a result of erosion
- to empower resource-poor farmers to implement soil and water conservation measures
- to prevent further deforestation as a result of increasing marginalisation of hillside farmers

The investment by international donors in the last decade into land-use improvement programmes has resulted in a plethora of technical prescriptions for soil and water conservation. However, the response of state and national authorities to implement the findings has been, in general, poor. In many developing countries, the environment rarely figures with any political importance in the face of more pressing economic problems to the, largely, urban-based voting population. In the past, environmental policy has had its basis in the premise that stewardship over natural resources was primarily the responsibility of the state (Leach and Mearns, 1996, in Shaxton *et al*, 1997). Policies have been formulated to enforce conservation measures, however, the lack of success in soil conservation increases the awareness at the technical level of the need to move away from a narrow focus on soil conservation *per se* and towards support for farmers' responses to a changing resource base (Shaxton *et al*, 1997).

The amount and intensity of rainfall in the elevated lands of the humid and sub-humid tropics are major factors causing erosion, but also favour the establishment of dams and reservoirs for multiple purposes. Such structures often yield relatively high storage capacities in relation to the catchment areas and the net benefit area is also therefore high. These dams are of major importance for municipal water supplies, irrigation in the lowlands and hydroelectricity amongst other functions, and are very costly to maintain. Consequently, in order to maintain their functions, governments and other organisations involved in their management have a keen interest in upstream measures to reduce sedimentation (de Graaff, 1996). However, because these downstream or off-site effects of soil erosion in upper watersheds trigger investment proposals for soil conservation and watershed management activities, historically, the emphasis has been less on reducing sheet erosion from agricultural fields to different sources of erosion resulting in greater sediment production. Such erosion control measures are seldom undertaken by individuals and need to be financed and executed by public agencies. The large-scale soil conservation measures (e.g. terracing) of the colonial governments were often forced on farmers who were not involved in decision-making, and who therefore did little to maintain them. Since many farmers associated these activities with colonialism, there was a reluctance to cooperate after independence, and governments lost interest in pursuing soil conservation measures.

Consequently, erosion-induced loss of soil-productivity is now recognised as one of the principal threats to agricultural sustainability (Pretty, 1995). This is not reflected, however, in an increasing awareness by authorities of the need to take an interest in upper watersheds - a recent review of over 100 reports of internationally funded projects on land-use improvement in the South Asia Development Triangle of lands (home to the world's poorest billion people), involving millions of U.S. dollars concluded a near unanimity of technical advice, but a general failure of national and state authorities to take action in their upper hill lands (anonymous reviewer).

All of this leads to a changing attitude towards maintenance of land productivity. More emphasis on helping farmers to improve their land husbandry, and less on efforts to combat erosion alone, will provide a more effective solution to an old problem. Where farmers find it feasible and worthwhile to improve the texture, organic matter content, porosity and nutrient levels of the soil, natural fertility will be raised and the soils recuperate (Shaxton *et al*, 1997). It is now crucial to identify these motivating factors, given the deterioration in living standards in many countries in recent years which can be directly linked to land degradation. For example, a recent World Bank study in the Caribbean identified that small-scale farmers have emerged as one of the groups of the chronic poor, alarmingly grouped with the disabled, elderly and generally disadvantaged people (Baker, 1997). Most of the poor in the Caribbean still live in rural areas and some of the immediate causes of poverty are attributed to limited land availability, land degradation and low agricultural productivity.

Due to a complex variety of factors a proportion of these poor farmers cultivate marginal land, on which rapid loss of crop yield (due to a variety of causes, loss of soil fertility often being the major one) generally forces them to carry out slash-and-burn agriculture, with fallow periods for soil restoration. Although in some environments this can be a sustainable form of land use in marginal lands, especially on hill-slopes and where there is limited land available per farmer, it is often unsustainable with insufficient recovery in productive potential during the fallow period. In these circumstances, current practice often keeps farmers in a state of poverty, as they produce only a low yield of crops from each area of land in return for the investment made in clearing and preparing it for cultivation. Thus, the context for this project is the urgent need to find a stable and sustainable alternative to slash-and-burn agriculture in the tropics. It has been accepted that cultivation will continue on many areas of sloping land, and ways must be found to make this environmentally acceptable - conventional land capability classification is no longer sufficient in the formulation of land management policy when there is increasing pressure on land. Sloping lands are an identifiable type of environment with a distinctive set of problems (Young, 1989). Thus, if control of soil erosion is only one aspect of soil conservation, then in practical development planning, it should not be treated in isolation, but integrated with maintenance of soil fertility, water availability and other aspects of agricultural improvement.

Land use problems in the Caribbean

The status of soil erosion and conservation in the Caribbean region has been reviewed by Gumbs (1992, 1994). He concludes that the steeply sloping mountainous topography in most of the islands, generally high rainfall, and poor soil management practices cause excessive soil erosion by runoff. In the Caribbean most of the farmers on hillsides are resource-poor small-holders who do not have a soil conservation culture, and who have limited formal education and training. Therefore, the methods of soil conservation must be simple, inexpensive, must preferably give an economic benefit quickly and must not compete seriously for scarce labour. In the past the focus has been on physical or engineering methods but adoption of these methods has been limited (Baxter 1975). A different approach is needed, and in this regard agronomic or biological methods are very important and relevant to the Caribbean region (Gumbs 1994).

Plate 1 The steep slopes, high rainfall and poor soil management of many of the Caribbean islands has led to erosion, loss of soil productivity, and often invasion by exotic weeds which prevent forest regeneration.

Sheng (1972, 1981) suggests that the options for successful management of soil erosion on steep slopes are relatively few: forms of agroforestry and forestry being the only sensible ones, although subsequent authors have not taken this stance (e.g. Young, 1989a,b). Agroforestry is best described in this instance as a land-use system in which trees or shrubs are grown in association with agricultural crops with the objective of stabilising and sustaining productivity. It has been practised in Jamaica for many centuries (often in a form of home-garden system), but not in any rigorous manner (Suah and Nicholson, 1986), and not to any great extent on mountainous, steeply-sloping agricultural lands. There is a need to investigate suitable systems for these environments, and to assess their contribution to the control of soil erosion and maintenance of soil fertility, and most importantly, their acceptability to the farmer. Recommendations for any agroforestry system must take account of local environmental, social and market factors to result in activities appropriate for the locality. Too often in the past, agricultural development projects have failed to take advantage of the enormous value of the knowledge held by rural communities and have introduced technologies which were too costly (in time and resources) for the local community to maintain after cessation of the project. They have also underestimated the time that it takes to bring about a change in people’s farming or failed to provide adequate demonstrations of technologies. Subsistence farmers have learned from bitter experience to be cautious about introducing change - they have neither the time nor the resources to take risks, and hence tend to be very conservative.

Contour hedgerow agroforestry

Much attention has been focused on the technique of hedgerow intercropping (or alley cropping) since the advent of agroforestry as a scientific discipline (Lal 1989a; Kang *et al*. 1990; Kang 1993). When the technique is primarily utilised to maintain or enhance soil fertility on flat land by the additions of organic matter and the redistribution of mineral elements, the results have sometimes been conflicting (Ong 1994). Young (1993) concluded that the technique would be unlikely to be widely adopted in practice on flat lands. However, the situation is different on sloping land where a large number of experimental results have confirmed the significant role of contour hedgerows in reducing runoff and soil erosion (Lal 1989b; Young 1989; Paningbatan 1990; Kang and Ghuman 1991; Dharmasena, 1995; Alegre and Rao, 1996). There is evidence that hedgerow intercropping has beneficial effects on soil fertility (e.g. Kang *et al*. 1985; Lal 1989c; Kang and Ghuman 1991) but Kang (1993), in a comprehensive review of the potential benefits and limitations of the technique, recognised that the magnitude of the effects varies with the species used and the quantity and quality of prunings produced. He concluded that further research is needed for specific ecozones, particularly with the inclusion of better adapted or indigenous hedgerow species. To refine the technology, more adaptability studies are needed, and the most encouraging results suggest that the greatest potential lies in the high base-status soils of the humid and sub-humid zones on steep hillslopes (Kang 1993). Young (1997b) concludes that on the basis of technical effectiveness, on gentle to moderate slopes (up to 20%), the contour hedgerow system provides a viable alternative to conventional methods of soil conservation. For steep slopes, further research is needed.

Contour hedgerow intercropping is a simple technique which has the potential to exist on fairly meagre resources, and to build gradually upon local initiatives, while depending on local knowledge, technology and labour. The technique involves the growing of hedgerows of trees, or a perennial crop, as a barrier along the contours of a slope, with the areas between the hedges being used for agricultural production. Most hedgerows have been established with a single species, the desirable characteristics of which include a supply of viable seed, vigour, fast growth, nitrogen fixation, copious biomass and useful by-products. On steep slopes, one of the principal reasons for agencies to promote hedgerows is erosion control; and in those places the by-products might be seen to be of secondary importance. However, crucially, this may not be the perception of the farmer (Pellek, 1992).

On slopes contour hedgerows can reduce erosion rates essentially by reducing the velocity of runoff water and increasing its infiltration into the soil. They may prevent soil loss by trapping and accumulating soil up-slope of them, leading to progressive terrace formation that results in the reduction of continuous slope length and angle. The hedgerow roots may stabilise the terrace risers and improve the soil's physical properties by reducing bulk density and improving water infiltration and aggregate stability (ICRAF, 1994). Where prunings are scattered on the soil surface, the surface mulch that they provide may reduce rainfall impact and soil erodibility by providing a protective cover, improve soil fertility through decomposition, improve soil physical properties by the addition of organic matter and conserve moisture by reducing soil evaporation. The combined effects of the barrier and cover function are unique compared with traditional soil conservation measures which only provide the barrier effect, or mulching which only provides the cover effect (Njoroge & Rao, 1995).

On-farm research

Many agroforestry development projects are introducing and promoting this technique with some success (e.g. Fujisaka 1993; Tacio 1993). However, it has still not been widely accepted because of technical problems and lack of fit with farmers' circumstances (Fujisaka *et al*. 1994). Therefore, it is recognised that further research is needed to refine and adapt this practice, especially on steep slopes. With a view to increasing the local appropriateness, and therefore, adoption rates of such practices, recent approaches have realised the importance of involving the participation of farmers in the technology development process, and on-farm research methodologies have been extensively developed (see Scherr 1991).

DFID FRP project R4611

On-farm research methodologies were utilised in our previous ODA FRP funded project R4611. Studies of erosion following forest clearance (Healey *et al.* 1994) demonstrated the use and effectiveness of *Calliandra calothyrsus* in hedgerow systems in the Blue Mountains of Jamaica in reducing rates of erosion to levels which may be considered sustainable compared to plots with conventional soil conservation methods. The method of research was one of farmer-participation, with each experimental block being 'managed' by a different local farmer.

There was only sufficient time available within project R4611 to record the first two years of the effect of agroforestry hedgerows on: surface water run-off, soil erosion, rainfall interception, organic matter input processes and soil condition; it did not have the resources to determine the effects on crop productivity and mineral nutrient cycling controlling longer-term soil fertility. The strategic research of that project, and collaborative work with NRI, took the bulk of available staff time. Therefore, only a limited extension effort was appropriate and possible. Nonetheless, important preparatory work for the adaptation of the research was carried out, in particular a socio-economic survey of the local farming community in collaboration with the University of Wageningen. This confirmed that marginalised hillside farmers in Jamaica work under considerable constraints of time, labour and finance, which explain the poor uptake of physical methods of soil erosion control (confirming the conclusions from field-work carried out in another area by Barker & McGregor (1988)). Therefore, it became apparent that it would be necessary to demonstrate direct economic benefit to the farming community before widespread adoption of a given method will occur. This can only take place with 'on-farm' trials involving the close collaboration of the local community, and active extension of positive research results. The participation of the farming community is critical.

Project R4611 was also active in other forms of preliminary extension, including the encouragement of the dissemination of the results of the project to the local community by diffusion via the participating farmers and the demonstration value of the experimental plots. We also maintained very active contacts with other land-use development organisations and projects in Jamaica. As a result project R4611 attracted considerable interest, both from existing institutions, and the executing officers of newly initiated forestry bilateral projects. The management of the new National Park project (PARC) involved us in the development of their management plans which have incorporated many of the recommendations resulting from this project; they were keen to promote the technology, particularly in conjunction with the decentralised system of community-run nurseries that they will be developing (PARC, 1994).

Species selection

A major factor in the success or failure of new agroforestry practices (both technically and in terms of farmer uptake) has been the choice of tree species. In the early stages of project R4611 *Calliandra calothyrsus* was chosen as the species for the main agroforestry experiment, because in the Caribbean it was already naturalised and had been recognised, potentially, as a very suitable species for hedgerow intercropping systems (Thompson, 1986; MacQueen, 1992). It has been identified as having potential for fuel-wood production in the Jamaican Blue and John Crow Mountains National Park buffer zone (PARC, 1994) and recognised as having global potential for the rehabilitation of degraded forest and abandoned agricultural land (NRC, 1983). It is very popular with the local farmers, nitrogen-fixing, fast-growing, produces large quantities of nitrogen-rich litter and dense fuelwood, coppices well after one year and branches close to the ground (and is therefore good for soil protection). In addition, it could be a valuable fodder source for livestock towards the end of the dry season when other sources are becoming scarce - it is precisely at this time that the trees should be cut back to capitalise on the forthcoming rains.

Plate 2 *Calliandra calothyrsus* is popular with the farming community for its fuelwood and fodder properties. It also fixes nitrogen and coppices readily.

International research in agroforestry, however, has lead to a recent questioning of the criteria that have been used to select tree species for agroforestry practices. Although, the existing scientific data is still limited, there is growing agreement that competition between trees and crop is likely to outweigh the positive benefit of mulching. Synthesis of the ICRAF experience with hedgerow intercropping suggests that the current strategy of using nitrogen-fixing and fast-growing trees may not be the solution, as these trees may prove to be too competitively aggressive in a number of situations. Rather, suitable agroforestry species are likely to be trees from local natural vegetation with non-aggressive rooting habits, which will not compete too greatly with crops (Ong 1994). Also, suitable agroforestry systems must have the potential to exist on local resources (which are often scarce), knowledge, technology and labour, so that they can build gradually via local initiatives. These criteria are more likely to be met by the use of native species for which there is a readily available, viable seed or seedling supply. Furthermore, there have been numerous examples in the tropics of exotic species which have become invasive subsequent to their introduction and then become a threat to local biodiversity, as documented for Jamaica by the results of our current ODA FRP project (R4742, Healey *et al* 1993). The resulting management problems led the PARC management to request specifically that we explore the potential of native species for agroforestry applications.

3. PROJECT PURPOSE

1 To elucidate the role of trees on soil processes and physical and chemical properties.

2 To develop management regimes for different local tree species to optimise tree and crop production using low-cost methods of controlling soil erosion.

3 To prepare an inventory of locally suitable species for contour hedgerow systems, and produce propagation guidelines for each.

4 To increase the awareness of local community and extension officers towards the benefits of trees in farming systems and appropriate agroforestry techniques.

5 To disseminate outputs throughout the Caribbean region.

4. ACTIVITIES AND OUTPUTS

4.1 MEASUREMENT OF THE EFFECTS OF SECONDARY FOREST CLEARANCE AND SUBSEQUENT LAND USE ON EROSION LOSSES AND SOIL PROPERTIES IN THE BLUE MOUNTAINS OF JAMAICA

4.1.1 SUMMARY

As pressure on land and forest resources increases, there is a growing need to assess and improve the sustainability of slash-and-burn agriculture in tropical uplands. On steep hillslopes (24 - 32º) in the forest buffer-zone of the Blue Mountains of Jamaica, following clearance of secondary forest the relative impact on surface runoff, soil erosion and soil properties of three land-use treatments: maintained weed-free without cultivation (bare); cultivated with herbaceous crops (agriculture); and cultivated with herbaceous crops and intercropped with Calliandra calothyrsus contour hedges (agroforestry) was assessed over a five year period and compared with an uncleared secondary forest control (forest). The forest provided good protection against surface runoff (which was consistently less than 0.2% of rainfall) and soil erosion losses (less than 500 kg ha^{-1} yr^{-1}); agriculture caused a seven-fold increase in surface runoff and 21-fold increase in soil erosion. However, agroforestry was effective in conservation of water (45% reduction in runoff compared with agriculture) and soil (erosion reduced by 35%). The clearance of the secondary forest led to large changes in most measured soil properties. Over five years concentrations of organic matter declined by 31%, total N by 38%, exchangeable K by 47%, Ca by 43% and Mg by 56%; over the same period bulk density increased by 48%. Of the soil properties more subject to year-to-year fluctuations, after five years the concentration of available P was 36% less in cleared plots than in forest, exchangeable Na was 50% less and moisture content 43% less. Only total P concentration and pH were unaffected. Five years after forest clearance there was no good evidence that these changes had stabilised and very little difference in soil properties was found amongst the three land-use treatments. However, within the agroforestry plots, exchangeable K, Na and sand concentrations became higher under the hedgerows than between them (by 14%, 9% and 8% respectively), whilst clay concentration became higher between them (by 9%). The results indicate that this low-input, contour-tree-hedgerow technology is effective at soil and water conservation through the sieve-barrier effect and increased water infiltration (respectively) and has the potential to enhance the sustainability of this land-use system at a plot scale.

OBJECTIVES

Purpose 1: To elucidate the role of trees on soil processes and physical and chemical properties

There is a lack of basic empirical data and understanding of the role of the secondary buffer-zone forest on the fertility of the soil and its productivity. There is a need to gauge the response of the land to the various changes of use by the measurement of a standard selection of soil properties and ecosystem processes, related to nutrient and water cycling, soil physical factors and soil biological processes.

The objective of this part of the project was to investigate the consequences of forest clearance on soil erosion, runoff and consequent fertility. The use of a potential agroforestry system - contour hedgerows was also investigated as a means to provide a stable and sustainable agricultural production system for sloping lands in the tropics.

4.1.2 INTRODUCTION

The Blue Mountains of Jamaica are a geologically recent tropical mountain range, characterised topographically by steep slopes (generally greater than 25°) and highly dissected terrain, with sharp ridges and deep gullies; the soils are generally poorly-developed Cambisols. The natural vegetation is montane tropical rain forest (Shreve, 1914). On slopes up to about 1600 m the forests have been subject to conversion for over 200 years; recently this has been for two major land uses: cash crop and subsistence cultivation of vegetables by small farmers and the establishment of commercial coffee plantations (Eyre, 1987). Typically, the former involves slash-and-burn clearance of the forest, and the farmers shift to a new area of land when levels of crop production fall (Barker and McGregor, 1988). The farming community in this area represents a marginalised population, suffering considerable constraints of finance and labour. After land is abandoned from agriculture, secondary forest regrows where the incidence of uncontrolled fires is sufficiently low to permit this. In a major section of the Blue Mountains this forest is often dominated by the introduced Australian tree, Pittosporum undulatum, with potentially serious negative consequences for biodiversity conservation (Goodland and Healey, 1995; Healey, et al., 1995). However, McDonald and Healey (2000) have recorded the occurrence of tight nutrient cycling and high levels of soil fertility after c. 20 years of succession in these forests. The importance of the remaining forests in the Blue Mountains as an ecological resource, from the point of view of their influence on water and soil conservation as well as being a unique ecosystem containing a large number of endemic species, has been acknowledged (e.g. Tanner, 1986), and this area has been incorporated into a new National Park of over 77,000 hectares. A major management objective is to reduce the rate of forest conversion and degradation by farmers, through improvement in the sustainability of the current forms of agriculture in the park's buffer zone. To this end it is important to assess the extent to which the current slash-and-burn practice in the Blue Mountains does lead to a decline in soil fertility, and the extent to which this decline can be prevented by alternative land-use practices.

The vast majority of studies into the impacts of slash-and-burn agriculture on soil properties have taken place in lowlands, and on sites that are flat, or gently sloping. However, as is the case in Jamaica, in many other countries an important agricultural frontier occurs in mountain areas where the resulting conversion and degradation of natural forest may threaten its important biodiversity and environmental protection functions. There is a lack of good evidence about the changes in soil properties caused by slash-and-burn agriculture in these very different, steep-hillslope mountain ecosystems where soils are often young, with higher inherent fertility, but potential rates of soil erosion are much higher. The impact of such land-use changes on hydrology and soil erosion is complex. Replacement of a tropical rain forest canopy with an agricultural crop has been shown to increase annual catchment water yields by 110-825 mm in the first year after clearance (Bruijnzeel, 1990). Reported increases in soil erosion are highly variable, with a range from 1- to 100-fold (UNESCO, 1978); in his review Wiersum (1984) found a median increase of 10-fold.

On steep hillslopes most attention has focused on the use of contour hedgerows (Young, 1997) and there is an increasing body of knowledge about their effects on soil erosion and soil properties. Young (1997) reviewed 14 studies which showed a range of 1- to 58-fold decrease in soil erosion rate compared with agricultural controls, and the results of subsequent studies have remained within this wide range (e.g. Alegre and Rao (1996)). However, only two of these have examined slopes as steep as those encountered in our study ($\geq 24^{o}$), and they only showed a 1-2 fold decrease in erosion rate (Young, 1997). There is a great lack of studies on the impact of contour hedgerow intercropping on soil properties on such steep slopes. On shallower slopes the recent work of Garrity (1996) and Agus et al. (1997, 1999) has focused on the redistribution of soil fertility from the upper to the lower sections of the cultivated land between contour hedgerows.

The objective of this study was to investigate the effects on surface runoff, soil erosion and soil properties of secondary forest conversion and alternative forms of subsequent use of steeply-sloping, montane, tropical land over a period of five years. The extent to which the net effect of forest conversion is due to the removal of forest cover (forest clearance) or to subsequent agricultural cultivation was assessed. The effect of agroforestry with contour hedgerows on overall rates of surface runoff, soil erosion and soil properties, and on the spatial distribution of soil properties (under and between hedgerows), was also investigated to assess its potential use as a means of providing a stable and sustainable agricultural system for sloping land.

Plate 3 The natural vegetation of the Blue Mountains is montane rain forest.

4.1.3 MATERIALS AND METHODS

4.1.3.1 STUDY AREA

The study area was located on the south-west slopes of the main ridge of the Blue Mountains in the catchment of the Green River, a tributary of the Yallahs River at an altitude of around 1300 m and in the vicinity of Cinchona, Westphalia, St Andrew, Jamaica, at latitude 18°N and longitude 76°W. The Yallahs is the largest river on the more populous southern slopes of the Blue Mountains and its basin as a whole has a high natural propensity for erosion: 85% of the land area of the Upper Yallahs Valley has slope angles greater than 25°, and cultivation on slopes of up to 45° has been recorded (McGregor et al., 1985). The underlying geology is complex, both the 'Blue Mountain Volcanics' which include granodiorite, and 'Blue Mountain Shales', which consist of mudstones, sandstones and conglomerates, are present. Soils of the area are reported as eutric and chromic Cambisols (FAO-UNESCO, 1975), and these soils were confirmed as present in the experimental area by the authors. Mineralogical examination revealed the presence of minerals that could be derived from mafic material (epidotes, chlorites and amphiboles), as well as from shale (quartz and hydrous mica) (D.A. Jenkins, personal communication). However, the soil included a mixture of these minerals associated with unweathered sources and those from highly weathered sources (e.g. magnetite and ilmenite). Soil depth varied depending upon the proximity of bedrock or presence of accumulations of colluvium, and soils were very stony. Average content of stones (> 2 mm) in the upper 10 cm was around 70% by weight, often with a substantial quantity of boulders. Soil texture was variable, ranging from sandy loam and silt loam to clay loam, but the soil was freely drained in all situations. Profiles under forest were marked by dark, humose A horizons, but after cultivation the topsoils apparently lose organic matter (OM) and display a noticeable reddish-brown hue.

Mean annual rainfall at the nearby Cinchona meteorological station (1525 m above sea level) over a 70- year period was 2180 mm, ranging from 905 mm in 1983 to 4464 mm in 1963 (Jamaica Meteorological Service, unpublished data). The distribution of the rainfall tends to be bimodal: in most years the major wet period occurs in October and November

(November mean monthly total was 405 mm) and a minor wet period in May (mean monthly total was 196 mm); March and July have the lowest mean monthly rainfalls (89 mm and 77 mm respectively). The area is subject to periodic hurricanes (most recently Hurricane Gilbert in 1988) contributing to high variability in rainfall amongst years. Over 90 years eight individual months had a recorded rainfall greater than 1000 mm (the highest being 2416 mm). Over 39 years the range in monthly mean temperatures at Cinchona was 14.6 - 17.6 °C (with an absolute minimum of 9.6 °C and maximum of 24.4 °C) (Shreve, 1914).

Plate 4 The experimental plots are located in the forest buffer-zone. These are blocks II and III, farmed by Mr Roy Bryan and Mr Sheraton Walker, respectively.

4.1.3.2 EXPERIMENTAL DESIGN

Four experimental treatments were selected to meet the study's objectives:

1. Secondary forest ('forest')
2. Forest cleared, burned and soil subsequently maintained weed-free ('bare')
3. Forest cleared, burned and soil planted with annual vegetable crops ('agriculture')
4. Forest cleared, burned and soil planted with agricultural crops and intercropped with Calliandra calothyrsus (Meissner) contour hedges ('agroforestry').

C. calothyrsus, a leguminous tree species native to Central America and Mexico with a low-branching habit, was selected for the agroforestry hedgerows because it has been found to be a suitable species for this purpose elsewhere in the tropics (e.g. National Academy of Sciences, 1980; Palmer et al., 1994; Evans, 1996) and was already present in the study area. Although it was only recently introduced to the Blue Mountains of Jamaica, following its introduction in a species trial in the 1980s (D. Thompson, pers. comm.), the local farming community already recognise its value for erosion control in their agricultural systems (as well as for a range of other uses) (Collins and McDonald, 1997).

Four blocks each consisting of four plots were established in areas of secondary forest, that had originally been cleared for cultivation of coffee, cinchona or other agricultural crops at various times up to the early 1970's and then abandoned by the early 1980's. The position, layout and management of each block was designed to minimise within-block variation. Each treatment was assigned randomly to one plot in each block giving a randomized complete block design. The experiment was "on-farm", and although researcher designed, each block was managed by a different individual farmer, who had control over the farming practices adopted in their agriculture and agroforestry treatment plots (e.g. the crops grown, and the timing of individual farming operations), leading to small between-block variation in farming practice.

The slope angle of the plots ranged from 24 to 32^{o} but within-block variation was only 2° on average: all the plots were in a mid-slope position between 1253 m and 1315 m altitude and none of them occupied or included obvious convex zones of higher than average net erosion, or deposition zones of net sedimentation. Each plot was 10 m (across slope) x 20 m (down slope), with an inner assessment area of 8 m x 15 m. The plots were bounded on the upper border with galvanized steel barriers, and trenched on the lateral borders to prevent erosion of sediment into the plots.

In the plots of the three cleared treatments the secondary forest vegetation was cut with the tree trunks removed and other material (branches, foliage, shrubs, herbs etc.) retained in-situ, in accordance with local practice, in July 1992. The retained material was subsequently left to dry until August 1992 and then burned. The plots were left for up to three weeks to 'sterilise the soil' (a local practice) and crops and trees planted in September, 1992. Various mixtures of escallion (Allium ascalonicum L.), thyme (Thymus vulgaris L.), carrots (Daucus carota L.), potatoes (Solanum tuberosum L.), beetroot (Beta vulgaris L. subsp. vulgaris), cabbage (Brassica oleracea L.), sweet pepper (Capsicum annuum L. var. annuum) and cucumber (Cucumis sativus L.) were planted in the plots of the two agricultural treatments. The farmers followed their usual practice in crop management, including weeding. In addition, each farmer kept their bare treatment plot weed-free by manual clearance with a cutlass (so that there was no up-rooting and consequent soil disturbance) on a fortnightly basis.

The trees were grown from seed collected during February and March 1992 from the population of C. calothyrsus naturalised in and around Cinchona Botanic Garden. The seeds were sown in March 1992 in seed trays, transplanted to pots after germination, and kept in a shade house at Cinchona until outplanting when the seedlings were about 15 cm high. Three contour hedgerows were established per plot. The hedgerows were 5 m apart and each comprised a triple row of trees at 1-m intra-row spacing and 0.5-m inter-row spacing. The tree planting positions in the rows were arranged in a staggered manner downslope to maximise the barrier effect. An A-frame was used to lay out the contour lines.

The hedgerows were cut back to a height of about 30 cm on a regular basis at approximately five-monthly intervals and were never allowed to grow more than about 1 m tall, at which point they started to shade the crops. Initially, during 1993 and 1994, the prunings were laid along the upper side of the hedgerows to help build up the barrier effect, but subsequently (from 1995) they were chopped up and used as mulch on the farmed area between the hedges. The biomass and N and P concentrations of the prunings were recorded at each cut: on average the prunings resulted in recycling of 2916 kg ha^{-1} yr^{-1} of OM, 122 kg ha^{-1} yr^{-1} of N and 7 kg ha^{-1} yr^{-1} of P to the soil.

4.1.3.3 SURFACE RUNOFF, ERODED SEDIMENTS AND RAINFALL

In order to select the method to measure runoff and eroded sediment best suited to this study the advice of Morgan (1986) was followed: "bounded runoff plots probably give the most reliable data on soil loss but there are several sources of error……one of which is an edge effect where runoff may collect along the boundaries…………An alternative method developed by Gerlach uses simple metal gutters………minimises edge effects…..cheap and simple way to measure selected sites over a large area". Furthermore, the experimental plots were carefully placed on areas of the hillslope directly perpendicular to the slope angle on land of even slope that gave the minimum potential for runoff/sediment to enter or leave the plots from the side. They were also trenched at the sides at the beginning of the study. With respect to the conclusions of Zobisch et al. (1996), it is of note that they found most errors in estimation of eroded sediment to be between observers. We counteracted this problem by restricting observations to just two individuals, Morag McDonald and Albert Hall, throughout the whole experiment. These two observers took careful steps to ensure that their methods were as similar as possible (e.g. by regularly carrying out the sampling together). Also careful observations were made to check that no differences in level between the soil surface and the edge of the trough sill; no major problems occurred and minor ones were rectified.

Three Gerlach troughs, each 1 m long, were installed at the lower edge of each inner plot (following Morgan, 1986) during June – July 1992 before forest clearance. The collecting gutter was covered with a lid to prevent the direct entry of rainfall, and sediment and runoff were channelled from the gutter into covered collecting buckets (three buckets per trough with overflow pipes delivering 1/6 of the volume to the second and third buckets respectively). At each sampling occasion all sediment was collected from the trough, and suspended sediment estimated by filtering a 1-l sample of runoff; runoff water quantity was measured; and water samples collected. In 1993 and 1994 sampling was carried out on a fortnightly basis or more frequently after rainfall events and, from 1995 to 1998, after every rainfall event of > 25 mm, since rain events with less precipitation were observed not to cause runoff in the preceding years. Each entire eroded-sediment sample was separated into litter, coarse (> 2 mm) and fine (< 2 mm) mineral fractions and the dry mass of each fraction recorded. A bulked sample of the sediments collected from each plot over each year was compiled and the < 2 mm fraction analysed for particle size distribution (hydrometer method (Anderson & Ingram, 1993)); organic matter (OM) (loss on ignition at 550 ^{o}C for 2 hours (Allen, 1989)); pH (in a 1:2.5 weight:volume soil:deionised water slurry). For mineral nutrients the following extraction methods were used: for total N and P a sulphuric acid/hydrogen peroxide digestion (Allen, 1989); for available P a sodium bicarbonate extraction at pH 7 (Anderson & Ingram, 1993); and for exchangeable Na, K, Ca and Mg an ammonium acetate extraction at pH 7 (Anderson & Ingram, 1993) shaking the soil/extractant for one hour on an orbital shaker. Concentrations were then measured: for nitrate-N using a Dionex automated ion chromatograph, for ammonium-N using an automated colorimetric system with indophenol blue; for P using an automated colorimetric system with molybdenum blue; and for Na, K, Ca and Mg using atomic absorbtion spectrophotometry. The litter fraction was also analysed for total N, P and OM using these methods.

In 1993 and 1994, runoff samples were filtered through 0.45 μm filters within 24 hours of collection and were stored with a 1% mercuric chloride preservative until analysis. Extractions and analyses were as follows: dissolved organic carbon (DOC) was analysed by colorimetry; reduced forms of N (organic-N plus ammonium-N) were extracted with a sulphuric acid/hydrogen peroxide digestion and then analysed using an automated colorimetric system with indophenol blue; nitrate-N was analysed using a Dionex automated ion chromatograph; total N was calculated as the sum of nitrate-N and the reduced forms of N; total P was extracted by sulphuric acid/hydrogen peroxide digestion and then it, and phosphate-P, were analysed using an automated colorimetric system with molybdenum blue; dissolved K and Ca were analysed using sequential inductively coupled plasma optical emission spectroscopy.

A data-logging rain-gauge was established in each block to record the amount and intensity of rainfall from September 1992 to March 1998. Erosivity of individual rain events was calculated as an EI_{15} index (Stocking and Elwell, 1973). Annual rainfall erosivity was calculated as the sum of all EI_{15} values.

4.1.3.4 MEASUREMENT OF TEMPORAL CHANGES IN SOIL PHYSICAL & CHEMICAL PROPERTIES

Three composite soil samples were collected from each plot of all treatments, prior to clearance in June, 1992. This soil sampling was repeated annually in October from 1993 to 1997, with an additional three composite samples collected from each agroforestry plot - three from the 1.5 m-wide zone under the hedgrows as well as three from between the hedgerows in the farmed area: the area of each of these two zones (per plot) were 36 m² and 84 m² respectively. This gave a split-plot design for the agroforestry treatment plots. Each composite sample was made up of five individual samples each taken to a depth of 10 cm with a soil corer of volume 785 cm^3. The composite samples were analysed as for the runoff sediments (above) and also for moisture content by oven-drying for 24 hours at 105^{o}C and bulk density (calculated from dry weight/volume). Particle size distribution was measured in 1992, 1995, 1996 and 1997 only.

4.1.3.5 MEASUREMENT OF NITROGEN MINERALISATION RATES

In September of 1994 - 1997, six soil cores were collected from each plot from the surface 10 cm soil depth, using a corer of 10 cm diameter. Twelve cores were collected from the agroforestry plots - six from under the hedgerows, and six from the farmed alley areas between the hedges. Half of the cores from each plot were enclosed as intact cores in gas permeable plastic bags and inserted back into the holes from which they were taken. The remaining cores were bulked by plot, and 10 g (wet soil) subsamples extracted for inorganic-N measurement by shaking for one hour in 100 ml of 1M KCl, and filtering through KCl pre-washed Whatman No. 44 filter papers. Inorganic-N concentrations were corrected to a per gram dry weight basis. The remaining cores were removed after 30 days and extracted individually for inorganic-N measurement. Extracts were then analysed for nitrate-N and ammonium-N colorimetrically by autoanalyser using methods (following Allen, 1989). The difference between the final inorganic-N content and the inorganic-N content in the initial bulked sample is net mineralisation. NO_3 and NH_4 contents of both sets of extracts were determined to assess rates of nitrification, as well as mineralisation.

4.1.3.6 BIOASSAYS OF SOIL FERTILITY

4.1.3.6.1 GREENHOUSE BIOASSAY

A bioassay was established in August, 1997, five years after forest clearance, to elucidate any limitations to crop growth. Soil was collected from 0-10 cm depth in the experimental plots in July, 1997. One bulked sample was passed through a 2 mm sieve and transported to Cinchona Botanic Garden. Soils were mixed with acid-washed sand in the ratio 2:1 soil:sand to improve drainage and 500 ml pots filled with the mixture. 45 pots were filled with soil from each plot, except for the agroforestry plots - in this case samples were separately collected from the alley between the hedgerow, and underneath the hedgerow, giving 90 pots per plot.

The test species used as a bioassay was *Melinis minutoflora* Beauv., commonly known as Molasses, Wynne or Christmas Grass (this species had been used successfully by Healey (1989) in his bioassay of forest soils). *Melinis* was introduced to Jamaica in 1920 (Barnett, 1936) as a fodder grass and is now naturalised. *Melinis* is a perennial, stoloniferous grass that also spreads from seed. Single node stems with one leaf were collected from the Cinchona area and 1 plant placed in each pot. Stems were approximately 5 cm long, and roots were trimmed to 5 cm length. Plants which died within 14 days were replaced after which time no further replacements were made. The pots were placed at random on wooden benches under shade and watered daily.

Thirty six days after planting, the pots were randomly divided into groups of 15; one group was left as an unfertilised control, one group was fertilised with phosphorus (equivalent to 25 kg P/ha) and the remaining group was fertilised with nitrate-nitrogen (equivalent to 50 kg N/ha). The fertilisers were applied as NaH_2PO_4 and $NaNO_3$ respectively. The pots were rerandomised and left for 14 days, after which a repeat application of the fertilisers was administered, and the pots again rerandomised.

The bioassay plants were harvested 65 days after the first application of fertiliser. Soil was washed off the roots and the plants were dried at 105 ^{o}C for 2 hours. The dry weights of the root biomass, and shoot biomass were determined, and the number of leaves. The replicate plants of each treatment were bulked for analyses of nitrogen and phosphorus.

4.1.3.6.2 *Zea mays* FIELD BIOASSAY

Zea mays L. is one of the commonest subsistence crops grown by farmers in the area of the study. It was selected as the most suitable crop for a field bioassay because of the ease and accuracy with which its productivity could be measured in terms of above-ground biomass and grain production. In this participatory experiment it proved impossible to obtain sufficiently reliable data of yield or economic return with the other crops grown by the farmers.

In March, 1996, seeds of *Zea mays* L. were planted by the farmers into the agriculture and agroforestry plots. Planting lines were demarcated - in the agroforestry plots, the rows were parallel to the hedgerows, with the first row immediately adjacent to the hedgerow and thereafter every 50 cm until the next hedgerow. Intra-row plant spacing was also 50 cm. The same spacing was used in the agriculture plots. Two seeds were placed in each planting hole. Twenty days after planting, surplus plants were removed, and empty holes filled with surplus plants to ensure full stocking. In September, 1996 sub-samples of five plants per planting position per plot were harvested, and measurements made of: plant height, above-ground fresh biomass, cob length, cob weight and percentage cob fill. Sub-samples of leaf and cob were removed for dry weight determination after oven-drying at 105 ^{o}C for two and eight hours respectively.

4.1.3.7 DATA ANALYSIS

The experiment has a randomised complete block design (with 15 df) and a split-plot structure for soil properties in the agroforestry treatment (with a further 4 df). A repeated-measures procedure was adopted and exploratory data analysis carried out which revealed no evidence of any consistent change in variability between samples within plots over time. This enabled the selection of two summary statistics: the post-treatment mean value (1993-1997) and, for the soil properties, the gradient of the 1993-1997 linear regression to test for treatment effects on the rate of change over time. At the main-plot level differences amongst treatments were tested by three a priori planned contrasts (each with df 1,9): forest vs the others; agriculture vs bare; and agriculture vs agroforestry, as well as the split-plot level analysis of the difference in soil under and between agroforestry hedgerows (df 1,3).

Statistical analysis was carried out by analysis of variance using Genstat 5.4.1 (ed. 3) and the General Linear Model of SPSS V. 9.0.0 (1998). Angular transformations were carried out for the 1993-1997 mean values of soil OM, total N, total P, moisture, clay, silt and sand. Log_{10} transformations were carried out for the runoff and erosion data. Following inspection of the results of the non-orthogonal a priori contrasts it was found that α could be kept safely at 5% without any adjustment to the critical value of F. All assumptions of ANOVA were checked by analysis of residuals.

4.1.4 RESULTS

4.1.4.1 RAINFALL CHARACTERISTICS

Total rainfall in all four years was higher than the long-term average at the nearby Cinchona meteorological station (56% higher in 1995/6). However, rainfall patterns differed greatly amongst the years; both the total amount and the erosivity of rainfall were markedly highest in 1995/6, intermediate in 1992/3 and 1996/7, and lowest in 1993/4 and 1997/8 (Table 1). The intensity of individual events with > 25 mm rainfall varied greatly from just 56 J mm^{-1} m^{-2} h^{-1} (17/1/94) to 1,432,639 J mm^{-1} m^{-2} h^{-1} (7/2/96); the four most erosive rainfall events all occurred in 1995/6. Whilst the wettest month, February 1996, had 910 mm rainfall all four years had months with > 400 mm rainfall (10 months in total).

4.1.4.2 SURFACE RUNOFF AND ERODED SEDIMENTS

The forest plots showed little fluctuation in their low runoff levels throughout the course of the study (mean annual total values ranged from 0.4 to 4.0 mm), and these were significantly lower than in the cleared treatment plots ($\underline{P} < 0.001$) (Figure 1a). Compared with the forest treatment, mean 1993-1997 runoff levels were increased by 360% in the agroforestry treatment, 460% in bare and 740% in agriculture. Total annual amounts of runoff since forest clearance remained high (10-33 mm) in the agriculture and bare treatments throughout. However, in the agroforestry treatment they declined from 21.7 mm in the second year to levels (7.4 mm down to 4.4 mm) that were closer in absolute terms to the forest than the agriculture treatment (Figure 1a). Mean runoff levels were significantly lower from agroforestry than agriculture ($\underline{P} < 0.001$).

The difference in erosion rates amongst the treatments was broadly consistent with the observed trends in runoff. Sediment yield was significantly greater in the three cleared treatments than the forest (Figure 1 b) and c), $\underline{P} < 0.001$). Compared with the forest treatment, mean 1993-1997 yield of total sediment was increased by 13.4-fold in the agroforestry treatment, 13.6-fold in bare and 21-fold in agriculture. For the < 2 mm diameter mineral fraction of sediment the increases in yield were even greater, especially in the cultivated treatments (they were by 53-fold in the bare treatment, 97-fold in agroforestry and 143-fold in agriculture). Agroforestry caused significantly lower levels of erosion than agriculture ($\underline{P} = 0.013$). Year to year variation in annual total runoff in the forest treatment was clearly correlated with variation in annual total rainfall (Table 1, Figure 1 a). However, there was a surprisingly poor correlation between annual total sediment yields in the forest, agriculture or agroforestry treatments and annual total rainfall, total erosivity or maximum erosivity (but the correlation was much better between sediment yield in the bare treatment and erosivity) (Table 1, Figure 1 b) and c)).

In all the cleared treatments total quantities of loss in eroded sediments were much greater than in runoff water for all nutrients measured in both (N, P, Ca) except for K (Tables 2 and 3). In the forest treatment, whilst eroded litter accounted for by far the majority of loss of N and P, losses of Ca, as well as K, were greater in runoff water than in eroded mineral sediment of < 2 mm diameter.

4.1.4.3 SOIL PHYSICAL AND CHEMICAL PROPERTIES

Forest conversion had a considerable impact on soil OM concentration. Between 1992 and 1997, whilst mean OM concentration remained between 200 and 250 g kg^{-1} in the forest treatment (values not untypical for freely draining soils under forest), it fell for the three cleared treatments to values between 110 and 150 g kg^{-1} in 1997 (Figure 2a, $\underline{P} = 0.006$). (Results of significance tests quoted in this section refer to the 1993-1997 mean values; the five significant results found for the 1993-1997 linear regressions are shown in Figure 2.) There was little difference between the three cleared treatments. The total N concentrations of the individual soil samples were highly correlated with OM concentrations ($r = 0.89$), which is expected as the majority of soil N is held in OM. Therefore, the trends over time in soil total N concentrations were very similar to those for OM: in the forest treatment mean values fluctuated between 5.6 and 6.8 g kg^{-1} with no overall trend, whilst they declined for all three cleared treatments to values between 3.1 and 4.1 g kg^{-1} in 1997 (Figure 2b); as a consequence this contrast was highly significant ($\underline{P} = 0.009$).

In contrast, mean total P concentrations in the soils changed little over time either in the forest or cleared treatments, varying between 0.9 and 1.5 g kg^{-1} (Figure 2c); no differences between the treatments were significant. Available P concentrations showed both considerable year to year fluctuation, rising to a peak in 1995 and then falling back again in all treatments (Figure 2d), and an effect of treatment: its mean concentration was significantly higher (by between 36 and 77%) for the forest than for the three cleared treatments ($\underline{P} = 0.021$). Both total P and available P concentrations showed clearer between-block variation than any other variable ($\underline{P} < 0.001$ and $\underline{P} = 0.005$ respectively) as their mean values were much lower in block 4 than the other three blocks.

Soils were moderately acid with treatment-mean annual pH values ranging from 4.75 to 5.85. There was very little difference in pH amongst blocks or treatments (Figure 2e). Exchangeable cation concentrations generally showed no trend over time in the forest treatment, whilst falling in all three cleared treatments. In the case of Mg whereas the concentration remained at c. 3 cmol kg^{-1} in the forest it fell to c. 0.9 cmol kg^{-1} in the cleared treatments by 1997 (Figure 2f; $\underline{P} < 0.001$). Results for exchangeable Ca were comparable, whilst its mean concentration remained at c. 12 cmol kg^{-1}

in the forest, by 1997 it had fallen to c. 6 cmol kg^{-1} in the cleared treatments (Figure 2g; P = 0.013, but P = 0.051 for the gradient of the linear regression).

For exchangeable K, there was also a marked general decline in concentrations in the three cleared treatments (which converged to very similar mean values of c. 0.3 cmol kg^{-1} in 1996 and 1997) in contrast to the forest (mean 0.8 cmol kg^{-1}); this was highly significant (Figure 2h; P < 0.001). In the agroforestry treatment plots, the mean K concentration in soil taken from under the hedgerows was significantly higher (by 30%) than that taken from between the hedgerows (P = 0.026, d.f. 1,3). Exchangeable Na concentration showed more year-to-year fluctuation than any other variable. However, these were consistent between the treatments and its concentration became significantly higher in the forest soils (by 67 to 83%) than in the three cleared treatments (Figure 2i, P < 0.001). In the agroforestry treatment plots, the mean exchangeable Na concentration in soil from under the hedgerows was significantly higher (by just 9%) than that between the hedgerows (P = 0.020, matching the result for K). Variation in the mean Na concentration between blocks was also significant (*P* = 0.039).

As expected, there was considerable year-to-year variation in soil gravimetric moisture concentration for all treatments as a consequence of variation in the rainfall regime (and thus the annual sampling date falling at different positions within the soil wetting-drying cycle). Treatment annual mean values varied between 9% and 31% (Figure 2j); nonetheless the mean values were significantly higher (by 62 to 84%) in the forest than in the three cleared treatments (P = 0.001), and they varied significantly between the blocks being 30 to 40% higher in blocks 1 and 4 than in 2 and 3 (P = 0.007). Mean soil bulk density showed no trend over time in the forest (remaining at c. 0.8 Mg m^{-3}) whereas it rose consistently in all three cleared treatments (especially in the first year after forest clearance) to reach c. 1.2 Mg m^{-3} by 1997 (Figure 2k, P < 0.001).

Significant differences in soil texture did develop amongst the treatments. For sand content, the 1995-1997 mean value was much lower for the two cultivated treatments (agriculture and agroforestry, both c. 36%) than the two non-cultivated treatments (forest and bare, both c. 46%) (Table 4, P (main-plot treatment) = 0.041). In contrast the 1995-1997 mean content of silt was higher in the cultivated agriculture and agroforestry (both c. 34%) than the bare treatment (27%) (P (agriculture vs bare) = 0.040), and all three cleared treatments had higher mean clay content (at 27–30%) than the forest (21%) (P < 0.001). In the agroforestry plots, the mean content of sand in soil taken from under the hedgerows was higher (by 8%), and clay content was lower (by 9%), than in the soil taken from between the hedgerows (P = 0.028 and 0.025 respectively). Block 4 had a lower mean content of sand (by c. 38%) and higher mean content of silt (by c. 55%) than the other three blocks (P = 0.002 and < 0.001 respectively).

4.1.4.4 NUTRIENT LOSSES AS A PROPORTION OF NUTRIENT STOCKS, AND CONTRASTS IN SOIL TEXTURE

Measured concentrations of nutrients in eroded material and in the soils were comparable. As a consequence, the total quantities of nutrient losses in runoff (Table 2), eroded mineral sediments < 2 mm diameter and eroded litter (Table 3) were low in comparison with total stocks of nutrients in these fractions in the top 10 cm of soil (calculated from concentrations and bulk density of these fractions, Figure 2) in all treatments. Mean annual losses were greatest in the agriculture treatment: as a percentage of mean stocks they ranged from 7.8% for K to 1.9% for Ca, 1.6% for N, 1.5% for OM and 1.4% for P. They were least in the forest treatment ranging from 1.6% of mean stocks for K to 0.17% for N, 0.09% for P, 0.06% for Ca and 0.02% for OM. Taking N as an example, in the forest mean annual N losses of 1.8 kg ha^{-1} y^{-1} (Tables 2 and 3) were much less than the N recycling of c. 80 kg ha^{-1} y^{-1} in fine litter and c. 11 kg ha^{-1} y^{-1} in throughfall (McDonald and Healey, 2000) and a mean annual stock (0-10 cm soil depth) of 1049 kg ha^{-1} which indicates how these secondary forests restore soil fertility during their regrowth after agriculture. By contrast, in the agriculture treatment mean annual losses were 14.8 kg ha^{-1} y^{-1} compared with a mean annual stock of 922 kg ha^{-1}. In the cleared treatments the large year to year variations in runoff and erosion rates (Fig. 1) are not mirrored at all by changes in the measured amounts of soil nutrients (Fig. 2).

In all four treatments the sand fraction dominated the < 2 mm diameter eroded sediments having a 16-21% higher concentration in the eroded sediments than in the in situ soils (Table 4). Concentrations of silt were 6-13% lower, and of clay were 7-10% lower, in the eroded sediments than in the in situ soils. Variation in the percentage of each particle size fraction amongst the treatments for eroded sediments (mean range 5.3%) was less than that for the in situ soils (mean range 9.3%).

Table 1 Amount and erosivity of rainfall over the experimental period.

Year	Total rainfall (mm)	Wettest month (mm)	Rainfall event of highest erosivity ($J\ mm^{-1}\ m^{-2}\ h^{-1}$)	Number of rainfall events > 25 mm	Proportion of total rainfall falling in rainfall events > 25 mm (%)	Total erosivity ($J\ mm^{-1}\ m^{-2}\ h^{-1}$)
1993	2817	May 1993: 774	22 Oct 1992: 124,014	29	55.8	922,142
1994	2299	Jan 1994: 683	16 Jan 1994: 132,840	19	59.1	816,215
1995	3403	Feb 1996: 910	7 Feb 1995: 1,432,639	31	78.8	3,617,350
1996	2646	Nov 1996: 536	1 June 1996: 228,844	30	61.6	1,246,733
1997	2268	Jan 1998: 436	5 Jun 1997: 233,286	13	51.2	824,909

Year refers to the 12 month sampling period, e.g. 1993 = September 1992 to September 1993. Total erosivity is the sum of erosivities of the rainfall events > 25 mm in each year.

Table 2 Nutrient losses in surface runoff water (mean values 1993-1994 ($kg\ ha^{-1}\ y^{-1}$), with standard errors in parentheses).

	DOC	Total N	NH_4-N	NO_3-N	Total P	PO_4-P	Ca	K
Forest	1.03 (0.19)	0.15 (0.03)	0.08 (0.01)	0.02 (0.01)	0.03 (0.01)	0.03 (0.01)	0.35 (0.10)	0.84 (0.15)
Bare	5.13 (0.22)	0.60 (0.25)	0.22 (0.11)	0.24 (0.12)	0.07 (0.01)	0.06 (0.01)	1.18 (0.48)	2.27 (0.83)
Agriculture	9.79 (1.75)	1.12 (0.23)	0.35 (0.05)	0.55 (0.12)	0.07 (0.01)	0.06 (0.01)	1.86 (0.10)	1.61 (0.14)
Agroforestry	8.26 (2.69)	1.00 (0.42)	0.25 (0.11)	0.51 (0.23)	0.06 (0.01)	0.05 (0.01)	1.51 (0.56)	1.02 (0.28)

Table 3 Nutrient losses from experimental plots a) in eroded mineral sediment < 2 mm diameter b) in eroded litter, together with total dry weight of litter (mean values 1993-1997 ($kg\ ha^{-1}\ y^{-1}$) with standard errors in parentheses).

a)

	Organic Matter	Total N	Total P	Exchang-eable Mg	Exchang-eable Ca	Exchang-eable K	Exchang-eable Na
Forest	4.69 (1.93)	0.12 (0.05)	0.02 (0.00)	0.01 (0.00)	0.11 (0.04)	0.01 (0.00)	0.02 (0.00)
Bare	298.00 (107.87)	7.95 (3.00)	1.60 (0.51)	0.57 (0.18)	7.11 (2.53)	0.45 (0.17)	0.08 (0.03)
Agriculture	505.02 (91.90)	12.88 (2.52)	3.42 (0.69)	0.97 (0.20)	11.32 (2.44)	0.81 (0.19)	0.15 (0.05)
Agroforestry	266.79 (17.85)	6.07 (1.74)	2.08 (0.70)	0.57 (0.18)	6.40 (2.19)	0.38 (0.11)	0.07 (0.02)

b)

	Total N	Total P	Dry weight
Forest	1.55 (0.17)	0.14 (0.01)	169.75 (23.30)
Bare	2.84 (1.19)	0.27 (0.11)	259.94 (74.73)
Agriculture	0.80 (0.11)	0.07 (0.01)	90.66 (12.04)
Agroforestry	0.54 (0.11)	0.05 (0.00)	54.65 (12.18)

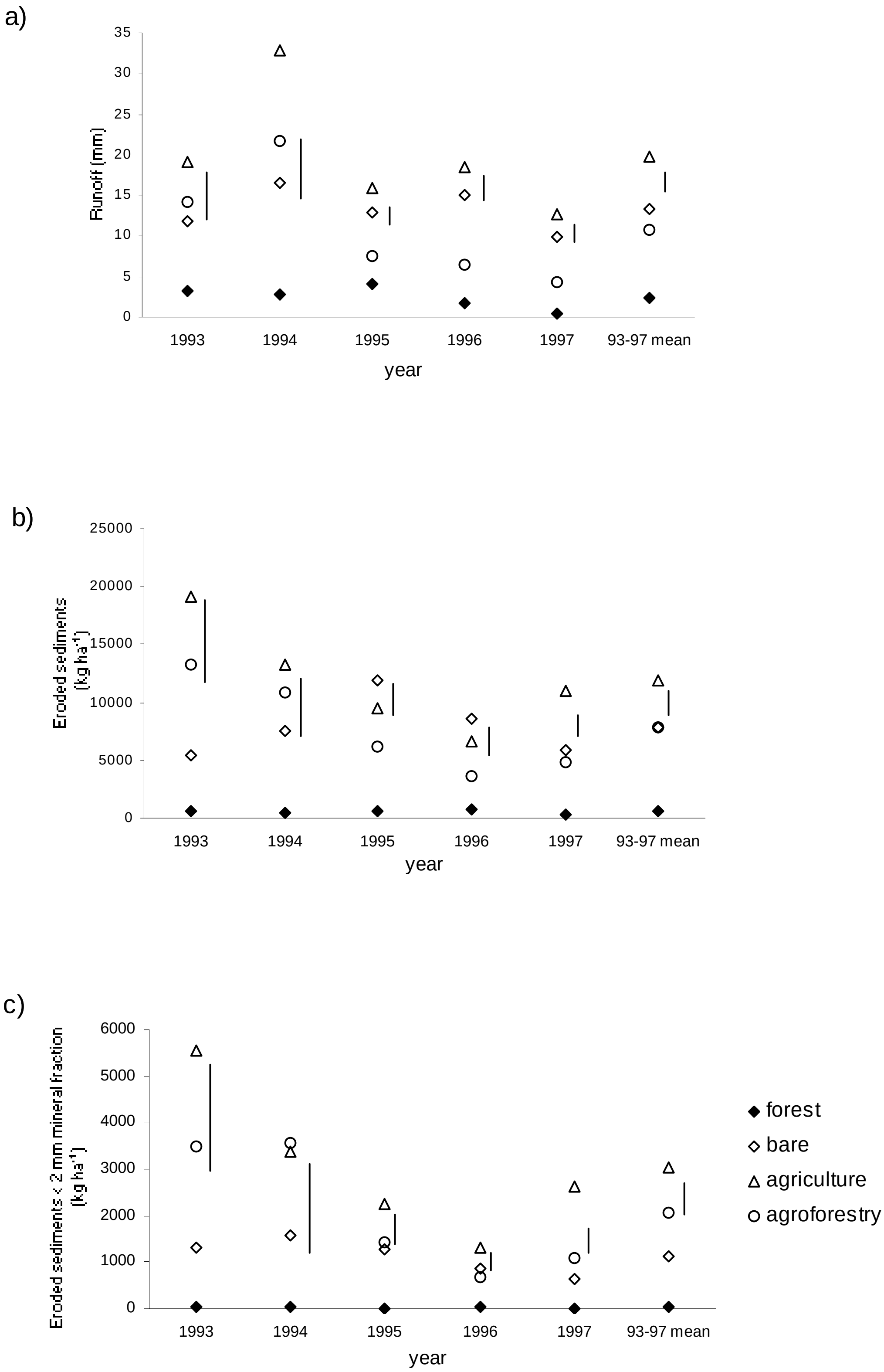

Figure 1 Quantity of surface runoff and eroded sediment per year from experimental plots a) surface runoff (mm); b) total eroded sediment (kg ha^{-1}); c) eroded mineral sediment < 2 mm diameter (kg ha^{-1}). Vertical lines are the standard error of the difference between treatment values; year refers to the 12 month sampling period, e.g. 1993 = September 1992 to September 1993.

Figure 2 Change over time in soil properties (0-10 cm depth) in experimental plots in 1992 (pre-clearance) and 1993-1997 (post-clearance) a) organic matter content; b) total N concentration; c) total P concentration; d) available P concentration; e) pH; f) exchangeable Mg concentration; g) exchangeable Ca concentration; h) exchangeable K concentration; i) exchangeable Na concentration; j) moisture content; k) bulk density. The annual means, 1993-1997 linear regression line and 1993-1997 mean value are shown for each treatment. The P values of the significant contrasts between the forest and the cleared treatments for the gradient of the 1993-1997 linear regression are shown.

Figure 2 Continued.

Table 4 Mean percentage particle size composition of the < 2 mm diameter fraction of soil (0-10 cm depth) in situ in the experimental plots (1995-1997), and of sediments eroded from the experimental plots (1993-1997), with standard errors in parentheses.

Fraction/treatment	Soils	Eroded sediments
Clay (< 2 µm)		
Forest	21 (2)	15 (1)
Bare	27 (2)	17 (2)
Agriculture	30 (2)	19 (2)
Agroforestry		21 (2)
- between hedgerows	30 (2)	
- under hedgerows	28 (2)	
Silt (2-60 µm)		
Forest	32 (2)	21 (1)
Bare	27 (2)	21 (2)
Agriculture	34 (2)	24 (2)
Agroforestry		22 (2)
- between hedgerows	35 (3)	
- under hedgerows	34 (3)	
Sand (60 – 2000 µm)		
Forest	47 (4)	64 (2)
Bare	46 (2)	62 (3)
Agriculture	37 (3)	57 (3)
Agroforestry		58 (3)
- between hedgerows	35 (4)	
- under hedgerows	38 (4)	

4.1.4.5 NITROGEN MINERALISATION RATES

There is a markedly higher rate of nitrification and total nitrogen mineralisation under the hedgerows in the agroforestry plots than in the other treatments/locations within two years after the establishment of the hedges (Figures 3 and 4). This is not, however, reflected in the soil total N concentration (Figure 2) which suggests that there is no accumulation of the assumed extra N inputs into the soil, which are presumably mineralised and rapidly taken up by the trees again. In subsequent years, there is an increased immobilisation (indicated by negative mineralisation values) of nitrogen in the alleys of the agroforestry plots compared to the forest control. By 1997, there was also net immobilisation under the hedgerows in the agroforestry plot. This may be attributable to the higher inputs of organic matter in the agroforestry plots (Figure 5). It is not attributable to higher soil total nitrogen contents (Figure 6).

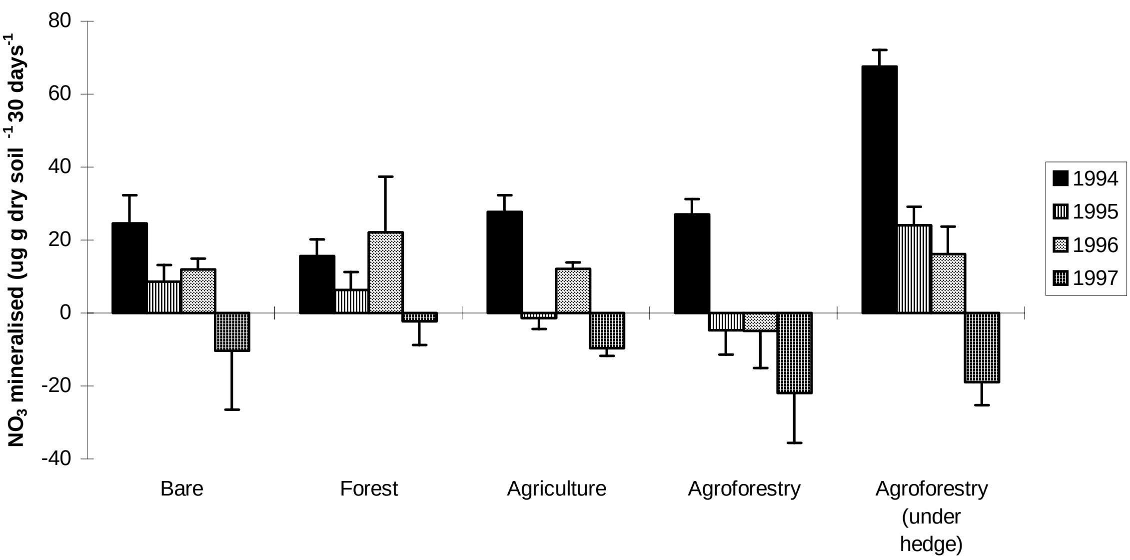

Figure 3 Nitrate mineralised over a 30 day period in the experimental plots (means and standard errors).

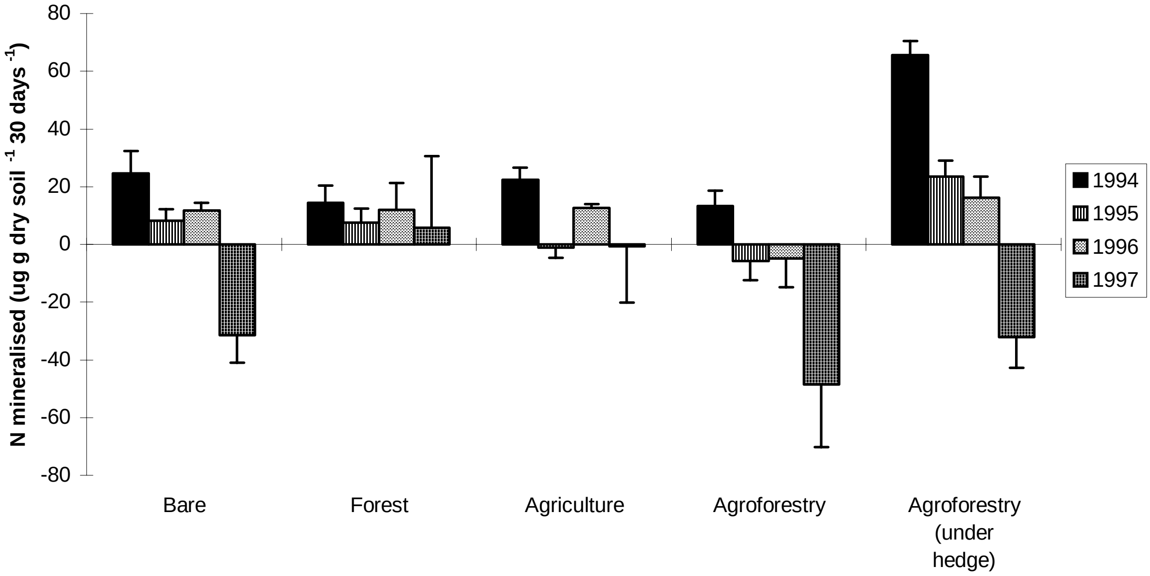

Figure 4 Total nitrogen mineralised over a 30 day period in the experimental plots (means and standard errors).

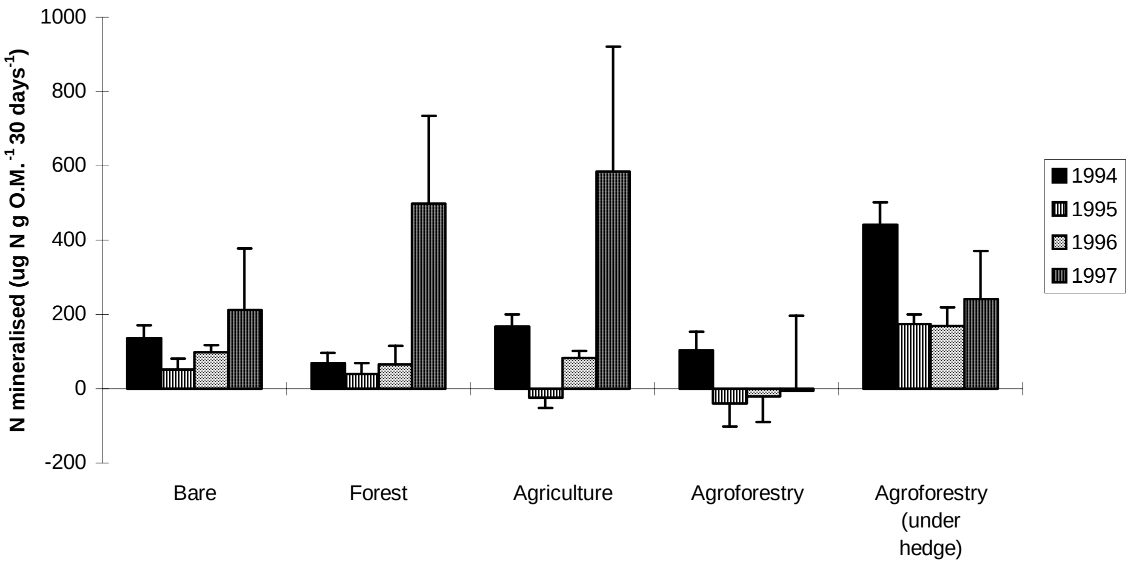

Figure 5 Total nitrogen mineralised over a 30 day period in the experimental plots, expressed as a proportion of organic matter (means and standard errors).

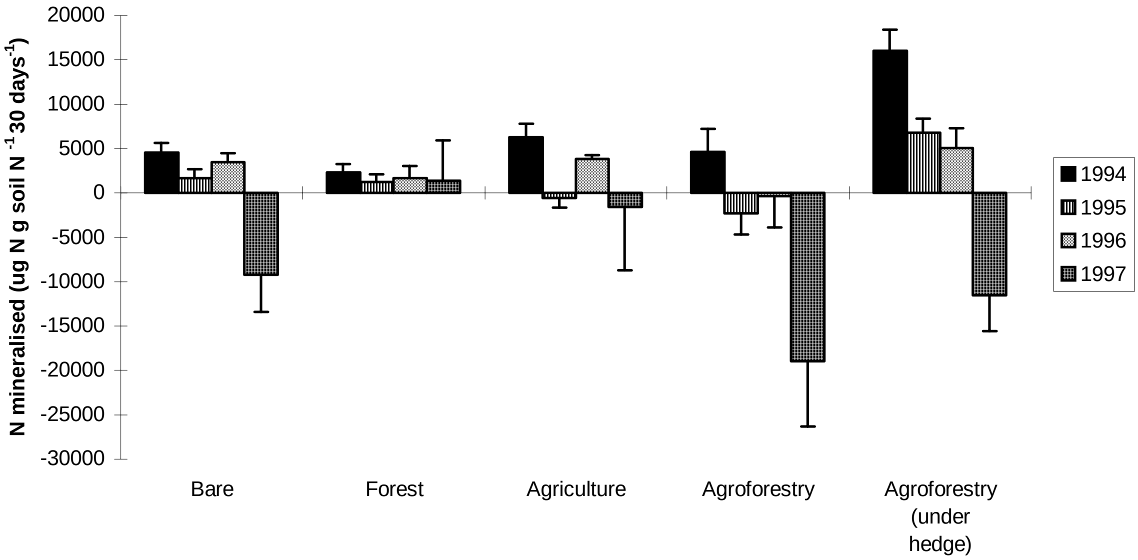

Figure 6 Total nitrogen mineralised over a 30 day period in the experimental plots, expressed as a proportion of total nitrogen (means and standard errors).

Plate 5 Established *Calliandra calothyrsus* hedgerow in an agroforestry treatment plot after pruning
See front cover of report.

4.1.4.6 BIOASSAYS OF SOIL FERTILITY

4.1.4.6.1 GREENHOUSE BIOASSAY

The mean root and shoot weights of the unfertilised plants were similar for all the treatment plots (Tables 5 and 6), consequently the root:shoot ratios (Table 8) were also similar. There were also no differences in the number of leaves (Table 7). Fertilization with phosphorus did not cause any significant increases in plant growth (and no more than two-fold increases in phosphorus concentration), and these plants also showed no difference between the treatment plots. However, nitrogen fertilization caused a large growth response for all the treatments (which was significant ($P < 0.05$) for all except the forest soils). The response was greater for the agriculture plots than the other three treatments. Nitrogen fertilisation decreased the root:shoot ratio for all treatment plots in comparison with control and P-fertilised plants, doubled the leaf number and it lead to a 1.7 - 3.4-fold increase in (plant) nitrogen concentrations (forest lowest, agriculture highest).

Table 5 Root weights (means and standard errors) of the bioassay plants; H. = hedgerows.

Root Weight (mg)	CONTROL	S.E.	+ N	S.E.	+ P	S.E.
BARE	446.7	63.5	766.7	59.7	463.3	52.5
FOREST	423.3	20.2	583.3	132.7	486.7	46.5
AGRICULTURE	435.0	58.1	1175.0	130.4	452.5	49.9
AGROFORESTRY (BETWEEN H.)	472.5	67.9	905.0	147.1	512.5	56.5
AGROFORESTRY (UNDER H.)	577.8	29.6	1107.5	116.1	555.0	30.7

Table 6 Shoot weights (means and standard errors) of the bioassay plants; H. = hedgerows.

Shoot Weight (mg)	CONTROL	S.E.	+ N	S.E.	+ P	S.E.
BARE	810.0	105.4	1786.7	252.7	886.7	66.6
FOREST	770.0	60.6	1340.0	285.5	866.7	80.9
AGRICULTURE	735.0	125.0	2730.0	361.8	802.5	88.0
AGROFORESTRY (BETWEEN H.)	790.0	108.9	2030.0	359.2	897.5	101.6
AGROFORESTRY (UNDER H.))	860.0	19.6	2100.0	213.3	932.5	50.7

Table 7 Number of leaves (means and standard errors) of the bioassay plants; H. = hedgerows.

Number of Leaves	CONTROL	S.E.	+ N	S.E.	+ P	S.E.

BARE	8.9	0.8	16.7	1.7	9.6	0.4
FOREST	8.8	0.1	14.1	2.6	9.3	0.1
AGRICULTURE	9.1	0.9	22.2	2.6	9.0	0.7
AGROFORESTRY (BETWEEN H.)	9.2	0.9	18.4	3.1	9.8	0.8
AGROFORESTRY (UNDER H.)	9.4	0.6	19.5	1.0	10.3	1.0

Table 8 Root:shoot ratios (means and standard errors) of the bioassay plants; H. = hedgerows.

Root:Shoot	CONTROL	S.E.	+ N	S.E.	+ P	S.E.
BARE	0.55	0.04	0.44	0.03	0.52	0.02
FOREST	0.56	0.05	0.44	0.03	0.56	0.03
AGRICULTURE	0.60	0.06	0.44	0.01	0.56	0.02
AGROFORESTRY (BETWEEN H.)	0.60	0.01	0.45	0.02	0.58	0.03
AGROFORESTRY (UNDER H.)	0.67	0.03	0.53	0.02	0.60	0.02

Table 9 Phosphorus content (means and standard errors) of the bioassay plants; H. = hedgerows.

P (mg)	CONTROL	S.E.	+ N	S.E.	+ P	S.E.
BARE	3.13	0.77	3.79	0.96	4.45	0.60
FOREST	1.93	0.50	2.46	0.77	3.97	0.47
AGRICULTURE	2.73	0.28	3.98	0.36	3.71	0.26
AGROFORESTRY (BETWEEN H.)	2.34	0.43	3.09	0.59	3.95	0.56
AGROFORESTRY (UNDER H.)	2.80	0.56	2.95	0.43	4.44	0.58

Table 10 Nitrogen content (means and standard errors) of the bioassay plants; H. = hedgerows.

N (mg)	CONTROL	S.E.	+ N	S.E.	+ P	S.E.
BARE	8.76	1.12	19.45	2.99	9.68	0.34
FOREST	10.36	1.45	17.92	1.88	11.23	0.97
AGRICULTURE	6.86	0.93	23.28	2.26	7.81	0.56
AGROFORESTRY (BETWEEN H.)	7.55	0.42	19.54	2.46	8.63	0.59
AGROFORESTRY (UNDER H.)	8.62	0.51	19.46	1.27	9.45	0.37

4.1.4.6.2 *Zea mays* BIOASSAY

In the agroforestry plots there was no difference in plant height or cob length between the planting positions (distance from hedgerow) (Table 11). However, plants growing 100 cm from the hedgerows in the agroforestry plots produced more above-ground biomass and had higher cob and grain weights than the plants grown in the agriculture plots. Plants growing at both 50 cm and 100 cm from the hedgerow produced higher grain weights than those growing in the agriculture plot. The plants adjacent to the hedgerow produced less grain than those 100 cm from the hedgerow. Despite the fact that there were fewer plants in the agroforestry plots than the agriculture plot due to the space taken by the hedgerows, there was no significant difference in production per hectare between the agriculture and agroforestry plots (Table 12).

Table 11 Production of *Zea mays* L. in the agriculture and agroforestry plots (means and standard errors).

	AGROFORESTRY								AGRICULTURE	
DISTANCE FROM HEDGEROW (cm)	0		50		100		150			
HEIGHT (m)	1.80	(0.08)	1.84	(0.08)	1.85	(0.08)	1.83	(0.07)	1.76	(0.03)
COB LENGTH (cm)	15.47	(0.50)	15.09	(0.58)	15.74	(0.52)	15.84	(0.74)	14.84	(0.25)
ABOVE-GROUND BIOMASS (g d wt plant $^{-1}$)	114.27	(8.92)	114.97	(12.47)	147.70	(18.61)	126.60	(14.89)	109.55	(5.79)
COB WEIGHT (g d wt plant^{-1})	88.54	(10.18)	89.88	(10.55)	104.28	(13.19)	84.41	(10.47)	71.79	(2.53)
GRAIN WEIGHT (g d wt plant^{-1})	54.73	(4.80)	64.59	(8.41)	76.54	(10.41)	57.75	(7.94)	46.83	(2.11)

Plate 6 Spaced rows of *Zea mays* were planted as a bioassay in all of the project's farmed experimental plots to evaluate the effects of hedgerows on crop productivity.

Table 12 Total production of *Zea mays* L. in the agriculture and agroforestry plots (means and standard errors).

	AGROFORESTRY		AGRICULTURE	
ABOVE-GROUND BIOMASS (kg ha^{-1})	3521.88	(284.96)	4382.89	(231.71)
COB WEIGHT (kg ha^{-1})	2599.21	(233.88)	2871.64	(100.91)
GRAIN WEIGHT (kg ha^{-1})	1773.80	(158.87)	1873.10	(84.43)

4.1.5 DISCUSSION

4.1.5.1 EFFECTS OF FOREST CONVERSION

Throughout the course of the study the forest plots showed low levels of surface runoff: mean total surface runoff per year never exceeded 4.0 mm, and the maximum for any one of the four plots was 4.78 mm, whereas total rainfall was 3403 mm in the wettest year (1995). Thus, in 1995 mean annual total surface runoff from the forest was only 0.12% of total rainfall. This indicates that the water storage capacity of the forest buffered the system highly against variations in rainfall amount and intensity. This explains the low rates of soil erosion observed under forest (0.3 - 0.7 t ha^{-1} y^{-1}) which are similar to those recorded by many other workers (e.g. Maass et al., 1988; Alegre and Rao, 1996). The forest in this study was secondary as it is predominantly that type of forest that is being cleared for agriculture in the Jamaican Blue Mountains at present. However, a high proportion of the erodible material may have been lost after the previous clearance of the forest, and this could also be a significant factor accounting for low rates of subsequent erosion (Richardson, 1982; McDonald and Healey, 2000).

In this study conversion of the secondary forest significantly increased surface runoff and erosion, as has also been found in many previous studies (e.g. Nye and Greenland, 1960; Lundgrun, 1980; Maass et al., 1988; Nortcliff et al., 1990). Wiersum (1984) reported that erosion rates recorded in agricultural and agroforestry systems vary widely across the range 400 – 70,050 kg ha^{-1} y^{-1} for the cropping period of a shifting cultivation cycle (with a median value of 2780 kg ha^{-1} y^{-1}). As expected, while the mean annual total erosion recorded in our study for the cleared treatments (3618 - 19,070 kg ha^{-1} y^{-1}, median 7488 kg ha^{-1} y^{-1}) lie well within the range, being on steep slopes they are well above average. However, our values only equate to 0.9 mm of soil depth and are lower than most reported estimates of soil erosion for Jamaica: under a range of agricultural production systems they vary from 17,000 kg ha^{-1} y^{-1} (Governmental experimental station 1980-1984, unpublished data) to over 100,000 kg ha^{-1} y^{-1} (eg. Champion, 1966; GOJ/UNDP/FAO, 1982). However, many of these values were not derived experimentally but from the

Universal Soil Loss Equation and are likely to be over-estimates. They do not allow for sediment sinks in individual fields and in the catchment as a whole, nor do they take into account the limiting effect of any soil conservation structures such as the hedgerows in this study. They also overestimate the importance of the erosivity of the rain and of the slope angle and length. In a study of erosion in the Fall River, which is a nearby tributary of the Yallahs River, McGregor (1988) observed considerable variability in total soil loss across farmed fields on 30-35° slopes (compared with a range of 24-32° in our study). He found that surface runoff levels were low and spatially variable, and that neither surface runoff nor soil loss were cumulative downslope, nor mutually correlated. He concluded that, in this environment, there is an imperfect correlation between rainfall and sediment yield because, while heavy rainfall events do lead to relatively large sediment yields, downslope movement of dry soil is a significant contributor to soil loss.

Forest conversion resulted in large changes to most measured soil variables: concentrations of OM, total N, available P, all the cations and moisture content all decreased whilst bulk density and clay content increased. Of the 14 measured variables, only total P concentration and pH were unaffected. Furthermore, for none of these measured variables is there any good evidence that, by five years after forest clearance, the changes in soil properties caused by this clearance (and subsequent land use) have stabilised.

Changes in stock of nutrients in the top 10 cm of soil in the cleared treatments were greatly influenced by the large increases in bulk density (on average by 13.8% per annum for the < 2 mm diameter mineral and litter fractions combined) as well as the changes in their concentration. Furthermore, it is likely that redistribution of soil by erosion will have significantly influenced what material lay within the top 10 cm of soil at each sampling occasion. Therefore, we do not attach great importance to changes in calculated nutrient stock between each year's 0-10 cm depth soil samples, and concentrate instead on directly measured concentrations.

The decreases in OM concentration in the top 10 cm of soil in the cleared treatment plots are consistent with the results obtained in the large majority of previous studies (e.g. Nye and Greenland, 1960; Tulaphitak et al., 1985; Juo and Kang, 1989; Mueller-Harvey et al., 1989; Tiessen et al., 1992; Lal, 1996; Funakawa et al., 1997; Roder et al., 1997; Shang & Tiessen, 1997; Silitoe and Sheil, 1999). These decreases were very similar in the bare treatment to the two cultivated ones, therefore burial of the surface OM below the 10 cm sampling depth by tillage cannot be the major explanation. Instead it is likely to be a result of the combination of a reduction in the quantity of inputs and changes in microclimate, soil fauna, and quality of inputs affecting rates of mineralisation (Nye and Greenland, 1960; Palm et al., 1996). Tulaphitak et al. (1985) found that rates of OM decomposition in farmed plots were 36% higher than in the forest in the first year after slash-and-burn, though the difference was much less pronounced in the second year. The decrease in OM concentration has implications for soil fertility and plant growth as the beneficial effects of soil OM on soil physical properties, nutrient availability (e.g. through cation exchange capacity) and biological activity are well documented (e.g. Tiessen et al., 1994; Young, 1997). However, in the cleared treatments after five years, OM concentrations were still above 100 g kg^{-1} and had not yet fallen to levels expected for tropical soils under permanent agriculture (e.g. Ramakrishnan and Toky, 1981), therefore they might still equilibrate at a level compatible with sustainable land use. These high levels of soil OM may play a significant role in limiting the rates of runoff and erosion. Application of organic fertiliser is not normal practice in this area, and none was applied to the plots.

Soil total N concentration was closely correlated with OM and declined rapidly following forest clearance by c. 5% per annum. This result is comparable to those obtained in numerous previous studies of slash-and-burn land use, e.g. Mueller-Harvey et al. (1989); Stromgaard (1992); Tiessen et al. (1992); Lal (1996); Salcedo et al. (1997); Funakawa et al. (1997); Roder et al. (1997); Silitoe and Sheil (1999). Total P concentration was not correlated with OM which was expected as organic P may constitute less than 20% of the total P in immature soils such as Inceptisols (Cross and Schlesinger, 1995). Also, the absence of any clear effect of forest conversion on total P concentrations in the surface soil is understandable as P has a low potential for loss by leaching or volatilisation. However, for plant nutrition the concentrations of P in available forms is much more important and from the second year following forest clearance available P concentration fell to a level lower than that in the secondary forest, despite the probable increase in mineralisation of organic P, which is in accordance with most previous studies, e.g. Mueller-Harvey et al. (1989); Tiessen et al. (1992); Salcedo et al. (1997); Funakawa et al. (1997); Roder et al. (1997). This could be explained by transformation of inorganic P to unavailable forms (Tiessen et al., 1992), a higher rate of fixation of P to the fine, clay mineral particles (whose content in the surface soil was increased by forest conversion (Table 4)), or a loss of exchange sites on the soil OM (though the r value for the correlation between OM and available P concentrations was only 0.24). Since the bicarbonate extraction used for available P in this study extracts a mix of 'labile' organic and inorganic P, it cannot detect any fluxes between the organic and inorganic labile pools (Cross and Schlesinger, 1995).

Burning of vegetation during forest clearance can be an important factor affecting soil properties in slash and burn agriculture. It adds ash to the soil and has been found to increase the concentration of exchangeable base cations in the soil, and as a consequence raise soil pH, to varying degrees and for varying durations (e.g. Nye and Greenland, 1960, 1964; Sanchez, 1976; Ramakrishnan and Toky, 1981; Sanchez et al., 1985; Stromgaard, 1985; Tulaphitak et al., 1985; Bruijnzeel, 1990; Juo and Manu, 1996; Holscher et al., 1997; Brand and Pfund, 1999). However, we found no increase in the concentration of exchangeable cations or pH over the first 14 months following burning (the experiment was, however, not designed to detect any immediate changes following burning, otherwise the soil would have been sampled more frequently during this period). Instead, there was a big decrease in the concentrations of all the measured exchangeable base cations in the soil following forest clearance in most cases by 14 months after burning, and in all others by 26 months, which is a more rapid rate of reversal from increase to net loss than in many studies (e.g. Nye and Greenland, 1960; Tulaphitak et al., 1985). Andriesse and Schelhaas (1987) found huge variation in effects of clearing through burning on soil properties between different studies in Asia, depending primarily on the thoroughness (i.e. duration and intensity) of the burn. Sanchez et al. (1985) noted that the speed of loss of increased concentrations from ash varies widely with ash content, initial soil properties, rainfall, and length of dry season. They also noted that reversal is generally faster in coarse-textured soils under high rainfall regimes (which were the conditions pertaining to our study). These are all factors affecting the capacity of the soil to store large additions of soluble nutrients versus their potential rate of loss through leaching, runoff and erosion (Juo and Manu, 1996).

A correlation between decline in OM concentrations and decline in exchangeable concentrations of base cations is expected due to the loss of exchange sites on the OM (Juo and Manu, 1996). Weak support for this mechanism is provided by the correlation analyses: the r values for the correlation between OM and cation concentrations were all above 0.5; for Ca it was 0.66 and for Mg above 0.76. As time progresses an increasingly important factor in the decline of soil cation concentrations may be the lower inputs of cations reaching the soil surface in incident rain, compared with forest throughfall (Parker, 1983). The consequent reduction in soil-water cation concentrations promotes desorption of cations from exchange sites and their subsequent leaching through the soil profile if not taken up by crops.

In the cleared treatments of our study annual losses of nutrients (as an approximate proportion of 0-10 cm depth soil nutrient capital in the < 2 mm diameter mineral and litter fractions combined) that were attributable to surface runoff and erosion were low (averaging, for the cleared treatments, c. 1.1% for OM, N and P, 1.4% for Ca, and 6.5% for K). Numerous previous studies have examined the relative roles of leaching, runoff, erosion and crop offtake in nutrient losses in contrasting agroecosystems (e.g. Nye and Greenland, 1960, 1964; Juo and Manu, 1996). Results have been highly variable and very site dependent: the relative importance of leaching and runoff/erosion vary greatly depending on slope angle, soil permeability and rainfall regime (Juo and Manu, 1996): whereas leaching is generally the dominant process in flat sites with permeable soil, in hilly sites with less permeable soil it is erosion and runoff that is dominant. In our study, although slope angles were high, so too was permeability, as reflected by the runoff results, indicating the potentially important role of leaching. Kellman and Tackaberry (1997) point out that although significant leaching losses of the more soluble nutrients nitrate, Mg, Ca and K have been recorded, most of the evidence of the importance of these losses is very uncertain. For all the base cations, measurements were made of the "exchangeable" fractions which are expected to be more mobile than the total amounts and more prone to year-to-year variation as a result of climatic variability. Na was most notable for the high year-to-year fluctuations in its exchangeable concentrations in the soil (with the same pattern shown across all blocks and treatments (Figure 1i)). This is not unexpected given its great solubility and the high variability in its input in rainfall in areas close to the sea (D.A. Jenkins, *pers. comm.*). Published estimates of nutrient loss in crop offtake vary massively: between 1 and 52% of contents in original forest biomass (Kellman and Tackaberry, 1997). The marked absence of any differences in cation concentrations between the bare and cultivated treatments in our study indicates that crop uptake had little role in these changes.

Such declines in top-soil nutrient concentrations during years of cultivation following the initial increases caused by forest clearance and burning have been found in many studies (e.g. Nye and Greenland, 1964; Sanchez et al., 1985; Juo and Kang, 1989; Lal, 1996; Roder et al., 1997; Salcedo et al., 1997; Brand and Pfund, 1999). Salcedo et al. (1997), for example, in north-east Brazil found an average decline of 55% in exchangeable base cations over five years. Similarly, over the five-year period between 1992 (pre-clearance) and 1997 we observed an average decline of 48% in exchangeable Mg, Ca and K concentrations in the three cleared treatments. Such declines could well continue over a longer period: in Madagascar, Brand and Pfund (1999) found that under long-term shifting cultivation top-soil cation concentrations fell to approximately two-thirds of their initial values. In our study, whilst most measured soil properties showed no good evidence of any change in their trends in the cleared plots during the five-year period, after a more or less continuous fall since clearance the mean concentration of K did increase slightly between 1996 and 1997 in all the cleared treatments (however, no firm conclusion of stabilisation can be drawn without further years' data being available).

There, are, however, many studies which have not found such declines in soil nutrient concentrations during cultivation following slash-and-burn (e.g. those reviewed by Jordan (1985)). On very infertile soils at San Carlos de Rio Negro, Venezuela Jordan (1985, 1989) found that whilst total ecosystem nutrient stocks (especially of K) declined over time (in agreement with the results of Nye and Greenland (1964)), the amounts of nutrients in the soil remained relatively high (i.e. soil Ca, K, Mg and N concentrations remained higher in the experimental slash-and-burn agriculture plots than in the forest control; only available P decreased probably because of the decrease in soil pH). Similarly, in Kalimantan Kleinman et al. (1996) found soil concentrations of cations, nitrate and pH were higher in currently farmed plots than woody fallows (though soil organic C and total P were lower). Our results are in stark contrast to these, and indicate that in these mountain steep hillslope sites, decline in soil fertility does have the potential to become the limiting factor to the sustainability of slash-and-burn agriculture and thus a critical factor driving the rate of forest clearance for new farmland. However, it is not yet possible to conclude with certainty that soil fertility is the primary limiting factor. From their work in the Southern Highlands of Papua New Guinea (a similar environment with similar land-use systems to the Jamaican Blue Mountains), Silitoe and Sheil (1999) concluded that even where nutrient concentrations decline significantly, on less-weathered tropical highland soils they may not reach critical levels, and provided the right crops are chosen slash-and-burn farming could still be a fairly sustainable long-term land-use option.

4.1.5.2 EFFECTS OF AGRICULTURE

No clear effect of agricultural cultivation on surface runoff or erosion rates was detected. Whilst rates of surface runoff were higher in the agriculture than the bare treatment throughout the study (on average by 50%), this difference generally declined over time and was not significant. Whilst total erosion rate was, on average, 54% higher in the agriculture than the bare treatment, this difference was not consistent amongst the years nor was it significant. These results were strongly influenced by high spatial variability, and it is likely that the effects of agriculture in increasing surface runoff and erosion rates through soil tillage (Lal, 1997) were off-set by reduction in rates due to the crop vegetation cover (Elwell and Stocking, 1976).

None of the measured soil chemical properties showed any differences between the agriculture and bare treatments; the only difference detected was the lower mean silt concentration in the bare treatment plots. However, a comparison between the two cultivated (agriculture and agroforestry) and two uncultivated (forest and bare) treatments indicated that cultivation greatly decreased the sand content of the soil (Table 4). Together these results indicate the potential importance of tillage and crop cover on physical soil erosion processes (Garrity, 1996; Lal 1997; Turkelboom et al., 1997). However, in terms of soil chemical properties, there were no detected effects of the tillage or crop growth and harvesting involved in agricultural cultivation.

In contrast, numerous studies have demonstrated significant effects of soil tillage on chemical soil properties in slash-and-burn agricultural systems: Nye and Greenland (1964) found that local no-tillage practice led to much greater losses of K, but less loss of Ca (with Mg unaffected) than practices with tillage; depth of tillage had little effect on losses; and bare fallow plots (with no crops and minimum tillage) had less loss of Ca and K than cropped plots (though Mg was unaffected). Lal (1997) found that the rate of decline of all soil chemical properties with cultivation duration was greater in plots that had received conventional tillage than those with no-till. Other factors than tillage may also be important in these comparisons: both Harcombe (1977) and Henrot and Robertson (1994) found that following forest clearance losses of soil nutrients were greater in plots that were kept bare by weeding than those where vegetation was allowed to regrow.

Other studies have documented effects on soil physical properties. An increase in soil bulk density, indicating soil compaction, has been widely reported during both the clearance and cultivation phases (e.g. Sanchez et al., 1985; Alegre and Cassel, 1996), especially on sandy soils and on sloping land. In contrast, the only factor we found to have any effect on bulk density was forest clearance. It is uncertain how many of the previous studies have distinguished the longer-term impact of forest clearance from the impact of cultivation per se, though in north-east Thailand Tulaphitak et al. (1985) found that during cultivation bulk density increased (and porosity and moisture retention decreased) to a much greater extent in a plot that underwent tillage than in a plot which did not. We found some evidence that reduction in OM concentration is associated with an increase in soil bulk density and together these are associated with a decrease in soil moisture concentration: the r value for the negative correlations between OM and bulk density was –0.63, and between bulk density and moisture content –0.71. Alegre and Cassel (1996) found that by 40 months after clearance, bulk density under agricultural land-uses had started to fall back towards secondary forest values, but there was no evidence for any such convergence even by 60 months in our study.

4.1.5.3 EFFECTS OF AGROFORESTRY

Rates of surface runoff and erosion were consistently lower in the agroforestry than the agriculture treatment in all five years of the study; the differences were significant and increased over time such that, by the fifth year, surface runoff rates were 65% lower and erosion rates were 56% lower. The magnitude of this large reduction in the surface runoff, in comparison with the relatively low productivity of the hedgerows, indicates that they must have greatly increased the rate of infiltration of water into the soil (as shown by Kiepe (1995); A. Young, pers. comm.). The effectiveness of barrier hedgerow intercropping systems in reducing erosion rates has been reported by many other studies (Young, 1997). The system tested in our study reduced erosion to below 5000 kg ha^{-1} y^{-1} which is lower than in six of the 14 studies reviewed by Young (1997). The percentage reduction is smaller than in 12 of these but corresponds closely to the studies on similarly steep slopes. However, in our study no differences were detected between the mean values of the agriculture and the agroforestry treatments for any measured soil variable. Therefore, within the time-frame, site and management conditions of this study, addition of agroforestry contour hedgerows had no overall effect on soil properties.

Young (1997) reviewed the large body of knowledge about the effects of hedgerow intercropping on soil properties in flat lands. He concluded that no changes could be predicted in less than three years, that over three- to five-year periods it is not uncommon to find either no significant differences between hedgerow treatments and controls or no clear changes over time, and that most effects that do occur are linked to improved soil OM concentrations. In the case of soil moisture specifically, a wide range of positive and negative effects have been found. Many of the studies have examined systems where soil properties are degrading during agriculture following the clearance of forest land by slash-and-burn; in some cases hedgerows have reduced or even halted this degradation. Rao et al. (1998) highlighted evidence that hedgerows can lead to higher crop yields as a result of fertility improvement despite the effects of competition from the hedgerows, but also circumstances where the fertility effects did not outweigh their large competitive effect. Although there is good evidence that this system can improve soil fertility in base-rich fertile soils (Kang et al., 1990), on acid and low fertility soils (which dominate most of the uplands in the humid tropics) its sustainability is limited (Szott et al., 1991). The soils of our study are probably intermediate between these two categories.

The limited number of studies published on the effects of contour hedgerows on soil properties have given variable results, though the clear majority show a lack of effect. On gently sloping land in Peru, Alegre and Rao (1996), in a study with a similar design to ours, found that after five years soil bulk density, organic C, P, K, Ca and Mg concentrations were significantly greater under agroforestry than under agricultural land use (the latter four properties were also higher under agroforestry than under the forest control). However, reviewing twenty years of research on moderate to steep slopes in northern Thailand over a range of altitudes between 480 and 1100 m, Ongprasert and Turkelboom (1996) found that whilst hedgerow systems can effectively control soil erosion, they cannot maintain soil fertility. Similarly, in the Philippines on moderate slopes a lack of overall effect of Gliricidia sepium hedgerows on soil physical or chemical properties compared with an open-field control was found by Agus et al. (1997, 1999), whereas hedgerows of the fodder grass Penisetum purpureum tended to reduce exchangeable K, Ca and Mg and extractable P concentrations. On gently sloping land with an acid soil in the Philippines Samsuzzaman et al. (1999) found that three year-old hedgerows made no significant difference to the rate of decline in soil organic C, total N, available P concentrations or pH values.

Young (1989) proposed that there were three main mechanisms by which contour hedgerows can affect soil properties: increasing water infiltration (which reduces runoff, but can increase nutrient losses through leaching (Ramakrishnan, 1990)); acting as a sieve barrier to eroding soil; and increasing OM inputs to the soil through the addition of hedgerow prunings as a mulch (which may also serve to increase the rate of nutrient cycling). In our study the addition of hedgerow prunings may have had an effect: from 1995 annual input from the prunings to the soil of OM was equivalent to c. 10.8% of the standing stock present in the < 2 mm diameter mineral and litter fractions combined in the top 10 cm of soil between the hedgerows, for total N it was c. 16.8% but for total P only 3.3%. However, no effect of the change from laying the prunings along the upper side of the hedgerows in 1993 and 1994 to spreading them as mulch between the hedgerows from 1995 was detected on the relative soil properties of the two zones. The inputs of OM and nutrients from root turnover of the hedgerow trees cannot be quantified, but are unlikely to exceed those in the prunings (Young, 1997). In the years soon after forest clearance, when soils still contain elevated quantities of OM and nutrients with high spatial variability, it is not surprising that no significant enhancement of these soil properties by the addition of hedgerow prunings in the agroforestry treatment was detected. However, as the stocks of these soil components become further depleted over time the ameliorating effect of the pruning inputs may become more important.

Ongprasert and Turkelboom (1996) also concluded that in the uplands of Northern Thailand the input of OM and nutrients from hedgerow pruning biomass was too low to maintain soil fertility. Studies in the lowlands have recorded much higher rates of biomass production and nutrient content in hedgerow prunings, though addition of these prunings to the soil has been found to acidify surface layers leading to leaching of cations and nitrate (e.g. Juo and Kang, 1989; Szott et al., 1991). Samsuzzaman et al. (1999) found that on infertile soils the level of nutrient cycling from added pruning biomass was insufficient to maintain the level of organic C, N and P in the soil (though there was some evidence that prunings of two of the species studied did reduce the rate of degradation of soil organic C). The only significant result that they found of addition of hedgerow prunings was that Cassia spectabilis did reduce soil bulk density, and they concluded that the hedgerow system was not sustainable without the addition of inorganic fertiliser. Young (1997) calculated that, in the humid tropics, to maintain soil OM contents, land-use systems need to add above-ground litter and prunings of the order of 10,000 kg^{-1} ha^{-1} yr^{-1} of dry matter. Such levels of hedgerow productivity have rarely been reported in published studies and Young (1997) found little evidence that addition of prunings led to higher between-row OM contents than agricultural control plots (though removal of prunings from hedgerow plots has been found to lead to lower soil OM contents than if they are added as a mulch).

4.1.5.4 EFFECTS OF CONTOUR HEDGEROWS ON SPATIAL DISTRIBUTION OF SOIL PROPERTIES

Evidence was obtained that the presence of contour hedgerows did lead to a spatial redistribution of the values of four soil properties within the agroforestry treatment plots. Exchangeable K and Na and sand concentrations became higher under the hedgerows, whereas clay concentrations became higher between them. However, in the case of K and Na this appeared to be a temporary phenomenon, the differences rising to a peak in 1994 and 1995, respectively, and then falling back to nothing in 1996 and 1997 (Figure 1h,i).

As well as the significant reduction in plot-scale erosion rates by the agroforestry treatment in contrast to agriculture, accumulation of soil material above the hedgerows was observed in these plots; the hedgerows did have a clear sieve-barrier effect. The higher sand concentrations there may be because sand is more easily moved down-slope than clay (which commonly leads to higher clay contents on sloping land (Fielding and Sherchan, 1999) or it may indicate that the hedgerow sieves trapped larger sand particles more effectively than the finer silt and clay ones. The higher K and Na concentrations under the hedgerows may indicate that transport above the soil surface is a significant mechanism in their movement, either in the eroded soil that accumulates there or in runoff water which is likely to have much higher rates of infiltration under the hedgerows (Kiepe, 1995, and as can be inferred by the effect of the agroforestry treatment on plot-scale surface runoff). Ongprasert and Turkelboom (1996) indicated that on hillslopes in northern Thailand, higher soil fertility is found under contour hedgerows than between them. Such results are influenced by the relative importance of the sieve-barrier effect (which tends to concentrate fertile top soil under the hedgerows), and the transfer of prunings to the between-hedgerow zone, as carried out in the present study from 1995, (which tends to redistribute the fertility) (Young, 1997). While the hedgerows also influence soil fertility through litterfall inputs and root uptake, the spatial distribution of these two processes is highly variable.

Strong evidence has been found for a “scouring” effect in hillslope contour hedgerow systems, in which soil is lost from the upper part of the between-hedgerow alley and accumulates in its lower part leading to a transfer of surface soil properties between the two (these two approximate to the between hedgerow and under hedgerow zones respectively in our study). As was the case in our study, the effects on soil properties of this redistribution have been found to be greater than the overall effect of the hedgerow system as a whole compared with agriculture-only controls (e.g. Garrity, 1996; Agus et al., 1997; Poudel et al., 1999). These redistribution effects were less (and present in fewer soil properties) in our study than these others, which is probably explained by: only superficial and infrequent hand-hoeing tillage being carried out (Garrity (1996) found the level of tillage to be a dominant factor in this process); having the hedgerows more closely spaced (due to the steeper slope angle) so the ratio of between- to under-hedgerow zones was much less; no contrasts being made between soil sampled in different positions in the between-hedgerow zone. The one nutrient found to be at a higher concentration in the upper part of the between-hedgerow zone in the previous studies, K, was actually found to be higher in the under-hedgerow zone in our study (though this difference had disappeared by four years after the establishment of the hedgerows (Figure 1h)).

4.1.5.5 BIOASSAY ASSESSMENTS OF SOIL FERTILITY

The results from the greenhouse bioassay indicate clearly that P is not limiting to the growth of the test plants in the secondary forest soils encountered in this study; whereas they provide some evidence of nitrogen limitation. This is at variance with the findings of Tanner (1977) and Healey (1989), who both found P to be limiting in montane forest soils in bioassay experiments. However, the soil from the cleared treatment plots show clear N limitation, most notably for the agriculture plots, less so in the agroforestry plots and less again in the bare plots. This would suggest that offtake in crops may be an important cause of loss in nutrient capital.

These results are borne out by the field bioassay where the agroforestry treatment had a positive effect on *Z. mays* growth in the alleys between the hedgerows in contrast to the crop-only agriculture plots. This effect is not indicated by conventional soil analyses which indicate similar nutrient concentrations in all the cleared plots. Nitrogen mineralisation rates indicate immobilisation in the alleys between the hedgerows but not in the agriculture plots, which suggests that, given the possibly greater nitrogen limitation apparent in the agriculture plot, soil nitrogen contents are higher in the agroforestry plots.

4.1.6 CONCLUSIONS

Considerable protection is offered to both the soil and water resource by this secondary forest. In particular, the forest acts as a buffer against fluctuations in runoff associated with rainfall events, which may be of significance in large-scale events. Agricultural use of cleared land does result in increased erosion, but not as much as anticipated from previous estimates, and the use of contour hedgerows reduces runoff and levels of erosion to acceptable levels. Whilst the technical potential of the barrier hedgerow system for sloping lands such as those in this study area has been demonstrated (Young, 1997), its adoption by farmers is limited by their awareness of its requirement for labour input and loss of land area available for agricultural crops. Adoption therefore depends on the simplification of establishment methods and its development into a flexible system. Experiences of farmer adoption of contour hedgerow intercropping in Indonesia demonstrate that the system is not an "off the shelf" technique, but rather one of a prototype, whose success was dependent on the farmers’ ability to adapt the practice to their specific farming conditions (Wiersum, (1984). The technologies must be flexible enough for farmers to make modifications so that they meet their short-term economic needs (Cramb et al., 1999; McDonald and Brown, 2000).

This study has demonstrated the major effects of forest conversion on soil properties and has found no clear evidence that they stabilise at a new equilibrium during the subsequent five-year period. For all the measured soil variables (except perhaps exchangeable K) there is not even any evidence that their rate of change has decreased over this period. Therefore, in general, a greater proportion of the current nutrient capital is being lost with progressive years after clearance. Following slash-and-burn the changes in the vast majority of the measured soil properties are attributable to the effects of forest removal and not to differences amongst the alternative forms of subsequent non-forest land use that were tested. The study provides evidence of the changes in soil properties that, if they continue, are liable to make these land uses environmentally non-sustainable at the plot scale. Continuation in the decline of OM concentration would be serious for the sustainability of agriculture because of its strong correlation with total N concentrations and cation exchange capacity. In addition, a continuation of the observed changes in soil physical properties, in particular the increase in soil bulk density, which together with the decline in OM may be contributing to the reduction in moisture content, would be serious for nutrient cycling and for nutrient and moisture availability to crops. The observed lack of differences between the soils of the bare and agricultural treatments indicates that nutrient losses due to a combination of erosion, surface runoff and especially leaching are a more important factor in these changes to soil properties than losses in crop offtake. The study has found no evidence that addition of prunings from agroforestry hedges as a mulch can compensate for these changes. Garrity (1996) has made three recommendations of how the efficacy of the contour hedgerow system could be improved, all of which should be tested in future studies: (i) minimizing soil tillage to reduce the scouring effect; (ii) placing the prunings in the upper part of the between-hedgerow zone to counteract the loss of nutrients there; (iii) over time moving the position of each hedgerow down-slope to even out the spatial variation in soil fertility that has been created.

The significance of the spatial variability in soil properties for experimental design were discussed by Mueller-Harvey et al. (1989) and our results indicated the crucial importance of including a sufficient number of independent experimental blocks, that control for both variation in site conditions and farmer practice, in order to produce conclusions of general applicability. There was evidence of significant between-block variation in six of the measured soil properties, and without this being removed from the residual sum of squares the treatment effects could not have been detected. Inspection of the individual plot results of this study indicated little evidence of block x treatment interactions, but if more than one independent replicate of each treatment is included per block in the design of future studies it would allow this to be tested formally. In future studies, location and layout of blocks should also take into account the evidence provided by Pickup (1985), Westoby (1987), Nortcliff et al. (1990), Brown et al. (1991a,b), Busacca et al. (1993), Garrity (1996) and van Noordwijk et al. (1998) that on hillslopes there will be major transfers of nutrients within the slope between areas of net erosion (sources) and net deposition (sinks) depending on the topography of the slope (even fine-scale changes that are undetectable to the human eye). Mid-slope sites (such as those of the present study) may undergo little or no net soil loss. A major impact of changes in land use, such as forest conversion, is likely to be on this rate of within-slope transfer. Farmers have learned to adjust their land-use practices to accommodate the effects of erosion (e.g. by planting different crops in zones of net loss and net deposition (van Noordwijk et al., 1998)), so expensive technologies that minimize such transfer by surface runoff and erosion may not actually meet farmer's needs. Ramakrishnan (1990) was also concerned that, on long-hillslopes, minimization of surface runoff (by increasing infiltration) may not be advantageous to overall soil fertility and agricultural productivity. Therefore, the objectives of studies need to be carefully framed to distinguish net impacts of changes in land use at the individual plot scale, at the whole hillslope scale, or at the bottom of the hillslope (rate of discharge into rivers).

Comparison of variation between blocks and treatments also has applied implications. In terms of wider land use planning, it is notable that for ten of the measured variables (all except total and available P, sand and silt) overall variation between the forest and cleared treatments was greater than that between the blocks. Thus, this study indicates that forest conversion has a major effect on soil properties that is greater than their inherent degree of variation within the variable landscape of these mountain catchments. However, for all 14 of the measured soil properties variation between blocks was much greater than that between the agriculture and agroforestry treatments. This indicates that, for individual farmers who operate slash-and-burn agriculture at a small scale, selection of more fertile sites in which to establish new farmland is a more important decision than adoption of agroforestry practices in achieving maximum soil fertility in their farmland (at least over a five-year time-course as monitored by this experiment). Forest restoration through secondary succession during a fallow period may be the most effective mechanism for the recovery of soil fertility in this environment in current circumstances (McDonald and Healey, 2000). However, adoption of agroforestry practices may become more important: (a) if greater shortage of farmland and restrictions of tenure prevent farmers selecting more fertile sites for new farm establishment; (b) after a longer period of cultivation by which time soil fertility levels have fallen much further; (c) if the other products and services provided by agroforestry practices are important.

4.2 ASSESSMENT OF THE EFFECTIVNESS OF SECONDARY FORESTS IN NUTRIENT CONSERVATION

4.2.1 SUMMARY

Secondary forests in the Blue Mountains of Jamaica, subject to human disturbance as well as hurricanes, are coming under increasing land-use pressure with a rising population density and the remaining primary forest becoming more remote from settlements. The practice of slash-and-burn agriculture is commonly carried out by local communities. This study reports on estimates of how the secondary forests have recovered to, or close to, the functioning of undisturbed forest, in terms of key soil and nutrient cycling variables. Nutrient conservation was assessed by measuring inputs in throughfall and litterfall, which were compared to site nutrient capital and losses in surface runoff and erosion. Litterfall, litter standing crop and the growth of bioassay plants were measured in paired plots of primary and secondary forest. The results were compared with data already published for key nutrient cycling variables in primary forests of the Blue Mountains to determine the extent to which nutrient cycling and soil fertility in the secondary forest has recovered to primary forest levels. Rates of nutrient loss in runoff and eroded sediment in the secondary forest were low, basal area had recovered to 81% of primary forest levels, and rates of litterfall were high. Litterfall nutrient concentrations were high, particularly for P, and nutrient cycling was rapid as judged by the high ratio of litterfall to litter standing crop. Soil fertility had recovered well in the secondary forests as judged both by chemical analyses and the growth of the bioassay plants. The results indicate that, for forests in the middle of steep slopes, following the cessation of agriculture, tight nutrient cycling and soil condition and fertility are effectively restored during c. 20 years of secondary succession. This results in the re-establishment of a forest with effective nutrient conservation which offers a high degree of protection of catchment soil and water resources, and the potential to sustain another cycle of agricultural production.

OBJECTIVES

Purpose 1: To elucidate the role of trees on soil processes and physical and chemical properties

4.2.2 INTRODUCTION

There has been a long-running exploration of the factors limiting natural forest productivity on tropical mountains and in particular the role of limitation in the availability to trees of particular mineral nutrients (especially N and P) (Tanner et al., 1998). Healey (1989) and Tanner et al. (1990) provided experimental evidence that the growth of these natural montane forests in Jamaica was limited by P and N. However, this work and others (e.g. Tanner, 1977a, 1977b, 1980a, 1980b, 1981, 1985) in Jamaica has been based, almost entirely, on the study of a series of forest types in close proximity in an area on or close to the crest of the main ridge of the Blue Mountains. Bellingham et al. (1995) have shown how great the impact of natural hurricane disturbance is on the vegetation dynamics of these forests, but the effects of disturbance and subsequent secondary succession on forest nutrient cycles have not been quantified. Due to growing land-use pressure, the primary forests of the Blue Mountains have suffered increasing encroachment. As elsewhere on tropical mountains, the forests in the middle of the steep hill-slopes are in a buffer zone between the intact forests remaining at higher altitudes above, and agricultural land below. As such they are under increasing pressure from wood harvesting and slash-and-burn agriculture which has created a mosaic of secondary forests of different ages. Secondary forests are increasing in area throughout the tropics and may comprise about 31% of the total closed forest land (Brown and Lugo, 1990). They are usually fast-growing ecosystems that can potentially provide a sustainable supply of valuable commodities to nearby human communities. However, their successful management requires us to know, following the abandonment of agriculture or reduction of harvesting pressure, how well nutrient cycling and soil condition and fertility recover. Is it sufficient to enable either the re-establishment of forest ecosystem with effective nutrient conservation which offers a high degree of protection of catchment soil and water resources and biodiversity; or another cycle of forest harvesting or agricultural production? These concerns are particularly acute for steep hillslope sites, where the loss of nutrients through down-slope runoff, erosion and leaching during periods of agriculture, and subsequently, may lead to a more serious reduction in soil fertility during the cropping cycle than in other sites.

This section investigates the extent to which secondary forests in the Blue Mountains of Jamaica, subject to human disturbance as well as a recent hurricane, have recovered to, or close to, the functioning of undisturbed forest, in terms of key soil and nutrient cycling variables. The objectives were to:

1. Establish how well secondary forest conserves nutrients.
2. Determine the extent to which nutrient cycling and soil fertility in the secondary forest have returned to the levels in primary forest.

The approach taken to meeting these objectives was: (a) to undertake detailed quantification of components of the nutrient cycle in four intensively studied replicate secondary forest plots; (b) to compare litterfall, litter standing crop and the growth of bioassay plants in three pairs of plots of primary and secondary forest.

4.2.3 METHODS

4.2.3.1 FOREST TYPES, PLOT LOCATIONS AND DIMENSIONS

In June and July, 1992, four main plots were established in the Green River Valley between 1250 m and 1310 m altitude (figure 7) in areas of secondary forest, cleared for agricultural cultivation most recently in the early 1970s for one cropping cycle (according to members of the local community) and subsequently abandoned because of declines in productivity. Following local practice a number of the larger trees would have been retained during the period of agriculture, and they are clearly identifiable in the present forest. Before the 1970s these forests had most probably been subject to at least one cycle of clearance for agriculture but had probably been allowed to regrow since c. 1900.

The slope angle of the four main plots ranged from 26 to 31^{o} between the plots and was constant within each of the plots (all the plots were in a mid-slope position and none of them occupied or included obvious convex zones of higher than average net erosion, or deposition zones of net sedimentation).

Each main plot was 10 m (across slope) x 20 m (down slope), with an inner assessment area of 8 m x 15 m. The plots were bounded on the upper border using galvanized steel barriers, and trenched on the lateral borders. All stems $\geq$ 2 cm diameter at breast height were identified and measured, and the density and basal area of each species calculated.

In the vicinity of the main secondary forest plots there was no remaining primary forest that could be used in a direct comparison. Therefore, in August and September 1992, subsidiary plots were established at three locations where primary and secondary forest did occur in close proximity. These were two locations at higher altitudes in the Green River catchment (mid-slope below Bellevue Peak, at 1430 m altitude (the closest to the main plots) and just below the main ridge adjacent to Newhaven Gap and Sir John's Peak, at 1590–1680 m altitude); and in one location in the adjacent Clyde River catchment (upper slope between Cinchona and Morce's Gap, at 1300 m altitude) (Figure 7). At each location, one 225 m^2 plot of 15 m x 15 m was located in an area of young secondary forest that had been disturbed within the last 30 years, and one in much older secondary or primary forest, which appeared to have suffered no significant disturbance within the last 150 years (hereafter referred to as primary). Each pair of plots was matched in aspect and slope angle, which were within the same range as the main plots. The disturbance histories of the forests concerned were determined by using a combination of local knowledge and observations of forest structure and composition. All stems $\geq$ 2 cm diameter at breast height were identified and measured, and the density and basal area of each species calculated.

4.2.3.2 NUTRIENT CYCLING IN SECONDARY FOREST MAIN PLOTS

4.2.3.2.1 RAINFALL AND THROUGHFALL

A data-logging rain gauge was established at each plot to record the amounts and intensities of rainfall over the measurement period. The sampling period commenced in September 1992, and concluded in September 1994.

Collectors to measure throughfall reaching the soil surface were placed in the plots. Five collectors each of 165 cm^2 surface area with sharp edges angled to 30º were located in each plot and were then emptied and randomly relocated on a fortnightly basis. Between September 1992 and September 1994 quantities were recorded and bulked samples collected on a per-plot basis each month for nutrient analysis. Samples were filtered through 0.45 µm filters within 24 h of collection and were stored with a 1% mercuric chloride preservative until analysis. They were analysed for dissolved K and Ca by sequential inductively-coupled optical emission spectrometry. Phosphate-P and total P were analysed using the molybdenum blue colorimetric method on an auto-analyser, in the case of total P after digestion using sulphuric acid and hydrogen peroxide (Allen, 1989). Nitrate-N was determined using automated liquid chromatography (Dionex model 2000). Ammonium-N was determined on an auto-analyser, using the indophenol-blue colorimetric method (Allen, 1989). Total N was calculated as the sum of nitrate-N and reduced forms of N (organic-N plus ammonium-N). The sum of these reduced forms was obtained using a sulphuric acid/hydrogen peroxide digestion followed by indophenol blue colorimetry on an autoanalyser (Allen, 1989). Dissolved organic carbon (DOC) was determined by auto-analyser, using UV-digestion and the phenolphthalein colorimetric method (Skalar Analytical, 1993). Blank samples were also analysed following the same procedure to ensure there was no contamination.

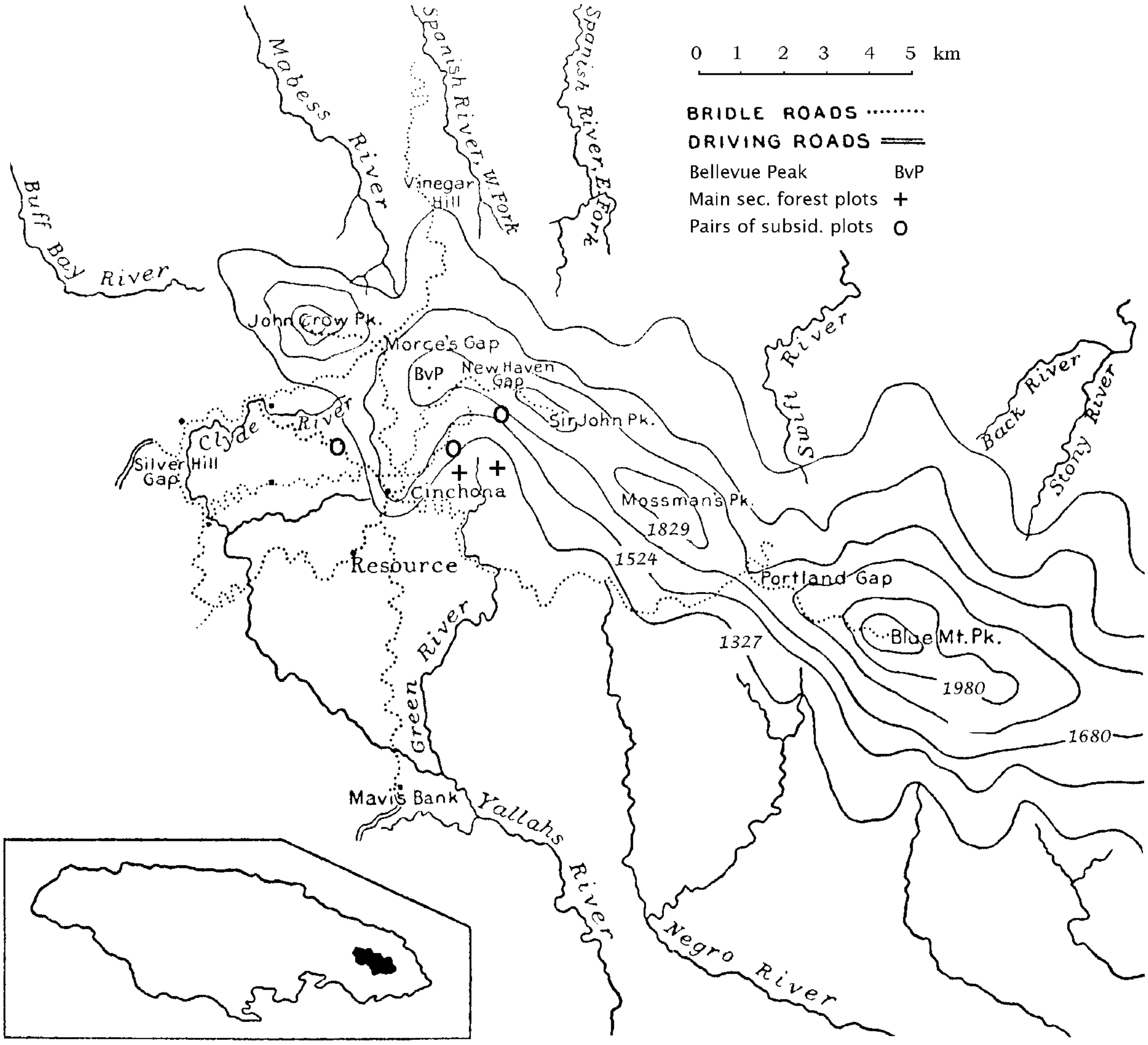

Figure 7 Map of study area (after Shreve, 1914) showing the positions of the sample plots. Contour heights are given in m. The Blue Mountains are indicated in black on the inset map of Jamaica.

4.2.3.2.2 SURFACE RUNOFF AND ERODED SEDIMENTS

Soil sediment and water from runoff were collected with a modified type of Gerlach trough (Morgan, 1979). The collecting gutter was covered with a lid to prevent the direct entry of rainfall, and sediment and runoff were channeled from the gutter into covered collecting buckets. Three of these metre-long troughs were placed at the bottom end of the inner assessment area of each plot during June-July 1992. Samples were collected on a fortnightly basis from September 1992 to September 1994. The total amount of runoff water collected was measured in the field and a sub-sample removed for chemical analyses carried out as for throughfall (section 2.3.1). The total mass of sediment eroded was recorded, collected, oven-dried, and the entire sample separated into three fractions: litter was separated by hand, and coarse (>2 mm) and fine (<2 mm) mineral fractions were separated by sieving. All mineral fractions were weighed, the fine mineral and litter fractions retained for analysis, and the gravel fraction (>2 mm) discarded (on the assumption that the elements in this fraction are much less available for plant uptake than those in the other two fractions). The litter fraction was analysed for total N and P using a sulphuric acid/hydrogen peroxide digestion (Allen, 1989).

The <2 mm fraction of eroded sediments was also analysed for total N and P using the same procedure, and also pH, percentage silt, sand and clay, exchangeable Ca, Mg, K and Na, loss-on-ignition and available-P by:

- particle size analysis - hydrometer method (Anderson and Ingram, 1993)
- loss-on ignition (OM content) - ignition at 550 ^{o}C for 2 hours (Allen, 1989)
- pH - in a 1:2.5 weight:volume soil:deionised water suspension after 30 minutes
- exchangeable Ca, Mg, K and Na - ammonium acetate extraction at pH 7 (Anderson and Ingram, 1993), but varying the method by shaking the soil/extractant for one hour on an orbital shaker, rather than using leaching columns
- available-P – sodium bicarbonate extraction, 0.5 M, pH 8.5 (Anderson and Ingram, 1993).

The analyses of OM, total N and total P were carried out at the Institute of Terrestrial Ecology (ITE) Merlewood Research station and the remaining analyses at the ITE Bangor Research Unit. In both cases, the integrity of results supplied by the laboratories was checked by the analysis of certified reference samples (if available), alongside laboratory reference samples, and in the case of total N and P the Merlewood laboratory also regularly participates in the International Soil Exchange and the International Plant Exchange quarterly inter-laboratory comparison schemes, organised by Wageningen Agricultural University. The results of all the chemical analyses are expressed on an air-dry basis.

4.2.3.2.3 SOIL PHYSICAL AND CHEMICAL CHARACTERISTICS

Three composite soil samples were collected from each plot in June, 1992 and October, 1993. Surface litter was removed before coring. The samples were composites of five randomly-located individual samples taken to a depth of 10 cm with a soil corer of volume 785 cm^3. Analyses were carried out as for the eroded sediments described in 2.3.2, plus:

- moisture content - oven-drying for 24 h at 105 ^{o}C
- bulk density - soil cores of known volume collected and bulk density calculated from dry mass/volume
- exchangeable acidity (= Al plus H) - unbuffered potassium chloride extraction (Anderson and Ingram, 1993), but varying the method by shaking the soil/extractant for one hour on an orbital shaker, rather than using a beaker. Also, the titration step was undertaken on an automatic titrator
- cation exchange capacity - calculated as the ‘effective’ CEC, which is the sum of the exchangeable bases (Ca, Mg, K and Na) plus exchangeable acidity
- base saturation - calculated as the percentage of the CEC occupied by the exchangeable base cations.

The results of all the chemical analyses were expressed on an air-dry weight basis.

4.2.3.2.4 N-MINERALISATION RATES

Six soil cores were collected from each plot from the surface 10 cm soil depth in September 1994, using a corer of 10 cm diameter. Half of the cores from each plot were bulked by plot, and 10 g (wet soil) subsamples extracted for inorganic-N measurement by shaking for one hour in 100 ml of 1M potassium chloride, and filtering through potassium chloride pre-washed Whatman No. 44 filter papers. Inorganic-N concentrations were corrected to a per-gram dry-weight basis. The remaining cores were enclosed as intact cores in gas permeable plastic bags and inserted back into the holes from which they were taken. They were then removed after 30 days and extracted individually for inorganic-N measurement. Blank samples of potassium chloride were also analysed after the same procedure to ensure there was no contamination.

Extracts were analysed for nitrate-N and ammonium-N colorimetrically by autoanalyser using methods following Allen (1989). The difference between the final inorganic-N content and the inorganic-N content in the initial bulked sample is net mineralisation. Nitrate-N and ammonium-N contents of both sets of extracts were determined to assess rates of nitrification, as well as mineralisation.

4.2.3.2.5 LITTERFALL

Five litter traps each of 0.15 m² were placed randomly in each of the four main secondary forest plots. These were emptied and randomly replaced in the plots on a monthly basis. The contents of fine litter (foliar and reproductive material and woody material < 2 cm diameter) were dried and weighed after separating the woody material from the foliar and reproductive material. The samples were bulked by three-month increment and analysed for N and P concentrations using a sulphuric acid/hydrogen peroxide digestion (Allen, 1989) and nutrient contents determined by multiplying concentrations and amounts of litterfall. The standing crop of fine litter was determined in September 1993 and September 1994 by harvesting all above-ground fine litter in five randomly-positioned 1m²-quadrats in each plot. The contents of fine litter were dried and weighed after separating the woody material from the foliar and reproductive material, and the biomass of both fractions determined.

4.2.3.3 COMPARISON OF NUTRIENT CYCLING IN PRIMARY AND SECONDARY FORESTS

4.2.3.3.1 LITTERFALL

Ten litter traps each of 0.15 m² were placed randomly in each of the six subsidiary plots in September 1992 and litterfall was measured over the following 16 months. The traps were emptied and randomly replaced in the plots on four occasions in January, May and October of 1993 and February 1994. The contents of fine litter were dried and weighed after separating the woody material from the foliar and reproductive material. The standing crop of fine litter was determined in February 1994, by harvesting all above-ground fine litter in five randomly-positioned 0.25 m²-quadrats in each plot. This was oven-dried, and the fine woody material was separated from the foliar and reproductive material and biomass determined.

4.2.3.3.2 BIOASSAY OF NUTRIENT AVAILABILITY

In April 1993, one bulked soil sample was collected as a composite of five randomly-located individual samples taken to a depth of 10 cm with a soil corer of volume 785 cm^3 from each of the six subsidiary plots. This was passed through a 2-mm sieve and transported to Cinchona Botanic Garden at 1525 m altitude and 2 km south of the plots. Soils were mixed with acid-washed sand in the ratio 2:1 soil:sand to improve drainage; 500 ml pots were filled with the mixture. Wildings of three tree species (Acacia mearnsii, Pittosporum undulatum and Clethra occidentalis) were collected from hillslopes around Cinchona. These plants were selected for uniformity of health and vigour and were approximately 10 cm in height. One plant of each species was planted into each of ten pots filled with soil from each site, and the height and root collar diameter of each plant was recorded (using 0.1 mm-accuracy calipers). The pots were placed randomly on benches under 50% shade cloth, and regularly watered until the end of the monitoring period 90 days after planting. At this time, height and root collar diameter were recorded and their increments over the 90-day period calculated.

4.2.3.4 STATISTICAL ANALYSIS

The data sets from the primary/secondary comparisons were subjected to one-way analysis of variance using the statistical package SPSS/PC+ V.2 (1988). Data were $\log_{10}$-transformed and significant differences expressed to $P < 0.05$.

4.2.4 RESULTS

4.2.4.1 FOREST TYPE

As expected from their southern-slope location, our ten sample plots correspond most closely to the Dry Slope Forest type of Grubb and Tanner (1976), though they also contained elements of the moister Wet Slope Forest and Gully Forest types. This was indicated by their species composition which was clearly dominated by between five and eleven species classified as having a Dry Slope Forest or broad-ranging distribution by Grubb and Tanner (1976) (Table 13). Confirmation was obtained by P. Bellingham (pers. comm.) who carried out a DECORANA detrended correspondence analysis ordination and TWINSPAN two-way indicator species analysis classification of our ten plots together with 23 other existing forest sample plots established in this area of the Blue Mountains by P. Bellingham, E. Tanner and J. Healey. No major difference was found in the regeneration types of the species present between our secondary forest plots (Table 13) and the primary forest plots of Tanner (1977a) and Goodland et al. (1998). This is expected because the high frequency of natural hurricane and landslide disturbance in the area maintains a high abundance of light-demanding species in the primary forests (Dalling, 1994; Bellingham et al., 1995). Nonetheless, our main secondary forest plots contained a lower proportion of shade-tolerant species than the flora reported for Dry Slope Forests as a whole (Grubb and Tanner, 1976; Goodland et al., 1998).

The mean density of stems $\geq$ 2 cm dbh in the four main secondary forest plots was 7813 stems ha^{-1} but was much lower in the three subsidiary secondary forest plots (3808 stems ha^{-1}) and lower still in the three subsidiary primary forest plots (2800 stems ha^{-1}) (Table 13). There was a corresponding increase in tree basal area with successional age from a mean of 30 $m^2 ha^{-1}$ in the main secondary forest plots to 32.5 $m^2 ha^{-1}$ in the subsidiary secondary forest plots (and 37.1 $m^2 ha^{-1}$ in the subsidiary primary forest plots) (Table 13). Thus, the tree basal area of the main secondary forest plots has already recovered to 81% of that in the subsidiary primary plots, though this could largely be attributed to the abundance of the exotic invasive tree species Pittosporum undulatum (Table 13) which is, in itself, an important indicator of their secondary status. This species is known to competitively exclude some native pioneer species, and cast a dense shade which would favour shade-tolerant species over more light-demanding competitors (Healey et al., 1995), a factor that may accelerate the successional development of the forest's species composition (whilst limiting total species richness).

4.2.4.2 NUTRIENT CYCLING IN THE SECONDARY FOREST MAIN PLOTS

4.2.4.2.1 SOIL PHYSICAL AND CHEMICAL CHARACTERISTICS

The soil had no distinct surface humus layer, and pH (5.25 (year 1), 4.93 (year 2)), base saturation and exchangeable Ca concentrations (Table 14) were all much higher than in the soils studied by Tanner (1977a), as expected for forests growing on more calcareous substrate and at a lower altitude. Total OM concentration, CEC and moisture content were lower than for Tanner's soils. Values for all the other comparable variables (total N and exchangeable Mg, K and Na) lay within the range of Tanner's four forest types. Dalling and Tanner (1995) measured soil bicarbonate extractable-P concentration in soil of 0-10 cm depth from five slope forests (four primary and one secondary) between 1460 and 1700 m altitude in the Blue Mountains as 21.4 (+/- 4.0) $\mu g\ g^{-1}$ in the forests and 4.8 (+/- 2.1) $\mu g\ g^{-1}$ on adjacent landslides. Our results fall in the middle of this range at 10.9 and 10.0 (+/- 2.1 and 1.4) $\mu g\ g^{-1}$). In a less precise determination of soil characteristics from a wider sampling area in the Blue Mountains, Grubb and Tanner (1976) reported that the younger "lithosols" of the slope forests had a pH range of mostly 4.0 – 5.5, a range that encompasses the pH values we obtained.

4.2.4.2.2 RAINFALL AND THROUGHFALL

Total annual rainfall was very similar between the two years of the study (2548 mm, 14 September 1992 – 13 September 1993 versus 2530 mm, 14 September 1993 – 13 September 1994), lying very close to the centre of the range of past values from the nearby Cinchona meteorological station (Shreve, 1914; Tanner, 1980b). There were, however, notable differences between the years in the seasonal pattern of rainfall. In the first year, the wettest month was May (with 22% of annual rainfall), then January, June and October had distinctly higher than average monthly rainfall, whereas in the second year, January was the wettest month (with 27% of annual rainfall) and February was the only other month with a distinctly high rainfall (Figure 8). Conversely, in the first year, the highest intensity of rainfall of 190 mm hr^{-1} was recorded on 26th January, 1993, whereas the highest intensity of rainfall in the second year (330 mm hr^{-1}) was recorded on 20th May 1994. During the two years, seven months had less than 100 mm of rainfall; three of these were isolated single months, but there was one pronounced dry period of four consecutive months (the middle July - October). Only the month of July had less than 100 mm of rainfall in both years.

There was a strong correlation between the total amounts of rainfall and throughfall for each sampling period ($r^2 = 0.92$) (Figure 9). Over the two years rates of canopy interception of rainfall remained close to 50% ($y = 0.491x+2.864$). The percentage interception did not decrease with increasing precipitation, probably because during major rainfall events (which would have dominated the higher fortnightly rainfall values) at first there was canopy storage and then stemflow continuously increased as a proportion of precipitation. We noted very high stem flow rates on trees in these forests during large rainfall events. Nutrient contents in throughfall differed between the years (Table 15). DOC was 135% greater in the second than the first year, and nitrate-N was 90% greater but all other throughfall nutrient contents were between 10% and 57% greater in the first year than the second.

4.2.4.2.3 SURFACE RUNOFF AND ERODED SEDIMENTS

When expressed as a proportion of rainfall the amount of surface runoff of water was very low (Table 16), suggesting that high water storage capacity of the forest and excellent drainage would buffer the system against peaks in rainfall amount and intensity.

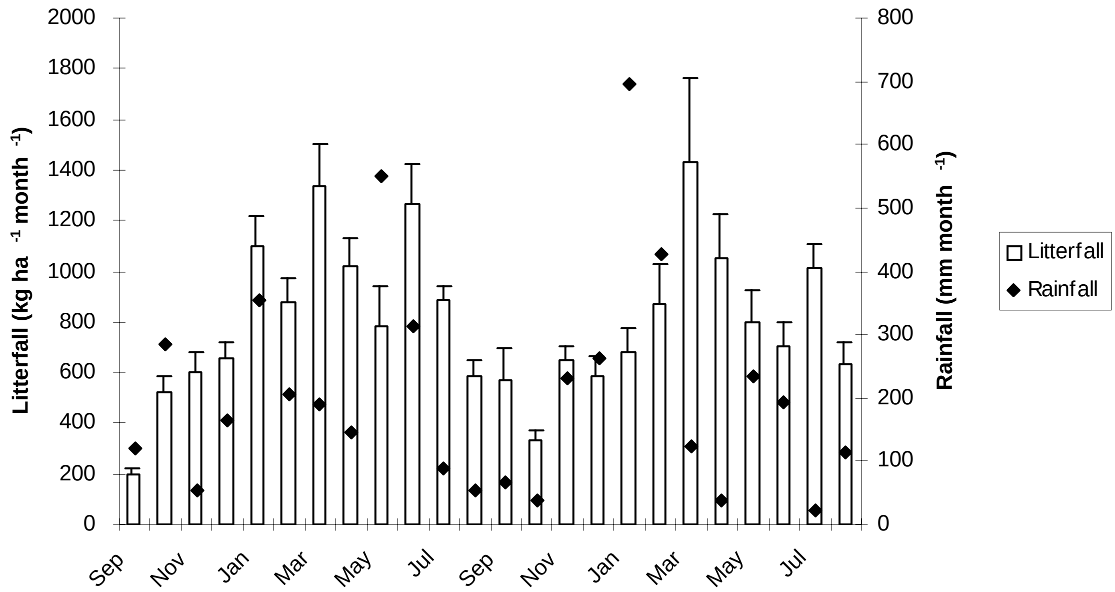

Figure 8 Seasonal distribution of rainfall and litterfall (means and standard errors, n=4) in the main secondary forest plots from September 1992 to August 1994.

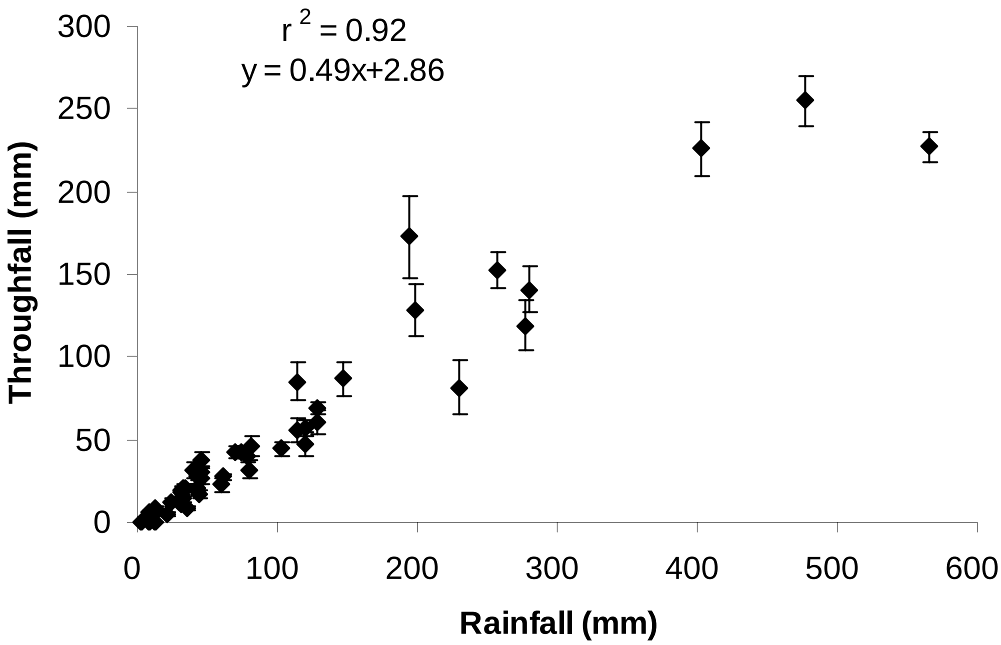

Figure 9 The relationship between the total amount of rainfall and throughfall in the main secondary forest plots (mean values, n=4, plus or minus standard error) for each fortnightly sampling period between September 1992 and September 1994.

Due to the small amounts of surface runoff, nutrient losses in runoff water were low (Table 17), especially when considered as a proportion of nutrient inputs and recycling in throughfall (inputs from atmospheric deposition and recycling by foliar leaching) (Table 15). The highest was loss of K in runoff, which was a little over 1% of the amount in throughfall in year 1. Losses of nutrients in eroded sediments (particles < 2 mm) were also low for the same reasons (Table 18). The eroded sediments were dominated by mineral particles > 2 mm and by litter (Table 16). Similarly, the analysed mineral fraction (< 2 mm) was dominated by the largest sized particles - the sand fraction (> 60 μm).

Over the two years, rates of loss of total P and N in the eroded sediment (< 2 mm) were just 35% higher than those dissolved in runoff water, whereas losses of Ca and especially K were much lower in the eroded sediment than the runoff water. Relative to the nutrient content of the top 10 cm of soil (Table 14), nutrient losses in runoff and eroded sediment were very small. For total P 0.018% was lost per year, whereas there was twice the rate of loss of total N (0.038%). Losses of cations were not measured in the litter fraction of the eroded sediment, however losses in runoff and the < 2 mm mineral fraction of the eroded sediment were just 0.013% of the nutrient capital in the top 10 cm of soil for exchangeable Ca, but higher for the more soluble exchangeable K (0.36%).

4.2.4.2.4 N MINERALISATION RATES

Net mineralisation of total N over 30 days in the top 10 cm of soil was 11.53 kg ha^{-1} (Table 14). This is equivalent to 173% of the amount of N in fine litterfall over the same period (Table 20) and is equivalent to just 0.21% of the standing stock of total N in the top 10 cm of soil. The rate of conversion to nitrate-N over 30 days (12.44 kg ha^{-1}) was very similar to that of total N.

4.2.4.2.5 LITTERFALL INPUTS

Total annual inputs of fine litter were nearly the same in the two years (9530 and 9107 kg ha^{-1} yr^{-1} respectively (Table 19)) as was the proportion composed of small woody material (10%). The seasonal distribution of fine litterfall showed the highest rates during the period January – July (year 1) and March – July (year 2), with low rates in August – December (both years) (Figure 8). There was no obvious correlation between each month's fine litterfall and rainfall. However the highest rates of litterfall did occur during and following the second half of the driest period of the year.

The standing crop of fine litter (mean of 5348 kg ha^{-1}) showed little variation between the years (Table 21). The annual amount of fine litterfall (Table 19) was equivalent to 174% of the standing crop, whereas the loss of litter down slope by erosion (Table 18) was equivalent to just 4% of the standing crop.

The amounts and concentrations of N and P in the fine litterfall were very constant between the two years (Table 20). Relative to the contents in the top 10 cm of soil (Table 14) the amount of N in the fine litterfall per hectare per annum was 1.4% in year 1 and 1.5% in year 2, and the amount of P was 8.2% of the available P in year 1 and 9.3% in year 2 (0.5% and 0.7% of total soil P respectively). Relative to the total loss of N and P in eroded sediment and dissolved in runoff (Tables 17 and 18), recycling of N in the fine litterfall was 3441% in year 1 and 4311% in year 2 and recycling of P was 2819% and 4126% respectively.

4.2.4.3 COMPARISON OF NUTRIENT CYCLING IN THE SUBSIDIARY PRIMARY AND SECONDARY FOREST PLOTS

4.2.4.3.1 LITTERFALL

The amounts of both the leaf and wood components of fine litterfall were consistently higher in the subsidiary primary forest plots than in the subsidiary secondary forest plots over the course of the year (Figure 10). Mean annual totals of fine litterfall were 9500 kg ha^{-1} in the primary forest plots and 7000 kg ha^{-1} in the secondary forest plots; the leaf litterfall components of these were 7400 kg ha^{-1} (78%) and 6000 kg ha^{-1} (86%) respectively. The total fine litterfall from the subsidiary primary forest plots was very similar to that obtained in the main secondary forest plots, which were at a lower altitude (Table 19). Litterfall in the subsidiary secondary forest plots were less than those in the main plots. There was no evidence of any association between the seasonal distribution of litterfall in the subsidiary plots and rainfall (Figure 10).

The difference in litterfall amounts between the primary and secondary forest plots was reflected in the standing crop of fine litter. Both the leaf and small woody components were 60% higher in the primary forest (Table 21). Litter standing crop in the subsidiary primary forest plots was slightly less than that in the main secondary forest plots (values for leaf litter were closer than for small wood).

Table 13 Species composition, basal area ($m^2\ ha^{-1}$) and density (stems ha^{-1}) of stems $\geq$ 2 cm diameter at breast height in the main and subsidiary plots.

Species	Distribution (Grubb and Tanner, 1976)	Regeneration type (Goodland et al., 1998)	Main secondary forest plots		Subsidiary secondary forest plots		Subsidiary primary forest plots	
			Basal area	Density	Basal area	Density	Basal area	Density
Acalypha virgata L. var. virgata	NR	SGB	0	0	0.4	44	1.2	74
Alchornea latifolia Sw.	DS	NP	1.7	250	0	0	0	0
Bocconia frutescens L.	DS	P	0.1	146	0	0	0	0
Boehmeria caudata Sw.	G	P-NP	0.2	396	0	0	0	0
Brunellia comocladiifolia Humb. & Bonpl.	DS	P	0	0	0	0	0.3	15
Cestrum hirtum Sw.	WS/G	unknown	0.2	63	0	0	0.2	74
Cinchona officinalis L.	NR	P-GB	1.3	708	0	0	0	0
Citharexylum caudatum L.	NR	SGB	0.6	250	0	15	0.1	30
Clethra alexandri Griseb.	HA	NP	0	0	0	0	5.2	207
Clethra occidentalis (L.) Kuntze	DS	NP	3.8	771	3.9	444	4.2	356
Clusia havetioides (Griseb.) Planch. & Triana	DS	ST	0.1	42	0	15	0	0
Critonia parviflora DC. ”montane”	DS	NP-SGB	0	0	0.2	30	0.1	89
Cyathea spp.	WD	various	0	0	1.1	237	7.2	578
Cyrilla racemiflora L.	DS	SGP	2.6	333	2.0	44	0.5	30
Dendropanax arboreus (L.) Decne & Planch.	WS	GB	0	0	0.2	74	0.3	44
Eugenia marchiana Griseb.	WD	ST	0	0	0.1	30	0	0
Eugenia monticola (Sw.) DC var. monticola	WD	ST	2.7	1313	2.0	148	1.0	148
Eugenia virgultosa (Sw.)	WD	ST	0.1	146	1.4	252	0.4	119
Gordonia heamatoxylon Swartz.	WD	SGB-GB	0	0	0.1	15	0.6	74
Guarea glabra Vahl	WD	ST	0	0	0	0	0.6	59
Hedyosmum arborescens Sw.	WD	SGB	0	0	0	0	0.1	30
Ilex macfadyenii (Walp.) Rehder	DS	SGB	5.8	1083	2.6	385	1.1	148
Juniperus lucayana Britton	DS	NP	0.2	21	5.6	15	0	0
Lyonia jamaicensis (Sw.) D. Don	DS	SGP	0.1	42	0.4	44	0	0
Maytenus jamaicensis Krug & Urban	MR/WS	ST	0	0	0.1	44	1.2	59
Miconia quadrangularis (Sw.) Naud. var. quadrangularis	DS	NP	0.1	63	0	0	0	0
Miconia spp.	DS	various	0	0	0	0	0	15
Myrsine coriacea (Sw.) R. Br. ex Roem. & Schult.	DS	SGB	0	0	0.1	59	0.1	15
Ocotea patens (Sw.) Nees	WS	GB-ST	0	0	0.5	89	0.4	44
Palicourea alpina (Sw.) DC.	DS	NP	0.5	63	0	0	0.5	59
Pittosporum undulatum Vent.	NR	SGB-GB	8.3	1542	2.0	1215	0.2	104
Podocarpus urbanii Pilger	DS	GB	0	0	1.1	30	0	0
Psychotria corymbosa Sw.	DS	SGB	0.2	146	0.1	74	0	15
Psychotria sloanei Urban	MR/WS	GB	0	0	0.1	15	0	0
Schefflera sciadophyllum (Sw.) Harms	WD	HE	0	0	1.2	89	0	0
Turpinia occidentalis (Sw.) G. Don	WD	SGB	0	0	5.4	89	5.5	89
Unknown			0	0	0	0	1.6	15
Vaccinium meridionale (Sw.)	DS	SGP	1.0	208	1.9	267	4.4	252
Viburnum spp.	DS	NP-GB	0	21	0.1	30	0	15
Wallenia calyptrata Urban	DS	ST	0.4	208	0	15	0.2	44
TOTALS			29.9	7813	32.5	3808	37.1	2800
Between-plot standard errors			5.8	1023	5.5	738	7.9	413

Distributions (Grubb and Tanner, 1976): DS = present in Dry Slope Forest; other species were not recorded as present in Dry Slope Forest but, instead WD = wide distribution (in at least three other forest types); MR/WS = Mull Ridge and Wet Slope Forests; WS/G = Wet Slope and Gully Forests; WS = Wet Slope Forest; G = Gully Forest; HA = High Altitude Forests; NR = not recorded.

Regeneration types (Goodland et al., 1998): P = pioneer; SGP = slow-growing pioneer; NP = near-pioneer; SGB = strongly gap-benefiting; GB = gap-benefiting; ST = shade-tolerant; HE = hemi-epiphyte.

Table 14 Soil, 0-10 cm depth, in the main secondary forest plots (n=4): a) chemical and physical characteristics; b) nutrient content (kg ha^{-1}) and N-mineralisation rate (kg ha^{-1} 30 $days^{-1}$). OM = organic matter.

	Year 1			Year 2	
	Mean	s.e.		Mean	s.e.
a)					
pH	5.25	(0.08)		4.93	(0.09)
Exchangeable Ca (cmol kg^{-1})	11.78	(1.10)		11.63	(0.35)
Exchangeable Mg (cmol kg^{-1})	3.22	(1.33)		2.16	(0.33)
Exchangeable K (cmol kg^{-1})	0.80	(0.13)		0.67	(0.16)
Exchangeable Na (cmol kg^{-1})	0.38	(0.01)		0.17	(0.02)
Total OM (g kg^{-1})	210.83	(18.48)		228.46	(16.96)
Total P (g kg^{-1})	1.53	(0.42)		1.43	(0.19)
Available P (g kg^{-1})	0.11	(0.02)		0.10	(0.01)
Total N (g kg^{-1})	6.83	(0.61)		6.46	(0.59)
Nitrate-N increase (g kg^{-1} 30 $days^{-1}$)	0.016	(0.004)	(1994 only)		
Total N mineralised (g kg^{-1} 30 $days^{-1}$)	0.014	(0.006)	(1994 only)		
Exchangeable acidity (cmol kg^{-1})	0.41	(0.08)	(1992 only)		
Cation exchange capacity (cmol kg^{-1})	16.89	(2.23)	(1992 only)		
Base saturation (%)	97.57	(0.30)	(1992 only)		
Moisture content (%)	19.94	(4.15)		12.47	(2.38)
Bulk density (Mg m^{-3})	0.85	(0.09)		0.80	(0.03)
% sand (>60 μm)	42.30	(12.95)	(1992 only)		
% silt (2-60 μm)	31.63	(6.85)	(1992 only)		
% clay (<2 μm)	26.07	(6.75)	(1992 only)		
b)					
Exchangeable Ca	4027.4	(573.9)		3585.1	(133.8)
Exchangeable Mg	617.2	(197.5)		422.1	(68.8)
Exchangeable K	278.8	(67.2)		208.0	(45.6)
Exchangeable Na	73.1	(7.0)		30.9	(2.0)
Total OM	177,233.3	(17,794.3)		182,669.4	(11,766.2)
Total P	1403.0	(481.5)		1143.8	(153.9)
Available P	92.7	(17.9)		84.6	(11.9)
Total N	5924.7	(1061.2)		5187.0	(493.8)
Nitrate-N increase (30 days)	12.4	(3.5)	(1994 only)		
Total N mineralised (30 days)	11.5	(4.5)	(1994 only)		

Table 15 Nutrient contents (kg ha^{-1} yr^{-1}) in throughfall in the main secondary forest plots (n=4). DOC = dissolved organic carbon.

	Year 1		Year 2	
	Mean	s.e.	Mean	s.e.
Ca	22.72	(1.05)	20.38	(3.19)
K	72.86	(6.48)	62.37	(2.70)
DOC	150.91	(9.68)	356.11	(15.07)
Total P	4.75	(0.64)	3.68	(0.20)
Phosphate-P	3.57	(0.58)	2.84	(0.16)
Total N	11.52	(0.72)	10.47	(0.58)
Nitrate-N	1.56	(0.17)	2.98	(0.27)
Ammonium-N	5.87	(0.35)	3.74	(0.17)

Table 16 Quantity of surface runoff from 120m^2 in the main secondary forest plots (n=4).

	Year 1		Year 2	
	Mean	s.e.	Mean	s.e.
Runoff (mm)	3.08	(0.58)	2.72	(0.56)

Runoff (% of rainfall)	0.12	(0.02)	0.11	(0.02)

Table 17 Nutrient content of runoff water (kg ha^{-1} yr^{-1}) from the main secondary forest plots (n=4). DOC = dissolved organic carbon.

	Year 1		Year 2	
	Mean	s.e.	Mean	s.e.
Ca	0.37	(0.09)	0.33	(0.07)
K	1.04	(0.21)	0.65	(0.14)
DOC	0.82	(0.18)	1.24	(0.23)
Total P	0.03	(0.01)	0.03	(0.01)
Phosphate-P	0.04	(0.01)	0.03	(0.01)
Total N	0.18	(0.03)	0.12	(0.03)
Nitrate-N	0.02	(0.01)	0.02	(0.01)
Ammonium-N	0.10	(0.02)	0.05	(0.01)

Table 18 Eroded sediments (litter, and < 2 mm and > 2 mm mineral fractions) from the main secondary forest plots (n=4): a) dry mass of each fraction (kg ha^{-1} yr^{-1}); b) N and P concentration and content of the litter fraction; c) chemical and physical characteristics of the < 2 mm mineral fraction; d) nutrient content (kg ha^{-1} yr^{-1}) of the < 2 mm mineral fraction. OM = organic matter.

	Year 1		Year 2	
	Mean	s.e.	Mean	s.e.
a)				
Litter	235.55	(41.19)	204.25	(42.17)
Mineral soil <2 mm	44.09	(15.99)	21.94	(15.94)
Mineral soil >2 mm	328.43	(182.14)	247.74	(140.75)
b)				
Total P (g kg^{-1})	0.94	(0.23)	0.88	(0.21)
Total N (g kg^{-1})	8.23	(0.62)	8.43	(0.44)
Total P (kg ha^{-1} yr^{-1})	0.18	(0.04)	0.14	(0.02)
Total N (kg ha^{-1} yr^{-1})	1.88	(0.51)	1.64	(0.51)
c)				
Exchangeable Ca (cmol kg^{-1})	13.14	(1.92)	9.59	(0, n=1)
Exchangeable Mg (cmol kg^{-1})	2.86	(0.66)	2.00	(0, n=1)
Exchangeable K (cmol kg^{-1})	1.87	(0.46)	1.90	(0, n=1)
Exchangeable Na (cmol kg^{-1})	0.95	(0.32)	0.30	(0, n=1)
Total OM (g kg^{-1})	272.50	(59.22)	210.00	(0, n=1)
Total P (g kg^{-1})	1.10	(0.17)	0.90	(0, n=1)
Available-P (g kg^{-1})	0.19	(0.03)	0.10	(0, n=1)
Total N (g kg^{-1})	6.58	(1.21)	4.10	(0, n=1)
% sand (>60 μm)	67.50	(4.24)	68.00	(0, n=1)
% silt (2-60 μm)	20.25	(3.89)	20.00	(0, n=1)
% clay (<2 μm)	12.25	(0.35)	12.00	(0, n=1)
d)				
Exchangeable Ca	0.24	(0.01)	0.08	(0, n=1)
Exchangeable Mg	0.04	(0)	0.01	(0, n=1)
Exchangeable K	0.03	(0)	0.01	(0, n=1)
Exchangeable Na	0.01	(0)	0	(0, n=1)
Total OM	12.01	(0.95)	4.61	(0, n=1)
Total P	0.06	(0)	0.02	(0, n=1)
Available-P	0	(0)	0	(0, n=1)
Total N	0.32	(0.02)	0.09	(0, n=1)

Table 19 Fine litterfall mass (kg ha^{-1} yr^{-1}).

	Year 1		Year 2	
	Mean	s.e.	Mean	s.e.
Main secondary forest plots (n=4)				
Leaves	8553.2	(760.8)	8213.5	(855.5)
Wood	977.0	(235.5)	893.8	(475.0)
Subsidiary primary forest plots (n=3)				
Leaves	7422.2	(851.6)		
Wood	2031.6	(736.2)		
Subsidiary secondary forest plots (n=3)				
Leaves	6017.1	(701.0)		
Wood	1200.6	(377.2)		

Table 20 Nutrient concentrations and contents in fine litterfall (foliar and reproductive material and woody material < 2 cm diameter) in the main secondary forest plots (n=4).

	Year 1		Year 2	
	Mean	s.e.	Mean	s.e.
N (g kg^{-1})	9.30	(1.44)	9.57	(0.99)
P (g kg^{-1})	0.89	(0.24)	0.94	(0.24)
N (kg ha^{-1} yr^{-1})	81.90	(11.65)	79.75	(9.84)
P (kg ha^{-1} yr^{-1})	7.61	(1.18)	7.84	(1.22)

Table 21 Standing crop of fine litter (kg ha^{-1}).

	Year 1		Year 2	
	Mean	s.e.	Mean	s.e.
Main secondary forest plots (n=4)				
Leaves	4180.7	(446.7)	4047.6	(558.3)
Wood	1264.7	(94.3)	1203.7	(157.7)
Subsidiary primary forest plots (n=3)				
Leaves	3455.8	(113.4)		
Wood	867.8	(277.3)		
Subsidiary secondary forest plots (n=3)				
Leaves	2194.4	(81.7)		
Wood	538.6	(157.2)		

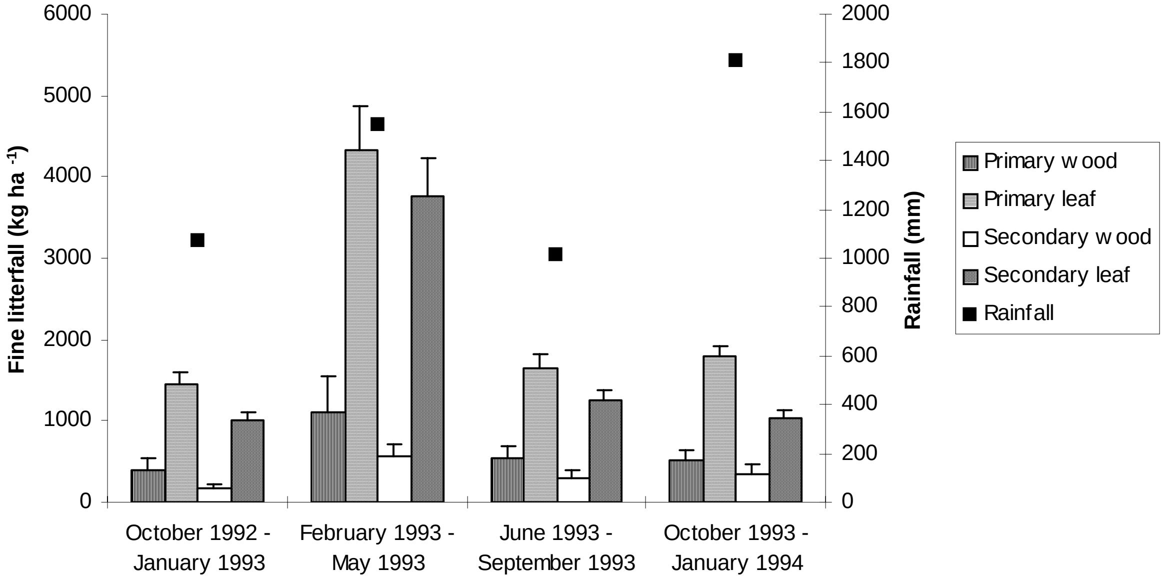

Figure 10. Fine litterfall (foliar and reproductive material (indicated as 'leaf') and woody material < 2 cm diameter (indicated as 'wood')) in the subsidiary primary and secondary forest plots (means and standard errors, n=3) in four month periods and total rainfall during the same periods.

4.2.4.3.2 BIOASSAY OF NUTRIENT AVAILABILITY

There were no significant differences ($P < 0.05$) in either root collar diameter or height increment for any of the three test species between the plants grown in soil from the subsidiary primary and from the secondary forest plots (Table 22). There were, however, differences between species, with Acacia mearnsii having much greater increments of both height and root collar diameter than either Pittosporum undulatum or Clethra occidentalis ($P < 0.05$).

Table 22 Root collar diameter (mm) and height (mm) increment over 90 days of bioassay plants of three tree species growing in soil from the subsidiary primary and secondary forest plots (means and standard errors, n=3).

	Height increment		Root collar diameter increment	
	Mean	s.e.	Mean	s.e.
Primary forest				
Clethra occidentalis	54.06	(7.43)	1.07	(0.18)
Acacia mearnsii	118.70	(11.32)	1.36	(0.13)
Pittosporum undulatum	46.23	(7.92)	0.89	(0.13)
Secondary forest				
Clethra occidentalis	49.70	(13.52)	0.82	(0.17)
Acacia mearnsii	125.00	(14.04)	1.67	(0.16)
Pittosporum undulatum	33.15	(8.18)	0.84	(0.16)

4.2.5 DISCUSSION

4.2.5.1 NUTRIENT CONSERVATION BY SECONDARY FORESTS

Rates of canopy rainfall interception were very high compared to other studies – throughfall was only 50%, whereas values for montane forests usually average 81% of incident rainfall (Bruijnzeel, 1990). However, recent rainfall interception studies in tropical montane cloud forests have produced lower throughfall values than this average (62-65%), even with significant cloud water inputs (Cavelier et al., 1996, 1997; Clark et al., 1998). Furthermore, Hafkenscheid et al. (1998) and Hafkenscheid (2000) observed throughfall levels of 59.5 to 73% in ridge top forest at 1825 m in the Blue Mountains. They also encountered a very high ratio of stem flow to precipitation (13 – 18.3%) which they attributed to a high proportion of leaning and multi-stemmed trees. Most montane forest tree species lack drip tips on their leaves, and many have a dominance of upwardly-growing (orthotropic) rather than horizontal (plagiotropic) branches in their canopies (in contrast to many lowland forest tree species); both factors are likely to contribute to a higher ratio of stemflow to throughfall in montane than in lowland forests. However, the high epiphyte loads of tropical montane trees (e.g. species of Bromeliaceae in Jamaica) are also likely to lead to high rates of retention of precipitation in the canopy. Whether interception is due to retention of water above ground on the leaf surfaces, bark and epiphytes (followed by its evaporation) or due to stemflow (taking water that has flowed over a long length of plant surface to one point on the ground) may have major implications for nutrient conservation as the latter has a far greater potential to cause nutrient losses through leaching, runoff (and associated erosion). There is no direct evidence of the mechanism leading to the high levels of interception found in the secondary forests of our study. However, these forests were on steep hill-slopes and contained a high proportion of multi-stemmed trees, and we observed high rates of stem flow. Therefore this is likely to have been a major mechanism.

Nutrient contents in throughfall water (Table 15) were generally in the range reported in three studies of tropical montane forests reviewed by Parker (1983) and Vitousek and Sanford (1986), e.g. 8 – 30 kg ha^{-1} yr^{-1} for N, 7 – 21 kg ha^{-1} yr^{-1} for Ca and 70 – 74 kg ha^{-1} yr^{-1} for K, though our values for total P (3.68 and 4.75 kg ha^{-1} yr^{-1} in each year) were above the values in the two previous studies (1.4 and 2.5 kg ha^{-1} yr^{-1}). These annual throughfall nutrient amounts were generally high in comparison with the standing-stock of nutrients measured in the live leaves of well-developed Mull Ridge forest at 1530 m altitude in the Blue Mountains by Tanner (1985): 113% for K; 100% for total P; 37% for Ca; 12% for total N.

Nutrient losses in runoff and erosion were, however, very low (less than 0.04% of the stocks in the top 10 cm of soil for all measured nutrients except for K, which was 0.4%). Nutrient contents in throughfall water (Table 15) were much greater than those in runoff water (Table 17), ranging from 24,610% for DOC, to 14,050% for total P, 8002% for K, 7330% for total N (11,350% for nitrate-N and 6407% for ammonium-N) and 6157% for Ca. There is no information about what proportion of throughfall nutrients were absorbed in the soil or leached through the soil into ground water. The coarse texture of the soils means that there was the potential for significant leaching of nutrients down through the soil profile, but, even so, it is unlikely on these long hill-slopes that (averaging out zones of deposition due to topographic variation) total nutrient losses from secondary forests down-slope exceed inputs from up-slope. Furthermore, high leaching rates cannot be assumed because the high concentration of polyphenolic compounds in the leaf litter of montane forests is likely to lead to strong binding and low leaching losses of many mobile nutrients (Bruijnzeel et al., 1993). At this stage, no firm conclusions can be drawn about the significance of throughfall nutrient contents for overall nutrient conservation by these secondary forests. However, overall, there are strong indications that they have a high net conservation of nutrients and may well, in fact, be experiencing a net increase in total nutrient stocks, which is the expectation for secondary forests (Vitousek and Reiners, 1975).

Where low rates of soil erosion occur in secondary or plantation forests it is not possible, with certainty, to determine whether this is due to good conservation of the soil by the forest, or due to the loss of a high proportion of the erodible material during the period following the initial clearance of the forest when the soil surface was left exposed. Thus, Richardson (1982) attributed the seven-times lower rates of erosion that she recorded in a Jamaican pine plantation versus in adjacent lowland rainforest, of the type cleared to establish the plantation, to the cover of the soil surface by pine needles. However, an equally likely explanation is that significant erosion of the more erodible material occurred prior to the establishment of the plantation trees. Nonetheless, the soils of the secondary forests in our study contained a high proportion of fine erodible material (e.g. 26% clay, Table 14)) and the annual rates of erosion recorded (e.g. 33 kg ha^{-1} yr^{-1} of particles < 2 mm, Table 18) represented a tiny proportion of the amount of potentially erodible material present in the surface soil (e.g. less than 0.2% of that present in the top 1 cm of soil). Therefore, despite the steep slopes and high rates of rainfall, these secondary forests are providing high levels of conservation of soil resources.

4.2.5.2 COMPARISON OF NUTRIENT CYCLING AND SOIL FERTILITY BETWEEN SECONDARY AND PRIMARY FORESTS

A wide range of tree stem basal areas have been reported from southern-slope forests in the Blue Mountains, from 56.2 (+/- 7.4) m^2 ha^{-1} (in Bellingham and Tanner's (2000) plots in essentially primary forest just 250 m down from the main ridge crest) to 15.8 (+/- 0.8) m^2 ha^{-1} (in Goodland and Healey's (1995) plots further down the slopes in secondary forest extensively invaded by the exotic tree species, Pittosporum undulatum). The basal area of all three sets of our plots lay towards the middle of this range, but there was a clear difference from the younger main secondary forest plots, 29.9 (+/- 5.8) m^2 ha^{-1}, to the subsidiary primary forest plots, 37.1 (+/- 7.9) m^2 ha^{-1}. Tanner (1977a) found that basal area was c. 40% higher in ridge-top forests of more upper-montane character than slope and gully forests with more lower-montane affinities. However, Bellingham and Tanner (2000) found evidence that relative basal area increment between 1990 and 1994 was higher in five southern-slope forest plots (0.028 (+/- 0.004)) than in six ridge-top forest plots (0.022 (+/- 0.003)). Secondary sub-tropical forests in Puerto Rico recovering from cultivation showed a basal area of 7.2 m^2 ha^{-1} after six years, increasing to 28.5 m^2 ha^{-1} after 20 years and 22.8 m^2 ha^{-1} after 50 years (Lugo, 1992). Thus, the secondary forests of our study in Jamaica have shown a greater rate of recovery of basal area than these, and there is no evidence of any limitation to their eventual recovery back up to primary forest levels.

The mean litterfall production from our main secondary forest plots (9319 kg ha^{-1} yr^{-1}) is very similar to that of 34 published studies of secondary forest litterfall (whose mean is 9200 kg ha^{-1} yr^{-1}, Table 23). Brown and Lugo (1990) found that in secondary forests high rates of litter production are established relatively quickly: mean annual litterfall increased from one-year-old to seven-year-old forests, and then showed no further increase up to at least 21 years (Table 23). Our values from c. 20-year-old secondary forest fall in the lower half of Brown and Lugo's (1990) range; and slightly below the average for mountain secondary forests (9800 kg ha^{-1} yr^{-1}, Table 23). In mountain environments this mean litterfall rate of studies of secondary forests is, surprisingly, higher than that of apparently primary forests (7900 kg ha^{-1} yr^{-1}); the same result has also been obtained in direct comparisons within the same study area (Table 23, Proctor, 1983; Vitousek and Sanford, 1986; Scott et al., 1992). The rates of fine litterfall in our main secondary forest plots were very similar to those in the primary forest plots (though rates in the subsidiary secondary forests were lower); a comparable result to that found by Zou et al. (1995) for lower montane forests in Puerto Rico (Table 23). However, the litterfall rates in our study were greater than those obtained by Tanner (1980b) and Hafkenscheid (2000) from six primary/old secondary forests on ridge-tops in the Jamaican Blue Mountains (Table 23). The proportion of fine litterfall comprising the leaf fraction was comparable between our study (90%) and the other two (74% - 97%).

The differences in the results obtained from the Jamaican Blue Mountains could be explained by altitude; our main secondary forest plots, at 1250 - 1310 m, were at least 244 m lower than those of Tanner (1980b) (1554 - 1620 m) and Hafkenscheid (2000) (1809 m). One block of our subsidiary plots was comparable in altitude to Tanner's (1980b) but the other two were 150-300 m lower. This difference in altitude/topographic position was reflected in the significant differences in soil pH and associated variables (section 3.2.1). Eight out of our ten plots can be categorised as "lower montane tropical rain forests" whereas three out of four of Tanner's and both of Hafkenscheid's are classified as "upper montane tropical rain forests" (Tanner, 1977a; Hafkenscheid, 2000). Such differences in altitude have a major impact on litterfall rates: mean litterfall in non-secondary upper montane forests is substantially lower than that in lower montane forests (Table 23). However, for secondary forests surprisingly little difference has been found in mean litterfall rates between mountain and lowland environments (Table 23).

In comparing the different litterfall data sets from the Jamaican Blue Mountains a second factor that must be considered is the influence of weather before and during the period of observation, in particular the impact of hurricanes that cause extensive defoliation of the forests (Bellingham et al., 1992). Tanner (1980b) reported litterfall data from two separate periods: 1974-75 and 1977-78. The first period had 3115 mm of rainfall (40% more than the long-term average), which he attributed to two hurricanes which passed near to the island. Daily litterfall rates were markedly higher in the hurricane period, but they were then much lower than average in the subsequent 98-day wet period. 1977-78, however, had 1745 mm of rainfall (22% lower than the long-term average). In contrast, the two years of our study (1992-94) had very similar annual rainfall that was close to the long-term average, with no exceptional seasonal events.

Our results may, nonetheless, have been influenced by the longer-term effects of the catastrophic impact of Hurricane Gilbert in 1988, which might have led to increased litterfall in 1992-1994 while the forests were still recovering from the effects of defoliation, branch damage and an overall 8% mortality (Bellingham et al., 1992, 1995; Bellingham and Tanner, 2000). The eye of Hurricane Gilbert passed within 15 km of our study sites, and many patches of the montane forest were completely defoliated (Bellingham et al., 1992). Refoliation took about 28 months (Bellingham et al., 1995) which, because it was synchronized, may have resulted in synchronized litterfall for several years. Scatena et al. (1996) found that, in the Luquillo Mountains of Puerto Rico, in the first year following the impact of Hurricane Hugo, mean total annual litterfall was 2300 kg ha^{-1} yr^{-1}; then, over the following four years, it increased steadily to 7300 kg ha^{-1} yr^{-1} (but still below the pre-hurricane level of 8700 kg ha^{-1} yr^{-1}). Similarly, Walker et al. (1996) in an independent study of changes in productivity in lower montane and upper montane forest in Puerto Rico following Hurricane Hugo, found that during the first four years total annual litterfall increased to approach (but not reach) the pre-hurricane levels. Looking at the impact of another category of disturbance Burghouts et al. (1992)

found that ten years after heavy selective logging of lowland dipterocarp forest in Sabah, Malaysia, annual litterfall in regrowth (11,900 kg ha^{-1} yr^{-1}) was slightly higher than that in unlogged primary forest (11,500 kg ha^{-1} yr^{-1}).

Table 23 Comparison of rates of litter production between different categories of tropical forest (kg ha^{-1} yr^{-1}).

	Secondary forests			Non-secondary mountain forests[1]		
	Lowland[2]	Mountain[3]	Combined	Unspecified/ lower montane[4]	Upper montane, Jamaica[5]	Upper montane, global[6]
Small litterfall – number of studies	26	9 (8[7])	35 (34[7])	20	2	11
Range	4500 - 13,200	7000 - 27,000 (12,500[7])	4500 - 27,000 (14,300[7])	2700 - 11,100	5500 - 6600	3600 - 11,000
Mean	9100	11,700 (9800[7])	9800 (9200[7])	7900	6140	6200
Total litterfall, one-year-old forests – range[8]			1000 - 5000			
Total litterfall, seven-year-old forests – range[9]			7000 - 13,000			
Total litterfall – mean[10]		8700	8700	9100		
Fine litterfall – mean[11]		9319				
Fine litterfall – mean[12]		7218		9454		
Leaf litterfall – number of studies	17		19 (18[7])	16	2	9
Range	3700 - 8400		2700 - 15,500 (8400[7])	2500 - 8500	4600 - 5500	2300 - 5700
Mean	6200		6500 (6000[7])	5500	5000	4400

[1] Forests not indicated to be secondary.
[2] 20 studies reviewed by Proctor (1983) and those of: Dantas and Phillipson (1989); Hegarty (1991); Morellato (1992); Burghouts et al. (1992); Herbohn and Congdon (1993); Sanchez and Alvarez-Sanchez (1995).
[3] Nine studies reviewed by Proctor (1983) and that of Zou et al. (1995).
[4] 18 studies reviewed by Proctor (1983) and those of: Weaver and Murphy (1990); Morellato (1992); Zou et al. (1995); Vitousek et al. (1995); Stocker *et al.* (1995); Pendry and Proctor (1996) of unspecified mountain or specifically lower-montane forest (those studies in clearly upper-montane forest were excluded from this set).
[5] Four ridge-top forests studied in 1974/75 and 1977/78 by Tanner (1980b) and two in 1995/96 by Harkensheid (2000) – these results are included in the global upper montane range and mean values shown to the right.
[6] Nine studies reviewed by Proctor (1983) and those of: Veneklaas (1991); Harkensheid (2000).
[7] One study of secondary forest reviewed by Proctor (1983) had exceptionally high litterfall rates. Although there are no good a priori grounds for dismissing this study, the maximum and mean values with this study excluded are shown in brackets.
[8] Four studies reviewed by Brown and Lugo (1990).
[9] Seven studies reviewed by Brown and Lugo (1990), this wide range was maintained until at least 21 years.
[10] Zou et al. (1995) provide a direct comparison between adjacent primary ("mature tabonuco") and secondary "mid-successional" (cleared at the beginning of this century and abandoned from agriculture in the 1920s and 1930s) forests in Puerto Rico – these results are included in the small litterfall range and mean values shown above.
[11] Our study, main secondary forest plots (from Table 7).
[12] Our study, subsidiary plots (from Table 7).

The invasive exotic species Pittosporum undulatum, occupied 28% of the basal area of our main secondary forest plots (Table 13), whereas it was absent as a tree from Tanner's plots before Hurricane Gilbert. The exceptional productivity of this species (as reflected in trunk growth) is a third factor that is likely to contribute to the high rates of litterfall that we recorded. Unpublished data from Goodland and Healey's (1995) plots show that, during 1991 – 1996, the relative basal area increment of P. undulatum (0.164 (+/- 0.029)) was substantially greater than that of the native species (0.013 (+/- 0.001)); it was also much greater than that found by Bellingham et al. (1995) for all the individual native tree species in Tanner's plots.

The final factor to be considered in comparing litterfall among the different Jamaican Blue Mountain data sets (in particular the contrast that the higher basal area of the primary forest plots was not generally matched by a higher litterfall rate) is Brown and Lugo's (1990) observation that in younger secondary forests litter production is a higher fraction of the net primary productivity than stemwood biomass production. Ewel (1976) found evidence in Guatemalan lowland rain forests that during the course of succession litterfall in secondary forests might even rise to levels higher than that in adjacent primary forests. He found that litterfall in two-year-old secondary forests was about half that in mature forests, and then increased until in a 14-year-old forest it was about 10% higher than in mature forest (though the difference was probably not significant). These observations may be explained by Swaine and Whitmore's (1988) conclusion that pioneer tree species (those that tend to dominate the early stages of secondary succession) have a higher rate of leaf turn-over than the non-pioneer "climax" tree species that dominate later in the succession and in undisturbed primary forest.

The standing crop of leaf litter in the main secondary forest plots (mean of 4114 kg ha^{-1} (Table 21)) was very similar to that recorded in ridge-top forest by Hafkenscheid (2000) (4300 kg ha^{-1}), but lower than that recorded in five ridge-top forests by Tanner (1980b, 1981) (range 6,400 – 11,700 kg ha^{-1}). However, they were higher than in our subsidiary primary (3456 kg ha^{-1}) and secondary (2194 kg ha^{-1}) forest plots. The annual amount of leaf litterfall in our main secondary forest plots (Table 19) was equivalent to 204% of the standing crop, a lower ratio than that in the subsidiary secondary forest plots (274%), similar to that in our subsidiary primary forest plots (215%), but much larger than the ratio found by Tanner (1980b): 62% and 83% for two ridge-top forest types. These results indicate that the forest in lower altitude, less acidic slope sites had a more rapid turnover of litter (and thus of nutrient cycling) than the higher altitude ridge-top primary forests. However, there was no evidence of systematic variation in litter turnover rates between secondary and primary slope forests.

The concentration of N in our main secondary forest plots' fine litterfall (9.2 g kg^{-1}, Table 20) was very close to the top of the range of four values obtained by Tanner (1977b) (5.9 – 9.0 g kg^{-1}). However, fine litterfall P concentration in our study, 1.0 g kg^{-1}, was substantially above the range for Tanner's (1977b) four forest types (0.2 – 0.4 g kg^{-1}). Whilst being in the upper half of the range of values obtained for tropical forests (Proctor, 1983), this value fits well within the range of litterfall P concentrations, 0.5 – 1.2 g kg^{-1}, obtained from a series of eight mountain secondary forests in the Philippines by Kellman (1970) (these also had high litterfall N concentrations, in the range 13 – 17 g kg^{-1}) and evergreen mountain forests in northern Thailand by Thaiutsa et al. (1978) (0.9 – 1.6 g kg^{-1}).

Litterfall mass and nutrient concentrations together determine the total recycling of nutrients in fine litterfall, which in our main secondary forest plots were 81 kg N ha^{-1} yr^{-1}, and 7.7 kg P ha^{-1} yr^{-1} (Table 20). These values were within the wide ranges reported in other studies in tropical forests at > 1000 m altitude (28 – 165 kg N ha^{-1} yr^{-1} and 1.1 – 12.0 kg P ha^{-1} yr^{-1}) (Vitousek, 1984; Vitousek and Sanford, 1986; Tanner et al., 1998). However, both values were high compared to Tanner's (1977b) values of 35 - 59 kg N ha^{-1} yr^{-1} and 1.3 – 2.4 kg P ha^{-1} yr^{-1} in primary/old-secondary ridge-top forests in the Jamaican Blue Mountains. Healey (1989) and Tanner *et al*. (1990) concluded that growth in ridge-top upper montane forests in the Blue Mountains was limited by the low availability of P and N. However, the much higher litterfall P concentrations in our main secondary forest plots indicate that productivity in these forests may be much less P limited (Vitousek and Sanford, 1986). The ratio of litterfall concentrations (g kg^{-1}) to contents (kg ha^{-1} yr^{-1}) of both N and P in our study lie well within the range of values of forests in the same altitudinal range reported by Tanner et al. (1998). Our results are thus compatible with recent tentative conclusions of Tanner et al. (1998) that productivity in tropical montane rain forests is, in fact, limited more by low availability of N than of P.

The rate of total N mineralisation (0.48μg g^{-1} day^{-1}) in in-situ soil cores in the main secondary forest plots (Table 14) was within the wide range obtained for ex-situ incubation of cores of soil from four ridge-top forest types by Tanner (1977a) (-0.775 to +4.00), whereas the rate of nitrate-N increase, 0.52 μg g^{-1} day^{-1}, lay below Tanner's (1977a) range of 1.3 – 3.4 μg g^{-1} day^{-1}. Tanner (1977a) found very variable rates of change in ammonium-N during incubation (for 40 days) and for three of his four soils it was negative. The amount of total N mineralised in our main secondary forest plots (Table 14) was a very high proportion, 173%, of the amount of N input over an equivalent time period and area in fine litterfall (Table 20), but within the broad range found by Tanner (1977a) (-315% to + 1327% of litterfall inputs). However, it was equivalent to just 0.2% of standing stock of total N in the soil (Table 14).

As indicated in section 3.2.1, the soils in our main secondary forest plots had values of most chemical indicators of fertility similar to those recorded in primary forests in the Blue Mountains, and, for pH, base saturation and exchangeable Ca, the values were larger. The bioassay indicated that soil fertility in the subsidiary secondary forest plots had recovered to the levels in the primary forest plots. However, Healey (1989) found a similar result of no significant difference in the above-ground growth of Melinis minutiflora plants grown in two very different (primary) montane forest soils from Mull Ridge and Col (Tanner's (1977a) "Gap") Forest. The only significant difference between the plants was that those in the less-fertile Mull Ridge Forest soil had greater root masses. Nonetheless, the indication of equivalence in soil fertility from our bioassay has greater significance because two of the species used are trees growing in the forests concerned.

4.2.6 CONCLUSIONS

For forests in the middle of steep slopes on a tropical mountain in Jamaica, following the abandonment of agriculture, tight nutrient cycling and soil condition and fertility are effectively restored during c. 20 years of secondary succession. In particular, the secondary forest acts as a buffer against fluctuations in runoff associated with rainfall events. The very small losses of nutrients in runoff and erosion compared with high rates of recycling through litterfall suggest that these forests are effective in restoring soil fertility. This is borne out by the similar rates of plant growth on the primary and secondary forest soils in the bioassay experiment. The secondary succession results in the re-establishment of a forest ecosystem with effective nutrient conservation that offers a high degree of protection of catchment soil and water resources and the potential to sustain another cycle of agricultural production.

4.3 EVALUATION OF TREES INDIGENOUS TO THE MONTANE FOREST OF THE BLUE MOUNTAINS, JAMAICA FOR REFORESTATION AND AGROFORESTRY

4.3.1 SUMMARY

Land pressures, growing rural populations and environmental degradation have led to marginalisation of farmers on steeplands in the Caribbean and other parts of the tropics. Forest areas are increasingly under threat as a result of these pressures. As a consequence, the establishments of protected areas for forest and biodiversity conservation can potentially further marginalise hillside farmers by restricting the practice of slash-and-burn cultivation. Depending on the management policy such protected areas may also reduce local people's access to forest products. Together, these factors have created an urgent need to find sustainable methods of hillside farming. In the Caribbean, there is a wide consensus amongst land-use professionals that the only environmentally, economically and socially acceptable means to achieve this is by intensified agricultural systems including tree crops.

Agroforestry projects have identified a reluctance on the part of most farmers to plant indigenous trees as they are unknown to them in a farming systems context. Therefore, a species elimination trial was undertaken in which 25 undomesticated local forest trees, which have potential for the conditions in the area, were grown on open mountain slopes to determine and demonstrate the usefulness of indigenous forest tree species and their potential value/role within the local farming systems. The trial was designed to test which ones performed well (in terms of survival and growth) in open conditions, had a growth form and canopy structure amenable to incorporation into agroforestry systems and to eliminate those that clearly cannot tolerate the exposed conditions outwith the forest environment. Selection of the 25 montane forest tree species was made on the basis of an ethno-botanical survey of local farmers, combined with existing ecological knowledge from research in the natural forests. Their performance was compared with *Cedrela odorata*, a native domesticated species, and *Grevillea robusta*, an exotic domesticated species.

Based on the farmers' opinions about the best trees for timber, fuelwood, fencing, poles and tool handles, and their field performance in the elimination trial, the promising multipurpose forest species are*: Juniperus lucayana, Clethra occidentalis, Cinnamomum montanum, Podocarpus urbanii* and *Turpinia occidentalis*..

OBJECTIVES

Purpose 2: To develop management regimes for different local tree species to optimise tree and crop production using low-cost methods of controlling soil erosion

Purpose 3: To prepare an inventory of locally suitable species for contour hedgerow systems, and produce guidelines for each.

4.3.2 INTRODUCTION

Land pressures, growing rural populations and environmental degradation have led to marginalisation of farmers on steeplands in the Caribbean and other parts of the tropics. Forest areas are increasingly under threat as a result of these pressures. As a consequence, the establishment of protected areas for forest and biodiversity conservation can potentially further marginalise hillside farmers by restricting the practice of slash-and-burn cultivation. Together, these factors have created an urgent need to find sustainable methods of hillside farming. In the Caribbean, there is a wide consensus amongst land-use professionals that the only environmentally, economically and socially acceptable means to achieve this is by intensified agricultural systems including tree crops.

Plantation forestry was common in the 1970's, and stock from forest nurseries reflect the concentration on a few well-known species, common throughout tropical regions (Evans, 1992). The principal species planted were *Pinus caribea*, *Eucalyptus* spp, *Hibiscus elatus*, with the Meleaceae becoming less popular because of *Hypsyplla* problems. Consequently, agroforestry projects have identified a reluctance on the part of most farmers to plant indigenous trees as they are unknown to them. A number of studies in the last decade have identified groups of undomesticated species from the natural forest that have promising survival and production rates which, with improvement programmes could provide quality sources of timber and other products under locally prevailing conditions (Condit *et al*., 1993; Butterfield and Fisher, 1994; González and Fisher, 1994; Butterfield and Espinoza, 1995; Butterfield 1995, 1996; Knowles and Parrotta, 1995; Davidson *et al*., 1998; Haggar *et al*., 1998). Furthermore, because of their adaptation to local conditions, native species can have significant site-enhancing properties (Montagnini and Sancho, 1994; Montagnini *et al*., 1994).

This identifies the potential to demonstrate the usefulness of indigenous forest tree species and their potential within the local farming systems. Many of the useful tree species of the Blue Mountains had been identified as early as the 1940s (Swabey, 1940, 1941, 1945) but only as extracted wood from the natural forest. No consideration has been made of their propagation or silvicultural requirements. There is now a very substantial database on the ecology of natural forest species (Tanner, 1977a, 1977b, 1980a, 1980b, 1981, 1985; Healey, 1989; Bellingham, 1993, 2000) within the forest environment which permits the identification of their regeneration characteristics (Swaine and Whitmore, 1988; Bazzaz, 1991).

Furthermore, in the Blue Mountains, the introduction and subsequent spread of exotic plant species have seriously eroded the native biodiversity. Areas originally cleared for agricultural production and subsequently abandoned are now largely dominated by either a stoloniferous grass, *Melinis minutoflora* Beauv., or a scrambling herb, *Polygonum chinense* L. The presence of *Melinis* is particularly problematic as it forms a highly flammable sward that burns on a regular basis, preventing both the restoration of soil productivity and tree establishment.

In light of this, an elimination trial was undertaken which would grow up to 25 different forest trees on open mountain slopes dominated by *Melinis* to establish which ones perform well in open conditions, have form and canopies amenable to incorporation into agroforestry systems and to eliminate those that cannot withstand the exposed conditions outwith the forest environment. Species selection was made on the basis of an ethnobotanical survey of local farmers, combined with existing ecological knowledge.

4.3.3 METHODS

4.3.3.1 ETHNOBOTANICAL SURVEY

The objective of the survey was to determine people's knowledge of local tree species, particularly native forest species; the uses of different trees and which products are obtained from them; the extent of dependency on forest resources; preferred species and whether or not people have considered planting local species on their farmland.
The area surveyed was the community of Westphalia, which is the closest settlement to the remaining forest of the Blue Mountains on the Southern slopes. A total of 27 people were consulted, of which 16 were men and 11 women. All the people in the target group were farming in the study area. The interviews were undertaken between August and September 1996. According to the 1991 Census of Population (STATIN), the total population of Westphalia was 554 of which 286 were over the age of 18. Consequently the sample size was 9.4 % of the adult population of the

area. The average age of the farmers in the study area is 39 years, 80% are full-time farmers and the median farm size is 0.81 ha (Douglas, 1995).

Stratified sampling was done to target adults actively involved in farming activities and to ensure that women were included. Many of the interviews were carried out during transect walks across the hillslopes. Others were done through meeting people in their homes in the village of Westphalia. Information was obtained using semi structured interviews. Certain 'core' questions were predetermined and the interviews were guided as to ensure that those were answered. However, new questions, or lines of questioning, were allowed to develop depending on the answers received. Interviews were carried out on a one to one basis. Each session took anything between 20 minutes to 1 hour depending on the answers given. All the interviews were carried out by the same person.

Local farmers already have experience of growing a range of fruit-tree species (largely exotic) in their farming systems. However, they don't have equivalent knowledge or experience of virtually all the natural forest tree species and therefore saw a greater need for a new trial to provide information on these. A further crucial context is that this project was designed to develop improved practices appropriate for the National Park buffer zone in which it was carried out. A range of stakeholders have identified the importance of testing the use of native species in the buffer zone both for its buffering role and for *ex-situ* conservation.

4.3.3.2 ECOLOGICAL ASSESSMENT OF INDIGENOUS TREES OF THEIR SUITABILITY FOR FARM AND COMMUNITY FORESTRY

Data of tree diameter growth and survival rates, and form, in contrasting environmental conditions from existing permanent forest sample plots were analysed. In the main analysis, of data on 3176 tree stems in existing sample plots (Tanner, 1977a, 1977b, 1980a, 1980b, 1981, 1985, Bellingham, 1993, 2000). The following parameters were calculated for all 60 tree species present: basal area growth rate and annual mortality rate over the periods: 1974-1989 ((mostly) pre-Hurricane Gilbert), and 1989-1994 (post-Hurricane Gilbert) (Goodland *et al*., 1998). This enabled assessment of species resistance to severe disturbance, and capacity to recover from it. Data on 9256 additional tree stems in other plots with fewer enumerations were analysed to assess the species' size-class and spatial distribution (including density in different natural forest types and in forest subject to different degrees of human disturbance).

Plate 7 A native species elimination trial was established on the farm of Mr Sheraton Walker in a fallow area overgrown with *Melinis minutoflora.*

4.3.3.3 SPECIES ELIMINATION TRIAL

A species elimination trial was chosen as the most expedient and inexpensive means to screen a large number of species for as a precursor to growth trials. The objective was to compare the survivorship and growth of a number of species which have potential for the conditions in the area. The 25 montane-forest species selected for outplanting were included in the trial in comparison with *Cedrela odorata*, a native domesticated species, and *Grevillea robusta*, an exotic domesticated species.

Field data was accumulated on the traits of wild seedlings to produce an identification guide to enable field collection of propagules (Healey and Goodland, 1996), and wildings of the target species were collected between August and November 1996. They were hardened in a nursery at Cinchona Botanic Garden prior to planting out commencing December 1996. Two sites were selected for out-planting - both were located on the farms of local people, currently under a fallow period dominated by *Melinis minutoflora* Beauv. Site 1 was located on an exposed ridge-top at 1555 m elevation, site 2 in a valley-bottom at 1440 m elevation.

The sites were prepared by manual clearing of the grass and a subsequent application of glyphosate herbicide ('Round-Up') three weeks prior to commencement of planting. The planting regime was one of single tree plots in 20 blocks at each site. Trees were spaced at 1 x 1 m giving a total planting area of approx. 1.2 ha per site. Height and basal diameters were recorded at planting, and at six, twelve and forty-two months after planting, and increments recorded. Mortalities were recorded one month, one year and forty-two months after planting. Trees which died within one month after planting were replaced, but no further replacements were made.

At the final enumeration, Dawkins' classification was used to assess crown form (scale of dead (0) to perfect (5)) and an ordinal ranking scheme was used to assess stem form (scale of a crooked bole; more than two bends present (1) to an absolutely straight bole (5)). Crown diameter was determined from the average of two perpendicular measurements across the base of the crown. Damage to a tree was categorised as caused by either weather or insects.

It was rated on a scale of 1 to 5 with 20% increment blocks of damage (i.e. 1=80%, 2=60%, 3=40%, 4=20% and 5=0%).

Differences between height and basal diameter increments between species and site were established using the General Linear Model of SPSS V. 9.0.0 (1998).

4.3.4 RESULTS AND DISCUSSION

4.3.4.1 ETHNOBOTANICAL SURVEY

Farmers in all commented on the uses of 62 species (Table 24).

4.3.4.1.1.TREES PRESENT ON FARMLAND

The vast majority of farmers interviewed (96 %) had some trees on their land. On average people would have seven different species. There was a majority of fruit trees amongst the most commonly present trees, principally A*nnona cherimola, Persea americana, Mangifera indica Citrus* spp and *Prunus persica,* but also *Cedrela odorata, Cupressus lusitanica, Grevillea robusta,* and *Calliandra calothyrsus.* Several farmers reported on having young, newly planted trees on their farm. The impression was that significant planting had taken place over the last two years or so. This was particularly the case for *Calliandra calothyrsus* and *Cupressus lusitanica*.

4.3.4.1.2 TREE USES

When asked what the most important products gained from trees are the majority of people said timber (64% (men 73%, women 54%)). Fruit was considered the second most important product (38% (men 47%, women 27%)), followed by firewood (19% (men 33 %, women 0 %)). Four percent mentioned yam sticks and shade as being of primary importance, whereas fence posts, fencing sticks, poles, tool handles and animal fodder were not highlighted as the most important products by any of the respondents. Several people (22 %) felt that they were unable to answer the question as all products were of equal importance to their livelihood. This was particularly true for women, where 45 % were unable to rank the importance of different products, compared with 7 % of the men.

Animal fodder had the lowest priority. People in the area do not use trees as a source of animal fodder. There is plenty of herbaceous grazing for the animals, thus leaf material is very rarely used. In farmers' experience, the tree leaves that animals like to eat are: *Mangifera indica*, *Citrus* spp, *Persea americana*, *Artocarpus altilis*, *Spondias mombin, Annona cherimola, Bambusa vulgaris, Calliandra calothyrsus, Coccoloba swartzii, Bursera simaruba* and *Dendropanax arboreus*.

4.3.4.1.3 MOST PREFERRED TIMBER TREES

According to the respondents the best timber trees were *Cedrela odorata, Juniperus lucayana*, *Hibiscus elatus* and *Pinus caribaea*, respectively. Most people mentioned more than one tree. Everyone knew about *Cedrela odorata* and its usefulness as a timber tree. Other trees such as *Swietienia macrophylla*, *Grevillea robusta* and *Clethra occidentalis* were not mentioned at all by some respondents. Consequently, their usefulness as a timber tree or other products may not have been known to people. This does not necessarily exclude them for being considered for planting, should knowledge about their potential be gained. Several trees were considered to have excellent timber properties amongst the people who were familiar with them, but overall they scored low in terms of their usefulness since only a limited number of people knew about them. One such tree, for example, was *Swietienia macrophylla* which was only known to 30 % of the respondents. Of these 63 % considered it being one of the best timber trees, this compares to 18% when all the respondents were included.

Juniperus lucayana was the favourite timber tree with the men, whilst it was only the fifth most preferred by the women. Only 18 % of the women rated *Juniperus lucayana* as one of the best timber tees, compared with 94 % of the men. Fewer women had knowledge about *Juniperus lucayana*. All the men mentioned this tree, but only 64 % of the women did. More women than men said that *Grevillea robusta* and *Pinus caribaea* were amongst the best timber trees.

4.3.4.1.4 MOST PREFERRED TREES FOR FUELWOOD

There was less consensus over which trees were the best for fuelwood. Most trees can be used for this purpose and people had different opinions of which are the best. *Pittosporum undulatum* was the preferred species, particularly by men. This is a very common species and most people were familiar with it. It is therefore unclear if it scored highly because it is because it is the most commonly used species, or because it has superior properties. Thirty-seven percent of the women considered *Cinammomum montanum* to be one of the best fuelwoods whilst only 15 % of the men thought so.

Women were less knowledgeable about fuelwood trees than men. Some women (27%) were unable to mention any trees with superior fuelwood qualities at all, and the ones that did, mentioned fewer trees (2 on average) than men (5 on average). Notably they did not have much knowledge of the forest species. With the exception of *Ilex macfadyenii*, *Clethra occidentalis* and *Lyonia jamaicensis*, the women did not name any forest trees.

4.3.4.1.5 MOST PREFERRED TREES FOR FENCING POSTS AND STICKS

Many different trees were used for sticks and fencing material. The two most commonly used were *Juniperus lucayana* and *Bursera simaruba*. *Juniperus lucayana* because it is a very durable wood and *Bursera simaruba* because it roots readily when stuck into the ground. As such, both these trees were considered excellent for use as fence posts. *Lyonia jamaicensis* and *Dendropanax arboreus* were also used as live fence posts, 22 % of the respondents named these trees as being amongst the most preferred trees for fencing. *Pittosporum undulatum* and *Clethra occidentalis* were the third most commonly used trees, followed by *Sideroxylon montanum* and *Comocladia pinnatifolia*. Several trees such as *Spondias mombin*, *Comocladia pinnatifolia*, *Hibiscus rosa-sinensis* and Bird Feeding Stick were described as a excellent tree for live fencing and hedging, but not many people mentioned them.

4.3.4.1.6 MOST PREFERRED TREES FOR POLES

Juniperus lucayana was by far the most popular tree for poles for light construction. *Sideroxylon montanum* and *Clethra occidentalis* were also listed amongst the best trees for this purpose. These three trees apart, peoples' opinions about which trees were best for poles varied greatly. In total, 23 trees were mentioned as being amongst the best. As was the case for fuelwood, women had limited knowledge about suitable wood for poles.

4.3.4.1.7 PREFERRED TREES FOR TOOL HANDLES

Redwood, Rodwood and Pimento were the trees farmers liked best to use for tool handles. They are slow growing trees with hard wood which does not easily split. Again, women had limited knowledge about which trees were best suited for this purpose.

4.3.4.1.8 PREFERRED TREES FOR ON-FARM PLANTING

Eighty nine percent of all the farmers interviewed expressed an interest in planting trees on their farms. The majority of people were only interested in planting trees which would provide benefits. Income generating trees, i.e. timber trees, fruit trees and Christmas trees were most popular. However, other benefits such as windbreaks, shade, firewood, poles, sticks and soil conservation were also mentioned as reasons for planting trees, albeit by fewer people. Trees with multiple purposes were noted as particularly desirable. Examples given of such trees were Mango, Breadfruit, Ackee and Orange. These yield both fruit and good fuelwood. Mango, Breadfruit and Ackee can also be used for timber. *Calliandra* was also mentioned as a good multi-purpose tree.

Few native forest trees had been considered by farmers. The ones that people said they would like to plant were Juniper, Soapwood, Bilberry and Yacca. The limited interest in planting native forest trees is not likely to be because of lack of knowledge about the uses of these trees. Farmers regularly utilise many of the forest species for a variety of purposes and many have a fairly comprehensive knowledge about the trees growing in the forest. People are still able to collect fuelwood, sticks and poles off-farm, and as long as they can do that most people do not see the need to plant trees for these purposes on their land. Some farmers did, however, say that they would like to have trees for firewood on their land, partly in order to secure a source for when they are no longer permitted to get wood from the forest, and partly for ease of access.

It is possible that people failed to express an interest in planting these trees because no tradition of doing so exists; that they simply did not consider the forest species as an option. In these interviews inductive questioning about this subject was not used. The aim was to find out what trees people would like to plant at the moment, without making any suggestions.

4.3.4.1.9 UNWILLINGNESS TO PLANT TREES

Some people expressed reservations about planting trees on higher slopes because of frequently occurring bush fires in the area. The Molasses grass (*Melinis minutiflora*) covering much of the hillslopes, contains an oil which makes it burn readily. Some fires spread by accident in the process of clearing farmland, others are started on purpose. These bushfires clearly pose a serious problem to people farming in the area and have major implications for farmers' decisions on investing in the planting of trees. Any money and labour invested in the establishment of trees and coffee can be lost overnight following a fire. One person suggested that trees which resprout after scorching (e.g. Beefwood, Milkwood, Red Birch and Plum) could be planted on land which tend to burn frequently.

Most people in the area either own the land they farm, or have a long-term lease (49 years) with the possibility of buying it at the end of the lease. As such they had no hesitations about planting on their farms due to tenure issues.

The few people interviewed who farmed land on a short-term basis were, perhaps understandably, not interested in planting trees on that land.

Some people said that they already had enough trees and that they did not have room for any more, either because their farms were small or because the land was already planted with coffee. There is no tradition of intercropping coffee with timber trees in the area.

One farmer indicated unwillingness to plant trees for security reasons. The farmland was isolated and far away from the homestead. The farmer felt that fruit and other valuable products could easily be stolen.

4.3.4.1.10 SOURCES OF PLANTING MATERIAL

The people interviewed propagate trees using a number of different methods. Most fruit trees were grown from seed, either having been consciously planted or having sprung up from seed which had been discarded when eating fruit. Some farmers had raised fruit tree seedlings in pots and then transplanted them. Non fruit-trees (e.g. *Grevillea*, Black Boy, Tamarind, Soldier Wisp, Bullet, Fig) had also commonly regenerated naturally and been left to grow. Many people reported actively encouraging natural regeneration and then moving the seedlings to a desired location on the farm when they reached the right size.

Another traditional way of obtaining trees is to dig up seedlings from the bush and forest, or, when available, on other farmers' land. People would actively go out and search for seedlings of the more valued trees such as Cedar, Juniper, Mahoe, Soapwood and *Grevillea*.

Christmas trees were obtained in several ways. Some got them from seeds, others collected sprouting seedlings under existing trees, and others again had acquired seedlings from the project nursery at Cinchona.

Trees which root easily are often established by putting a growing stick into the ground. This method is typically used for fencing, using Red Birch, Man-jack, Plum etc.

In spite of the many different traditional ways of regenerating trees, people expressed a clear interest in getting seedlings from nurseries. All the farmers asked would like to have tree seedlings if possible. They would rather pay money for seedlings, especially timber trees, than to use seed or rely on natural regeneration.

Non-timber forest products are widely used by people in the area and they play an important role in the local household economy. Products harvested from the forest are predominantly for subsistence use; few people have, or admitted to having, an income from such products.

The majority of the people consulted in this study were interested in planting trees on their farms. Trees for timber and fruit were considered of the highest, and by some, of sole priority. However, multipurpose trees, with timber and/or fruit being one of the uses, were most popular.

There was limited interest expressed in planting forest species on farmland. The forest species that people did want to plant were: Soapwood, Juniper, Yacca and Bilberry. However, when farmers were asked if they would like to plant trees on their land and if so, which ones, they were not specifically prompted to consider forest trees. It is the feeling of the authors that people did not think about the forest trees as an option since there is little tradition of their propagation and domestication. Given the general interest in planting trees, it is reasonable to assume that farmers would consider native forest trees if they had the opportunity to obtain seedlings and additional knowledge about them.

Local people are generally aware of the restrictions imposed on harvesting from the montane forest and realise that there is a need to develop alternative sources of fuelwood and non-timber building materials. Based on the farmers' opinions about the best trees for timber, fuelwood, fencing, poles and tool handles, promising multipurpose forest species are: Juniper, Soapwood, Mountain Bullet, Rodwood, Yacca, Beefwood, Bitterwood and Black Tea.

The work to develop propagation techniques for several indigenous montane tree species to enable their domestication and incorporation into agroforestry systems (Section 4.4) has great potential providing a farmer participatory approach is taken. There is a need for more extension work and educational and promotional activities in the region.

4.3.4.2 ECOLOGICAL ASSESSMENT OF INDIGENOUS TREES OF THEIR SUITABILITY FOR FARM AND COMMUNITY FORESTRY

From the analyses, species were ranked on their potential suitability for out-planting in farmed situations, on the basis of their availability, growth rate and timber potential (Table 25).
On the basis of the ecological ranking, in combination with the ethnobotanical survey, 25 native montane-forest tree species were selected as having the highest local potential for agroforestry and other forms of reforestation and were included in the species elimination trial.

4.3.4.3 SPECIES ELIMINATION TRIAL

Initial mortalities were low (Table 26). The differences in initial mortalities between species did not correlate well with the ecological characteristics of their natural populations. As expected high rates occurred in the more exposed site in three within-forest species rare in disturbed sites (*Gordonia haematoxylon, Solanum punctulatum* and *Sideroxylon montanum*). However, high mortality rates also occurred in *Vaccinium meridionale* (a notable coloniser of exposed landslides) and *Ilex macfadyenii* (a species abundant in dry and disturbed southern slope forests - its mortality rate was as high in the valley-bottom as the ridge-top).

Mortalities were much higher 12 months after planting (Table 26), primarily as a result of the extreme drought encountered in this, El Nino, year - the worst drought in Jamaica in seventy years. Rainfall in the first six months after planting was only 737 mm, and during the latter six months 1106 mm, making the annual total of 1843 mm well below average. This was also reflected in the seasonality, the total for the minor May wet season was only 49 mm, and the October total was 173 mm. Continued high mortalities were observed amongst those species which had displayed high initial mortalities. In addition, *Guarea glabra*, which is a common understorey plant, showed high mortality, especially on the more exposed site. Common plants of landslides and gaps including *Cyrilla racemiflora* and *Myrica cerifera* also showed high mortality. However, high mortality was also evident in *Cedrela odorata* and *Grevillea robusta* which is surprising given their degree of domestication , particularly so for *Grevillea* which is native to drought-prone regions of Australia. Therefore, interpretation of the later mortalities with respect to ecological niches must be treated with caution, since they can be assumed to be associated with extreme conditions. Nonetheless, it can also be assumed that species capable of surviving these conditions, such as *Turpinia occidentalis, Viburnum alpinum, Juniperus lucayana, Myrsine coriacea* and *Podocarpus urbanii* are particularly robust and well suited to growth in open environments. 20 out of the 26 species planted showed higher mortalities on the ridge-top compared with the valley-bottom site. *Alchornea latifolia* showed high mortality on the exposed site after heavy winds in December 1997 as a result of its poor rooting, which resulted in considerable mechanical damage.

Increments of height and root collar diameter were variable both within and between species (Table 27). However, there was a clear effect on species in all variables measured, but no interaction between species and site. The effect of site was only significant in the height of the seedlings after 12 months (Table 29). The relative rates of diameter increment were similar between seedlings within species as between mature trees in the forest (Tables 25 and 27) in that the faster growing seedlings were also the fastest growing in the forest. This related, in general to their regeneration requirements – pioneers or near-pioneers showing higher rates of production than more shade-tolerant species. There was little relationship between mortality in seedlings and mature trees.

Most species displayed better crown and stem forms in the more sheltered valley-bottom site, but there was little difference in the incidence of damage at either site (Table 28). In the valley-bottom, several of the native species had better crown form than either *Cedrela* or *Grevillea*, notably *Cinammommum, Citharexylum* and *Podocarpus*. With the exception of *Alchornea, Ilex, Lyonia, Myrica, Myrcine, Solanum* and *Viburnum*, all the surviving native species had better stem form than *Grevillea*, and *Cinammommum* and *Gordonia* also had better stem form than *Cedrela* (Table 28).

Plate 8 Some of the wildings used in the establishment of the species elimination trial.

Table 29 Tests of between-subjects effects; HI = height increment, BDI = basal diameter increment.

Source	Dependent variable	Type III sum of squares	df	Mean square	F	Sig.
Corrected Model	HI 6	8644.039	37	233.623	2.482	.000
	BDI 6	4.115	37	.111	2.100	.001
	HI 12	102230.653	37	2762.991	3.527	.000
	BDI 12	47.188	37	1.275	3.236	.000
	HI 42	935867.970	37	25293.729	3.347	.000
	BDI 42	394.219	37	10.655	3.828	.000
Intercept	HI 6	19983.264	1	19983.264	212.261	.000
	BDI 6	9.577	1	9.577	180.794	.000
	HI 12	219449.544	1	219449.544	280.131	.000
	BDI 12	91.600	1	91.600	232.403	.000
	HI 42	2775540.024	1	2775540.024	367.325	.000
	BDI 42	1117.961	1	1117.961	401.705	.000
SITE	HI 6	246.814	1	246.814	2.622	.107
	BDI 6	1.561E-04	1	1.561E-04	.003	.957
	HI 12	12046.504	1	12046.504	15.378	.000
	BDI 12	2.044	1	2.044	5.186	.024
	HI 42	8024.858	1	8024.858	1.062	.304
	BDI 42	4.054	1	4.054	1.457	.229
SPECIES	HI 6	5836.583	22	265.299	2.818	.000
	BDI 6	3.552	22	.161	3.048	.000
	HI 12	52759.774	22	2398.172	3.061	.000
	BDI 12	30.558	22	1.389	3.524	.000
	HI 42	828334.439	22	37651.565	4.983	.000
	BDI 42	339.113	22	15.414	5.539	.000
SITE * SPECIES	HI 6	816.376	14	58.313	.619	.846
	BDI 6	.473	14	3.379E-02	.638	.830
	HI 12	12751.751	14	910.839	1.163	.309
	BDI 12	4.747	14	.339	.860	.603
	HI 42	71037.983	14	5074.142	.672	.799
	BDI 42	52.442	14	3.746	1.346	.187
ERROR	HI 6	14686.584	156	94.145		
	BDI 6	8.263	156	5.297E-02		
	HI 12	122207.661	156	783.382		
	BDI 12	61.486	156	.394		
	HI 42	1178750.184	156	7556.091		
	BDI 42	434.154	156	2.783		
TOTAL	HI 6	71732.576	194			
	BDI 6	35.695	194			
	HI 12	741140.838	194			
	BDI 12	333.328	194			
	HI 42	8464862.131	194			
	BDI 42	3290.258	194			
CORRECTED TOTAL	HI 6	23330.623	193			
	BDI 6	12.379	193			
	HI 12	224438.314	193			
	BDI 12	108.674	193			
	HI 42	2114618.155	193			
	BDI 42	828.372	193			

4.3.5 CONCLUSIONS

Non-timber forest products are widely used by people in the area and they play an important role in the local household economy. Products harvested from the forest are predominantly for subsistence use; few people have, (or admitted to having), an income from such products. The majority of the people consulted in this study were interested in planting trees on their farms. Trees for timber and fruit were considered of the highest, and by some, of sole priority. However, multipurpose trees, with timber and/or fruit being one of the uses, were most popular. There was limited interest expressed in planting forest species on farmland. The forest species that people did want to plant were: *Clethra occidentalis, Podocarpus urbanii* and *Vaccinium meridionale*. However, when farmers were asked if they would like to plant trees on their land and if so, which ones, they were not specifically prompted to consider forest trees. It is the feeling of the authors that people did not think about the forest trees as an option since there is little tradition of their propagation and domestication. Given the general interest in planting trees, it is reasonable to assume that farmers would consider native forest trees if they had the opportunity to obtain seedlings and additional knowledge about them.

Local people are generally aware of the restrictions imposed on harvesting from the montane forest and realise that there is a need to develop alternative sources of fuelwood and non-timber building materials. Based on the farmers' opinions about the best trees for timber, fuelwood, fencing, poles and tool handles, promising multipurpose forest species are*: Juniperus lucayana, Clethra occidentalis, Sideroxylon montanum, Eugenia* spp., *Podocarpus urbanii, Lyonia jamaicensis, Picramnia antidesma* and *Ilex macfadyenii.*

It is common that local people will depend on the local forest resources, not simply because it is habitual or traditional, but more usually because of a lack of alternatives (e.g. Badola, 1998). It is also apparent that they have a wide range of requirements from tree products, many of which could be met by the native forest resource as efficiently as by exotic material, particularly when the opportunity costs of producing native species is offset (Montagnini *et al*., 1995).

There is a pressing need to find a greater range of forestry options in Jamaica. The country was reported to have one of the highest rates of deforestation in the world between 1990-1995 (FAO, 1999). The rate of deforestation is probably unrealistically high, as the high proportion of secondary scrub and woodland would have been included in this figure (Palo & Mery, 1996), but it nevertheless highlights the importance of encouraging use of secondary species as a resource. The secondary forest notwithstanding provides valuable catchment protection and has been shown to restore soil productivity in as short a time as 20 years (McDonald and Healey, 2000).

Taking forward the application of the forestry species selection procedures in this new context, the next step is to test in more detail the species selected from the first trial. Four distinct objectives can be identified for subsequent phases of trials with the most promising species:

(a) further testing of their performance in contrasting environmental conditions;
(b) testing of their performance under contrasting management conditions (the farming systems context provides wide contrasts here, e.g. growing trees in woodlots, in boundary hedges, interplanted with crops (silvo-arable) and with animals (silvopastoral systems));
(c) examining genetic variation within each species to match tree to site;
(d) yield determination.

A judgement about the relative balance between resources and time available should determine the decision about whether to establish large single-stage trials with a complex factorial design to test several of these objectives together, or whether to work through them one at a time. In any event, the serious pressures now affecting many mountain environments create an urgent need for information and researchers must be willing to provide "best-bet" recommendations about species choice (with appropriate words of caution), even if they have not yet reached the stage of scientific certainty.

Land pressures, growing rural populations and environmental degradation have led to marginalisation of farmers on steeplands in the Caribbean and other parts of the tropics. Forest areas are increasingly under threat as a result of these pressures. As a consequence, the establishment of protected areas for forest and biodiversity conservation can potentially further marginalise hillside farmers by restricting the practice of shifting cultivation. Together, these factors have created an urgent need to find sustainable methods of hillside farming. In the Caribbean, there is a wide consensus amongst land-use professionals that the only environmentally, economically and socially acceptable means to achieve this is by intensified agricultural systems including tree crops.

Agroforestry projects in Jamaica and the Caribbean have identified a reluctance on the part of most farmers to plant indigenous trees as they are unknown to them (the current populations are relative new-comers to most islands in the Caribbean). This identifies the need to demonstrate the usefulness of indigenous forest tree species and their potential within local farming systems.

Furthermore, in the Jamaican Blue Mountains, the native biodiversity has been seriously eroded by the introduction and subsequent spread of exotic plant species. Areas originally cleared for agricultural production and subsequently abandoned are now largely dominated by either a stoloniferous grass, *Melinis minutoflora* Beauv., or a scrambling herb, *Polygonum chinense* L. The presence of *Melinis* is particularly problematic as it forms a highly flammable sward that burns on a regular basis, preventing both the restoration of soil productivity and tree establishment.

Therefore, a species elimination trial was undertaken which would grow up to 25 different forest tree species on open mountain slopes to establish which perform well in open conditions, have form and canopies amenable to incorporation into agroforestry systems and to eliminate those that cannot withstand the exposed conditions outwith the forest environment. Species selection was made on the basis of an ethno-botanical survey of local farmers, (which was reported in full as Appendix 1 of the 1996-1997 project annual report), combined with existing ecological knowledge (and availability of planting material).

4.4 PROVENANCE EVALUATION OF *Calliandra calothyrsus* Meissner

4.4.1 SUMMARY

Forested land cleared for agriculture in the Blue Mountains of Jamaica rapidly loses its productivity leading to further slash-and-burn cultivation and the degradation of more forest. Contour hedgerows of *Calliandra calothyrsus* Meissner have been shown to reduce water runoff and soil erosion, and products of the species have a wide range of uses in the local farming community. A trial was established at 1550 m in which the locally naturalised population of *C. calothyrsus* was compared with seven provenances from across the species' ecological range. There was considerable variation between provenances of *C. calothyrsus* in all the above-ground growth variables measured and, although the local provenance performed moderately well, it was clear that there is potential to improve the suitability of the species for a range of local uses by the introduction of new provenances. One provenance combined high above-ground productivity with low fine root-length density, especially in the inter-hedgerow area: it offers particular potential for use in simultaneous agroforestry systems providing wood and foliage products whilst not imposing high levels of competition with crop plants for below-ground resources. Although there were significant differences between provenances in the distribution of roots between the hedgerow and inter-row areas, they did not differ in the distribution of roots between soil depths. There were only limited differences between provenances in the response of their subsequent growth to harvesting. However, significant block x provenance interactions suggested that the performance of *C. calothyrsus* provenances may be difficult to predict between sites and farmers should be encouraged to carry out trial planting of a number of provenances to find those which best match their farm environment and needs.

OBJECTIVES

Purpose 3: To prepare an inventory of locally suitable species for contour hedgerow systems, and produce guidelines for each

To compare the relative productivity of the local provenance of *Calliandra calothyrsus* with a variety of other seedlots collected from climatically similar regions, with a view to potential selection of an improved seedlot for promotion of the use of the species in contour hedgerow systems.

4.4.2 INTRODUCTION

The Blue Mountains are a geologically recent tropical mountain range, characterised topographically by steep slopes and highly dissected terrain; the soils are generally poorly-developed. The natural vegetation is montane tropical rain forest (Shreve, 1914). There is a long history of forest conversion, most recently for two major land uses - cash crop cultivation by small farmers and the establishment of commercial coffee plantations (Eyre, 1987). The soils are stony because of rapid weathering of the sub-soil, and the erosive loss of fine soil particles results in low sustainability of agricultural production. This, together with land tenure difficulties and the loss of tree cover from settled areas, is leading to continuing degradation of the remaining natural forest, especially through slash-and-burn agriculture. Despite the problems, it is generally accepted that cultivation will continue on many areas of sloping land because of the high population density and lack of opportunity to participate in other forms of economic activity. It is therefore necessary to find ways of making such cultivation sustainable and environmentally acceptable. Since the control of soil erosion is only one aspect of soil conservation, in practical development planning it should not be treated in isolation but integrated with the maintenance of soil fertility, water availability and other aspects of agricultural improvement. Given the potentially valuable roles of trees in both control of soil erosion and maintenance of soil fertility, as well as diversification of products, agroforestry could play an important role in the improvement of the current agricultural practice. Young (1997) suggests that the greatest need for agroforestry lies in such densely-populated steeplands of the humid and sub-humid tropics.

A growing number of experiments have shown the role of contour hedgerows in reducing runoff and soil erosion in steeplands (Young, 1997; Riha and McIntyre, 1999). These results have been confirmed in the Blue Mountains of Jamaica by Healey *et al*. (1998) who showed that on steep slopes the conversion of secondary forest to agriculture did result in increased surface-water runoff and erosion, but that these were reduced by the incorporation of a contour hedgerow system with the tree species *Calliandra calothyrsus* Meissner. Both the researchers and the participating farmers concluded that *C. calothyrsus* was technically suitable for a contour-hedgerow agroforestry system in this mountain environment.

C. calothyrsus is a leguminous tree species native to Central America and Mexico. It has been introduced and become naturalised throughout the tropics, where it is extensively used for multiple purposes including improvement of soil fertility (especially as a green manure), control of soil erosion, and production of fuelwood, fodder and honey. Jamaica has four native species of *Calliandra* (including three endemics) (Adams, 1972). *C. calothyrsus* is an exotic that became locally naturalised in disturbed areas with open vegetation in the Jamaican Blue Mountains in the 1980s having spread from the sites of a Forestry Department species trial. However, it has not been observed to invade natural forest. A formal ethnobotanical survey showed that it has already become popular with the local farming community for a wide range of uses, including shade, fuelwood, posts/poles, and erosion control (Collins and McDonald, 1997). In further discussions, local farmers also cited the use of *C. calothyrsus* for green manure, fodder and honey production, and indicated that the species is valued for its diversity of uses rather than for any single dominant use. The potential use of *C. calothyrsus* for fodder production in silvopastoral agroforestry systems in dry lowland (150 m) and moist mid-altitude (500 m) sites in the north of Jamaica has been researched by Morikawa *et al.* (1995) and Roshetko *et al.* (1996).

Considerable genetic variation has been observed in *C. calothyrsus*, manifested in morphologically and ecologically distinct populations (Chamberlain, 1998). However, the naturalised population of *C. calothyrsus* in Jamaica is believed to have a narrow genetic base, being derived from the introduction of a very limited number of seedlots from Indonesia (D. Thompson, *pers. comm*.). This may in the future limit the real potential of the species because of problems with insect pests or pathogens (MacQueen, 1993) and a lack of capacity to select the genetic material most suited to the environment and to farmers' needs. Accordingly, a trial of provenances was established in the Blue Mountains in conjunction with the Oxford Forestry Institute (OFI) and following the design of their network (MacQueen, 1993). The first objective was to compare the relative productivity of the local provenance of *C. calothyrsus* with a range of provenances from climatically similar regions. The results would inform a decision as to whether the introduction of new provenance(s) is justified before the species is promoted to farmers for use in agroforestry systems.

Provenance selection in agroforestry is a more complex process than in conventional plantation forestry (Huxley, 1985; Owino, 1996). The multiple purposes for which people grow agroforestry trees indicate a wide range of different character traits (attributes) by which provenances should be selected. These attributes will vary in their relative importance to the farmer, the extent to which their values (levels/states) are affected by the site environment and by management, and the extent to which their values are associated with the values of other attributes (or are independent of them). The second objective of the study was to determine for each of these attributes the proportion of the variation in its value that was accounted for by differences between provenances; differences between environments (experimental blocks); the interaction between provenance and environment; and the residual variation between trees within each provenance and environment. This will indicate for which attributes provenance selection offers good potential for obtaining trees with desirable characteristics; which attributes are most inherently variable among farm sites irrespective of provenance; which attributes are most dependent on the matching of provenance to farm site; and which attributes are most inherently variable irrespective of farm site and the provenance of the planting material.

The third objective of the study was to determine for which attributes phenotypic variation between provenances was positively or negatively correlated. This will indicate which combinations of desirable traits can most readily be achieved by provenance selection in *C. calothyrsus*. There is particular interest in the extent to which the provenances' above-ground growth rates were positively correlated with their root system development; Cannell (1985) pointed out that within-species variation in root/shoot relationships may offer important opportunities for genetic advance in yield. In addition, measurement of the growth rates of the trees over successive periods, and before and after the trees are cut back for harvesting of wood and foliage, will provide an indication of the extent to which the relative performances of the different provenances are maintained over time and are affected by cutting.

4.4.3 MATERIALS AND METHODS

The study was conducted in the valley of the Green River, a tributary of the Yallahs River, in the region of Cinchona, Westphalia, Upper St. Andrew, Jamaica (Table 30). The Yallahs is the largest river on the more populous southern slopes of the Blue Mountains and its basin as a whole has a high natural propensity for erosion (McGregor *et al.*, 1985). The study site was near to the top of an exposed ridge and variable in slope aspect and angle. The soil was typical of the lithic phase Chromic and Eutric Cambisols reported for this area (FAO-UNESCO, 1975; equivalent to Xerochrept and Cryochrept Inceptisols in the USDA soil-classification system), with a sandy loam texture, free drainage and a pH of 5.4 (Table 30). The site was covered in weedy vegetation dominated by the exotic grass species *Melinis minutiflora* Beauv. Previously the original forest vegetation had been cleared and at least one cycle of slash-and-burn agriculture carried out.

Of the 66 provenances of six species from the genus *Calliandra* acquired by OFI between 1990 and 1993 (Pottinger, 1996), a random set of 14 provenances of *C. calothyrsus* from climatically similar regions to the study site were selected for comparison with the *C. calothyrsus* now naturalised in the study area (Table 31). At Cinchona Botanic Garden seeds from the 15 different provenances were mechanically scarified and *Rhizobium* applied in 1 ml of a solution of one part sugar with two parts water per 50 g of seed. Seeds were placed in black plastic potting bags (7 x 12 cm) with drainage holes in the base in a medium of two parts clayey soil: one part sand. Two seeds per pot were placed in 1-cm deep holes, and second germinants were pricked out into another pot as soon as their first adult leaves showed. The pots were placed under 50% shade, and moved into the open after three months. The number of live germinants of each provenance were counted (reflecting the net results of germination and subsequent seedling survival) and their vigour asessed after 6 and 16 weeks. To select seven OFI provenances for out-planting together with the local provenance, provenances 57/93 and 58/93 were rejected because of their low germination rates, then six others were rejected because of the low health and vigour of their surviving seedlings (Table 32).

The field experiment had a single tree-line planting design along the contour with six trees per row and two rows per plot (giving two border trees at the end of each row, but no border rows). The intra- and inter-row spacings were 0.5 m and 3 m respectively, giving a density of 6400 trees ha^{-1}. Five blocks of plots were established on one farm with an average separation of 9 m between blocks. In order to control for the topographic variability of the site, the blocks were located in positions differing in slope-angle and aspect. In a balanced design, each block contained one plot of each provenance. Out-planting took place on 30 April 1996, when the seedlings were less than 30 cm in height. The farmer grew plants of thyme (*Thymus vulgaris*) and lettuce (*Lactuca sativa*) between the *C. calothyrsus* plants with weeding but minimal cultivation. This management was expected to have a minimal impact on the trees.

A number of measurable attributes were selected which corresponded to the wide range of uses for *C. calothyrsus* that had been identified by local people. Six months after establishment, in October 1996, the following variables were measured on the inner two plants in both rows of each plot: height from ground level to the highest point (using a graduated pole); root collar diameter (using calipers); the number of upwardly-growing stems, originating between the root collar and 0.3 m from the ground; flowering status (no flowers; buds; buds and flowers; dead buds). Twelve months after planting, in April 1997, these measurements were repeated on the same plants, plus observations of fruiting (no pods; immature pods; mature pods; dry empty pods; mixture of pods).

In April 1997, after measurement, all the trees were cut back to 50 cm with a small saw. The material cut from each tree was divided into leafy (non-lignified leaves and branches) and woody (lignified stem) material. Total fresh weight for each tree was recorded with a field balance, and sub-samples of c. 200 g fresh weight of both leafy and woody material for each tree were removed for laboratory moisture content analyses in order to obtain a fresh weight – dry weight conversion factor. Soil cores were collected for root analyses using a corer of 3 cm diameter to depths of 0-15 cm and 15-30 cm. Three cores were collected from random positions along the centre of the tree row and three from random positions along the centre of the inter-row in each plot in three of the blocks. The cores were washed with an automated root washer and the roots stored in 50% ethanol. Roots of *C. calothyrsus* were subsequently sorted from weed and crop roots in a total of 199 of the core samples which were selected to provide a balanced representation of block, provenance, sampling position and depth. Fine root length densities (of roots < 2 mm in diameter) were estimated using a modified line intersect method (Tennant, 1975). Sorted samples were dried and weighed.

Eighteen months after planting, in October 1997, measurements of height, root collar diameter, and stem number were recorded on the same trees as earlier. All the trees were again cut back to 50 cm and the biomass production recorded.

All data were subjected to analyses of variance with a random effects model using the general linear model procedure in Minitab for Windows Release 12.1. Root collar diameter, height, biomass and root variables were log_{10}-transformed and number of stems square root-transformed before analysis. Correlations between the provenance mean values for all pairs of variables were also calculated using Minitab. Overall provenance mean values (for all blocks combined) were used for this analysis as the experimental design was balanced, and variation between provenances generally exceeded variation between the experimental blocks.

Table 30 Environmental characteristics of the study site near Cinchona in the Green River Valley, Blue Mountains, Jamaica: a) location and climate, b) soil properties (0–10 cm depth).

a) Location and climate[1]

Latitude and longitude	Elevation	Mean annual rainfall	Mean annual temperature
18^o 04' N and 76^o 39' W	1550 m a.m.s.l.	2180 mm	16.0 ^{o}C

b) Soils

	Total (g kg^{-1})			Exchangeable (Cmol kg^{-1})				Particle size composition (%)		
PH[2]	N	P	C	Ca	Mg	K	Na	Sand (60-2000 μm)	Silt (2-60 μm)	Clay (< 2 μm)
5.38	2.2	0.9	32.9	2.46	1.37	0.53	0.40	50.45	19.75	19.15

[1] Climatic data are from the nearby Cinchona meteorological station (at 1525 m), where there is a continuous record since 1901 (Jamaica Meteorological Service, unpublished data). Annual total rainfall and its seasonal pattern are highly variable between years. The distribution tends to be bimodal: the major wet period usually occurs in October and November and a minor wet period in May. However, the seasonality is not strong: the longest dry period since 1901 was three months (<50 mm rainfall) and the average maximum length of dry period per year was 1.4 months.

[2] 1:2.5 water

Table 31 Seed sources of 15 provenances of *Calliandra calothyrsus* tested in a trial at Cinchona, Jamaica.

Provenance seedlot code	Location	Country	Latitude	Longitude	Altitude (m)	Mean annual rainfall (mm)	Mean annual temperature (^{o}C)
Local[1]	St. Andrew	Jamaica	18 ^{o} 04' N	76 ^{o} 39' W	1550	2180	16.0
49/93	Trujillo	Honduras	15 ^{o} 51' N	85 ^{o} 49' W	50	2715	26.7
17/91	La Ceiba	Honduras	15 ^{o} 43' N	86 ^{o} 50' W	80	2884	26.74
9/91	Patulul	Guatemala	14 ^{o} 24' N	91 ^{o} 09' W	330	3185	26.06
53/92	Santa Maria	Honduras	14 ^{o} 07' N	86 ^{o} 12' W	500	1145	24.28
46/93	Lago Yojoa	Honduras	14 ^{o} 39' N	87 ^{o} 53' W	550	2596	21.8
10/91	Flores	Guatemala	16 ^{o} 55' N	89 ^{o} 52' W	220	1994	25.05
62/92	Bonampak	Mexico	16 ^{o} 50' N	91 ^{o} 16' W	400	2156	26.4
44/92	Plan del Rio	Mexico	19 ^{o} 27' N	96 ^{o} 47' W	240	1957	18.9
46/92	Gracie Rock	Belize	17 ^{o} 16' N	88 ^{o} 34' W	90	2313	24.96
11/91	San Romon	Nicaragua	12 ^{o} 54' N	85 ^{o} 48' W	850	1394	22.4
108/94	Fortuna	Costa Rica	10 ^{o} 30' N	84 ^{o} 48' W	not known	not known	not known
147/91	Maduin	Indonesia	7 ^{o} 3 6' S	111 ^{o} 30' E	800	1884	26.1
58/93	Salitrales	Costa Rica	9 ^{o} 48' N	84 ^{o} 25' W	900	2146	24.9
57/93	San Isidro del General	Costa Rica	9 ^{o} 21' N	83 ^{o} 41' W	700	2951	22.8

[1] The local provenance is from a location very close to the trial site used in this study.

4.4.4 RESULTS

4.4.4.1GERMINATION

There was considerable variation between provenances in their seed dormancy period, thus, whilst the local provenance had reached its maximum germination percentage after six weeks, seeds of other provenances, such as 49/93 continued to germinate up to the 16-week census (Table 32). Therefore, the change in number of seedlings recorded for each provenance between the two census dates reflected the combined effects of survival of the previously germinated seedlings and new seed germination. The local provenance had the highest total germination rate, though c. 25% of these seedlings died between 6 and 16 weeks, by when it was second equal in rank order of seedling number amongst the provenances (Table 32). At 16 weeks, the mean number of seedlings alive amongst the provenances was 57% of the numbers of seeds sown, with a range between 11.5 and 81.0%.

Table 32 Seed germination and early seedling survival of 15 *Calliandra calothyrsus* provenances in a trial at Cinchona, Jamaica.

Provenance seedlot code	Number of seeds sown 22/11/95	Number of seedlings alive (% of seeds sown) 3/1/96	Number of seedlings alive (% of seeds sown) 13/3/96
LOCAL [1]	*240*	*97.1*	*72.9*
49/93	*240*	*70.8*	*81.0*
17/91	*240*	*75.0*	*72.5*
9/91	*240*	*69.2*	*64.6*
53/92	*240*	*75.8*	*60.8*
46/93	*240*	*70.0*	*60.0*
10/91	*240*	*54.2*	*60.0*
62/92	*240*	*47.9*	*47.9*
44/92	240	63.3	67.9
46/92	240	54.6	55.8
11/91	240	57.1	55.0
108/94	240	72.9	55.0
147/91	240	30.4	45.8
58/93	110	45.5	42.0
57/93	120	21.7	11.5

[1] Values in italics are the eight provenances selected for the growth trial.

Plate 9 A *Calliandra calothyrsus* provenance trial was established on the farm of Mr Roy Bryan.

4.4.4.2 EFFECTS OF BLOCK AND PROVENANCE ON GROWTH VARIABLES

There was a significant effect of block and of provenance on all variables measured except root length and mass densities (Table 33). The interaction between block and provenance was significant for all variables except the number of stems at 12 and 18 months. The amount of variation attributable to provenance was usually higher than that to block: this was particularly clear for the number of stems and for height and root collar diameter at 12 and 18 months. However, block and provenance accounted for similar amounts of variation in leafy and woody biomass at 12 and 18 months.

The proportion of variation attributable to trees within provenances varied between 20 and 46%. It was high for number of stems (>40%) and lowest (<30%) for height and root collar diameter (Table 33). There was a notable increase in the proportion of variation attributable to trees within provenances for leafy and woody biomass from the 12 to the 18 month harvest. As expected, root length and mass densities showed a high degree of between sample variability (c. 65% of variation (Table 33), of which less than 3% was attributable to depth and less than 10% to position). The percentage of the variation attributable to the block x provenance interaction for all variables was in the range 11-26%.

The significant block x provenance interactions indicated that the patterns of variation in growth between provenances varied between environments. However, inspection of the provenance means within blocks revealed that there were some general trends in the performance of the provenances which held across blocks.

At 6 months, provenance 46/93 had the lowest root collar diameter in all five blocks (Figure 11) and lowest height in two of the five blocks (and had the second lowest height in the other three). Provenances 62/92, 53/92 and 49/93 had the largest root collar diameters and heights overall (Figures 11 and 12), although 53/92 and 49/93 each performed relatively poorly in blocks 3 and 1 respectively. Provenances 62/92 and 53/92 had the largest root collar diameters again at 12 months, while for height, 10/91 had the highest overall mean and was the highest ranked in three of the five blocks. Provenance 46/93 had the smallest root collar diameter in all blocks and again the lowest height in two blocks. At 18 months, six months after the trees were cut back, provenances 62/92 and 53/92 remained amongst the higher-ranked provenances for root collar diameter and also for height, although provenance 9/91 and the local provenance now had higher overall means for height. Provenances 46/93 and 17/91 had the smallest means for root collar diameter and height respectively.

The relationship between number of stems and height or root collar diameter varied markedly between provenances: of the two provenances with the lowest heights and root collar diameters, one (17/91) had the largest number of stems throughout the measurement period while the other (46/93) had the smallest (Figure 13). The provenance with the second largest number of stems throughout, 49/93, also had a spreading growth form, producing stems that initially grew horizontally over the soil surface. Local farmers considered that this habit made the provenance unacceptable for hedgerow agroforestry because it occupied too much of the growing area for crops.

The patterns in height and root collar diameter were broadly repeated for harvested biomass at 12 and 18 months (Figure 14). Provenance 46/93 had the lowest leafy and woody biomass at both 12 and 18 months and provenances 53/92, 9/91 and 62/92 had the highest.

There was no significant effect of provenance on root length density or root mass density, although there were significant block x provenance interactions (tested against the much lower between-core error term mean square values under the random-effects model) and between block differences in root length density (Table 33; Figure 15). No provenance had a consistently high root length density among blocks, but 46/93 was fairly consistently low: it was eighth in rank in two blocks and sixth in the third, in line with its low values of above-ground growth variables.

The soil cores collected within the tree rows had significantly greater mean root length density (63.4% of the total) and mean root mass density (63.1% of the total) than those between the rows (36.6% and 36.9% respectively) ($P < 0.001$). The interaction between this position factor and provenance was also significant ($P < 0.05$ for root length density and $P < 0.01$ for root mass density): mean root length density in the cores between the tree rows varied from 33% higher than those in the within-row cores in provenance 9/91 to 63% lower in 46/93 (Figure 15). The variation in root distribution between provenances was not strongly related to their overall mean root length densities: relatively low root length densities in the between tree-row cores were found in provenances with both high (e.g. 10/91) and low (e.g. 46/93) overall mean values.

Overall sampled root length densities were significantly greater at 0-15 cm depth (57.0%) than at 15-30 cm (43.0%) ($P < 0.01$), although for root mass density the difference was not significant ($P = 0.094$). There was no evidence of any interaction between provenance and depth ($P > 0.7$) and no significant interaction between position and depth.

Although some changes in the ranking of provenances occurred for variables that were measured repeatedly over the course of the 18 month monitoring period, overall 46/93 was found to be consistently the slowest-growing provenance while 62/92 and 53/92 were consistently amongst the group growing faster above ground. The local provenance and 9/91 increased their ranking relative to other provenances with time (especially after the trees were cut back at 12 months), while 17/91 declined from its position as a middle ranking provenance at 6 months to become the second-slowest growing provenance by 18 months (again its relative decline accelerated after the harvesting).

Flowering trees were observed in all the provenances by 6 months with no significant differences between them in the percentage of trees flowering (33 to 68%) (Figure 16). At 12 months, however, there was significant variation among provenances in fruiting (Figure 17); 46/93 and 10/91 had not produced any pods, four provenances had pods on between 5 and 35% of their trees, while 47% of 49/93 trees had pods at various stages of development as did 72% of 17/91. To some extent this corresponded with their state of flowering at 6 months, when no flower buds of 46/93 had yet opened and 17/91 had the highest percentage of trees with open flowers. However, the incidence of flowers did not necessarily result in the production of seeds, e.g. for 9/91 and 10/91.

Table 3. Percentage of the variation in growth attributes accounted for by block, provenance, block x provenance interaction and trees within provenance, and the significance of each effect in the general linear model in a *Calliandra calothyrsus* provenance trial in the Blue Mountains, Jamaica.

Character	Block (%)	Provenance (%)	Block x provenance (%)	Trees within provenance[1] (%)
6 months				
Height	24.5***[2]	26.8**	19.2***	29.5
Root collar diameter	32.4***	29.5***	13.5***	24.7
Number of stems	9.5*	22.1*	23.5**	44.9
12 months				
Height	18.5**	31.8**	21.4***	28.3
Root collar diameter	17.6***	38.2***	17.9***	26.3
Number of stems	7.6**	38.2***	11.3 NS	42.8
Leafy biomass	27.3***	32.4***	12.7**	27.9
Woody biomass	28.2***	20.0**	18.7***	29.2
Fine root length density	12.0*	7.8 NS	16.4***	63.8
Fine root mass density	5.9 NS	12.6 NS	18.3***	63.2
18 months				
Height	18.6***	49.8***	11.2***	20.4
Root collar diameter	10.2*	35.5**	25.3***	29.0
Number of stems	4.3 NS	35.0***	15.1 NS	45.7
Leafy biomass	17.7**	16.1*	21.0**	45.2
Woody biomass	20.1***	19.8*	21.8***	38.4

[1] For the root variables, this column indicates variation between the root cores within each plot.
[2] *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS $P > 0.05$.

Figure 11 Mean root collar diameter of eight provenances of *Calliandra calothyrsus* at 6, 12 and 18 months in a provenance trial in the Blue Mountains, Jamaica. Vertical bars show standard errors of the difference between provenance means on each recording occasion.

Figure 12 Mean height of eight provenances of *Calliandra calothyrsus* at 6, 12 and 18 months in a provenance trial in the Blue Mountains, Jamaica. Vertical bars show standard errors of the difference between provenance means on each recording occasion.

Figure 13 Mean number of stems in eight provenances of *Calliandra calothyrsus* at 6, 12 and 18 months in a provenance trial in the Blue Mountains, Jamaica. Vertical bars show standard errors of the difference between provenance means on each recording occasion.

a)

b)

Figure 14 Mean biomass of eight provenances of *Calliandra calothyrsus* at a) 12 and b) 18 months in a provenance trial in the Blue Mountains, Jamaica. Vertical bars show standard errors of the difference between provenance means: lower bars refer to woody biomass and upper bars to leafy biomass.

Figure 15 Mean a) fine root length density and b) fine root mass density in cores taken within tree rows and between tree rows of eight provenances of *Calliandra calothyrsus* at 12 months in a provenance trial in the Blue Mountains, Jamaica. Vertical bars show standard errors of the difference between provenance total mean values.

Figure 16 Incidence of flowering in eight provenances of *Calliandra calothyrsus* at 6 months in a provenance trial in the Blue Mountains, Jamaica (means and standard errors).

Figure 17 Incidence of fruiting in eight provenances of *Calliandra calothyrsus* at 12 months in a provenance trial in the Blue Mountains, Jamaica (means and standard errors).

4.4.4.3 CORRELATIONS BETWEEN VARIABLES

Provenance means for each of the above variables were used to construct a correlation matrix: root collar diameter and stem number after 6 months were expressed as the increment during each of the two subsequent measurement intervals; height was expressed as increment between 6 and 12 months, and absolute height at 18 months (6 months after all the trees were cut back to 50 cm height) (Table 34). In assessing these results it is important to bear in mind that *circa* seven of the 136 combinations could be expected to be significantly correlated by chance.

Root collar diameter at 6 months was positively correlated with the increment in root collar diameter between 6 and 12 months, the increment in the number of stems during the same period and with the harvested leafy and woody biomass at 12 months. It was not significantly correlated with any of the 12-18 months increments or 18 month harvested biomass measurements, however. Height at 6 months was also positively correlated with the increment in the number of stems between 6 and 12 months and with the harvested woody biomass at 12 months. Height increment between 6 and 12 months was positively correlated with the leafy biomass harvested at 12 months.

The number of stems at 6 months was significantly positively correlated with the increment in the number of stems following cutting at 12 months, but negatively correlated with the height that the trees had regrown to at 18 months. This suggests that provenances that produce more stems on undamaged trees respond to cutting by continuing to allocate biomass to stem production rather than height growth. The increment in root collar diameter between 6 and 12 months was positively correlated with the increment in the same variable between 12 and 18 months and with leafy and woody biomass at both 12 and 18 months.

Root collar diameter increment before cutting (6 to 12 months) was significantly positively correlated with root collar diameter increment after cutting (12 to 18 months). In addition, height increment between 6 and 12 months was positively correlated with the height that the trees regrew to by 18 months (6 months after harvesting). The harvested biomasses were, as expected, especially positively correlated with the preceding root collar diameter increments. Woody and leafy biomass were highly positively correlated with each other (there was no evidence of any variation between provenances in their partitioning of biomass between woody stem and leaf tissue). Biomass at 18 months was also positively correlated with increment in root collar diameter between 6 and 12 months and biomass harvested in the first cut at 12 months. This indicates that those provenances that had the fastest growth rates before cutting were also generally best able to regrow following cutting. Furthermore, those provenances whose biomass was allocated more to height or to diameter growth appeared to conserve this trait following cutting.

The percentage of trees flowering at 6 months was not significantly correlated with any other variable, and the correlation coefficient between incidence of flowering and fruiting was only 0.562. The percentage of trees fruiting at 12 months was, however, positively correlated with both the number of stems at 6 months, and the increment in the number of stems between 6 and 12 months. Thus, there was a tendency for the more multiple-stemmed provenances to have a higher incidence of early fruiting.

Root length and mass densities (at 12 months) were significantly positively correlated with both the leafy and woody biomasses at 12 months and with the increment in height during the preceding 6-12 month period. This indicates that the provenances growing faster above ground also had a higher root growth per unit soil volume.

4.4.5 DISCUSSION AND CONCLUSIONS

4.4.5.1 COMPARISON OF LOCAL WITH OTHER PROVENANCES

Considering its uncertain origin, the locally naturalised provenance of *C. calothyrsus*, derived from seed collected in Indonesia, performed fairly well in comparison with the seven other provenances selected from parts of the species' native range with a similar climate to the study site in the Jamaican Blue Mountains. It was second in rank in germination and early seedling survival, and plant height at 18 months, and fourth in root collar diameter and woody biomass at 18 months. However, its rate of stem production, leafy biomass, root length and mass densities and flowering and fruit production were below average. It was one of the provenances that responded most positively to cutting in terms of subsequent height growth and biomass production. However, the total biomass production at 18 months of the fastest growing provenance, 53/92, exceeded that of the local provenance by 32%. Other provenances may have value for specific uses: although the biomass production of provenance 49/93 was only average, its observed spreading growth form may make it suitable for reclamation forestry, where the objective is to maximise soil cover and organic matter input to the soil by trapping litter and minimise erosion. However this growth form makes it unsuitable for hedgerow agroforestry. Therefore, there is the potential to improve the suitability of *C. calothyrsus* for the range of local uses by the introduction of new provenances and their promotion in place of the local naturalised provenance.

Table 34 Correlations between variables in a *Calliandra calothyrsus* provenance trial in the Blue Mountains, Jamaica. Coefficients significant at $P < 0.05$ are indicated in bold: critical values are 0.71 (P=0.05), 0.83 (P=0.01) and 0.93 (P=0.001).

	root collar diam. 6 months	height 6 months	no. stems 6 months	incr. diam. 6-12 months	incr. height 6-12 months	incr. no. stems 6-12 months	incr. diam. 12-18 months	incr. no. stems 12-18 months	height 18 months	leafy biomass 12 months	woody biomass 12 months	leafy biomass 18 months	woody biomass 18 months	flowering 6 months	fruiting 12 months	fine root length dens. 12 months
height 6 months	**0.88**															
no. stems 6 months	0.36	0.26														
incr. diam. 6-12 months	**0.81**	0.63	-0.02													
incr. height 6-12 months	0.27	0.29	-0.52	0.56												
incr. no. stems 6-12 months	**0.89**	**0.71**	0.67	0.66	-0.03											
incr. diam. 12-18 months	0.62	0.42	-0.21	**0.82**	0.32	0.47										
incr. no. stems 12-18 months	0.27	0.29	**0.84**	0.05	-0.48	0.53	-0.06									
height 18 months	0.13	0.05	**-0.76**	0.55	**0.80**	-0.21	0.61	-0.60								
leafy biomass 12 months	**0.77**	0.68	-0.12	**0.97**	**0.71**	0.58	**0.75**	-0.03	0.61							
woody biomass 12 months	**0.85**	**0.80**	0.02	**0.93**	0.66	0.67	0.67	0.10	0.47	**0.98**						
leafy biomass 18 months	0.60	0.52	-0.31	**0.90**	0.53	0.39	**0.88**	-0.03	0.68	**0.89**	**0.82**					
woody biomass 18 months	0.61	0.45	-0.25	**0.91**	0.58	0.42	**0.92**	-0.03	**0.74**	**0.89**	**0.82**	**0.96**				
flowering 6 months	0.52	0.68	0.34	0.45	-0.03	0.47	0.26	0.66	-0.11	0.44	0.54	0.50	0.36			
fruiting 12 months	0.41	0.31	**0.82**	0.20	-0.59	**0.72**	0.13	**0.85**	-0.64	0.06	0.15	0.07	0.03	0.56		
fine root length dens. 12 months	0.51	0.55	-0.21	0.65	**0.93**	0.26	0.32	-0.20	0.62	**0.79**	**0.81**	0.53	0.59	0.18	-0.34	
fine root mass dens. 12 months	0.56	0.63	-0.26	0.61	**0.89**	0.23	0.34	-0.27	0.63	**0.75**	**0.78**	0.51	0.56	0.18	-0.41	**0.97**

Subsequent research on the genetic diversity of seed collected from a number of locations in Jamaica indicates that the naturalised population shows considerable genetic diversity - more diverse than many of the natural populations in the native range of the species in Mexico and Central America (Chamberlain and Hubert, in press). Thus, a general recommendation is that provenance trials of national populations of *C. calothyrsus* should be conducted in conjunction with the introduction of any non-naturalised germplasm.

4.4.5.2 SOURCES OF VARIATION

Variation between *C. calothyrsus* provenances was significant for all of the measured above-ground attributes and was the biggest source of variation above the between-tree level for most of them, which was also the finding of Duguma and Mollet (1998). However, the present study found that a surprisingly high proportion of variation was accounted for by variation between the experimental blocks, despite their close proximity. For harvested biomass, this was as great as the proportion of variation accounted for by provenance. Duguma and Mollet (1998) only found a significant difference between their two sites, which had contrasting soil types (one had a pH range of 5.5–6.0 and the other of 4.4–4.5), for plant height at two intermediate measurement dates and for pod development. The variation in *C. calothyrsus* growth between blocks in the present study can best be explained by its ridge-top site, which led to marked environmental differences between the blocks in aspect, slope angle and exposure, though there could also have been undetected variation in previous land use within the site.

The significant block x provenance interactions observed throughout this trial indicate that the performance of *C. calothyrsus* provenances between environments may be difficult to predict. Duguma and Mollet (1998) also found provenance x environment interactions for height and stem diameter, but not for the other attributes measured, including stem number (as was the case in the present study). Variation in relative provenance performance between more contrasting environments (lowland Cameroon and montane Jamaica) can be assessed for the three provenances that were tested both by Dugama and Mollet (1998) and in the present study. In Cameroon, 53/92 was one of the least productive provenances, 62/92 of average productivity and 10/91 one of the most productive. However, in Jamaica the sequence was reversed, e.g. for total biomass at 18 months 53/92 was the most productive provenance, 62/92 third and 10/91 sixth out of the eight provenances tested. Together these results indicate that promotion of *C. calothyrsus* to farmers should not concentrate on a single provenance, but instead should encourage farmers to carry out trial planting of a number of provenances to determine which best match the environmental conditions on their land.

4.4.5.3 CORRELATIONS BETWEEN VARIABLES

Positive correlations between different attributes reflected many of the functional linkages in plant growth and development. Provenance mean values for incidence of fruiting were correlated with number of stems. Harvested biomass was correlated with previous diameter growth increment (but less so with height, particularly for leafy biomass). At 6 months there was a significant correlation between provenance mean height and diameter, but after that provenances showed considerable variation in their ratios of height to diameter growth. This offers farmers the potential to select provenances according to the relative value of harvesting longer poles *versus* volume of fuelwood. Leafy biomass was well correlated with woody biomass, especially at the 12-month harvest. By 18 months, provenance mean leafy to woody biomass ratio had started to vary from 1.12:1 (local) to 1.63:1 (46/93, the least productive provenance). Whilst there may be little interest in provenances that maintain low overall productivity, if this trend continues, it offers farmers the potential to select provenances according to the relative value of harvesting fodder and green manure *versus* wood products. Cannell (1985) found considerable variation among forest stands in the proportion of the above-ground dry matter increment allocated to wood, as opposed to foliage. However he concluded overall that foliage and wood production are closely coupled.

Although analysis of variance did not indicate any significant effects of provenance on the below-ground variables recorded, they were positively correlated with height growth and leafy and woody biomass over the same period. Six of the provenances showed a good correspondence in their rank positions for above-ground productivity and for below-ground productivity (Figures 14 and 15). However, two provenances showed an inverse relationship: 53/92 was first in rank for above-ground productivity but fifth below ground for root mass density and sixth for root length density, whereas 10/91 was first in rank for the below-ground variables but fourth (at 12 months) and then sixth (at 18 months) for above-ground productivity.

Given the functional linkage between plants' above-ground growth and root system development, their correlation would be expected to be strong (Cannell, 1985). However, plant allocation of assimilates to shoot and root growth is known to vary with environment (Bleasdale, 1966; Ledig, 1983) and among provenances within some species (e.g. Zimmer and Grose, 1958; Cannell and Willett, 1976; Ledig, 1983). Owino (1996) found non-existent or weak correlations between stem and root growth characteristics of 154 families of *Grevillia robusta*. Whilst the trees' root systems may help to bind soil and thus reduce the rate of soil erosion, if they are to be used in a simultaneous contour-hedgerow agroforestry system, a key consideration is that they should not reduce the yield of the agricultural crop beyond a point acceptable to the farmer through excessive competition for below-ground resources. Local farmers indicated their concern about the potential for *C. calothyrsus* to compete with crops grown in the inter-row in a hedgerow agroforestry system. Our results provide evidence that the spatial distribution of their roots could be an important factor in *C. calothyrsus* provenance selection. Provenance 53/92 had the lowest root growth in the inter-row area relative to above-ground production. There has also been significant interest in agroforestry in the possibility that deeper-rooting trees compete less with crops for below-ground resources (Schroth, 1995). However, our results showed absolutely no evidence of variation in rooting depth between provenances of *C. calothyrsus*, at least down to 30 cm.

Our results suggest that there is potential for farmers to select a provenance that combines high above-ground production with relatively lower levels of below-ground competition with their agricultural crops. Provenance 53/92 can, provisionally, be recommended in this regard, but this subject requires further research to see if this negative relationship between its above- and below-ground production continues during the trees' longer-term development and to determine its mechanistic basis. The effects of management should also be considered. Whilst the farmer is better able to regulate above-ground competition (and any beneficial effects of the shade cast by the trees) than below-ground competition, Jones *et al.* (1998) showed that shoot pruning greatly reduced root length density in one agroforestry tree (*Prosopis juliflora*) but not in another (*Acacia nilotica*).

A higher proportion of the variation in root length and mass densities were accounted for by the block x provenance interaction, than by provenance itself. This supports the suggestion of Bowen (1985) that the production and turnover of roots confer flexibility to trees, permitting phenotypic response to a wide range of site conditions. There is an extensive literature showing that high levels of water and nutrient availability increase shoot growth relative to root growth (e.g. Gales, 1979; Ledig, 1983; Cannell, 1985). Sinclair *et al.* (1994) concluded that soil conditions might, therefore, be more significant in determining tree root distribution than the actual tree genotype planted. However, Habeck (1958) demonstrated differences in root system plasticity between ecotypes of *Thuja occidentalis.*

The results confirmed the expected correlation of provenance mean root collar diameters over different time periods: in general provenances with a high initial growth rate (as indicated by their diameter at 6 months) continued to grow more over the following 6 months than those with a low initial growth rate. From 12 months, the cutting back of the trees has a potentially major influence on correlations of variables over time. However, provenance increments in height and root collar diameter after harvesting were strongly correlated with their respective increments before harvesting. Therefore, early growth measures may be used to predict subsequent provenance growth, but such extrapolation is safer for diameter than for height. Nonetheless, it would not be safe to base provenance selection on such early performance, and longer-term data sets are required. Although there is some evidence of differences between the provenances in their response to harvesting, this was limited and it was notable that after cutting individual provenances retained their initial tendency to allocate growth to height or to diameter. There was no evidence that cutting back to 50 cm at 12 months reduced absolute growth rates over the following six months (in fact they increased). The continuation of a 6-month cutting cycle could, however, lead to a longer-term decline in growth. Morikawa *et al.* (1985) found that a 12-week cycle of cutting back to 75 cm or 150 cm was not sustainable for *C. calothyrsus* at sites with a lower altitude and rainfall in Jamaica: however yield recovered after a 6-month period without cutting.

This study provides preliminary information about several of the research priorities for selection of multipurpose trees proposed by Huxley (1985), notably in the distribution of dry matter, the "adaptability" of provenances, flower initiation times and the response to pruning/lopping. Further information could be obtained by farmers themselves as they try out alternative agroforestry species and provenances. However, more work is required to improve the advice offered to farmers about which planting material has the best potential for a given set of environmental conditions, and thus should be considered for their trials. Effective mechanisms must also be established for communication between farmers of the results of their trials to avoid too much "reinvention of the wheel".

4.5 PROPAGATION OF NATIVE SPECIES

4.5.1 OBJECTIVE

Purpose 3: To prepare an inventory of locally suitable species for contour hedgerow systems, and produce propagation guidelines for each.

4.5.2 METHODS

Research into the propagation of the smaller sub-set of native and naturalised tree species that were already accepted by farmers for agroforestry was carried out in the project's shade house facility and non-mist propagators at Cinchona Botanic Garden, with the participation of the garden staff, who had previously had little opportunity to learn these skills and gain experience of this kind of work. Eighteen mature selected trees were felled as stock plants to obtain cuttings for propagation. A stock plant area was established at Cinchona Botanic Garden and now contains over 500 individuals selected for seedling form and vigour. Factorial experiments have tested different means of producing and treating single node cuttings of three species.

4.5.3 RESULTS

The initial screening indicated that suitable species for experimentation were: *Clethra occidentalis, Vaccinium meridionale, Podocarpus urbanii, Alchornea latifolia, Cedrela odorata, Calliandra calothyrsus*, and possibly *Lyonia jamaicensis*, *Ilex macfadyenii* and *Juniperus leucayana*. So that these species can be used for genetic selection of clonal propagated material, and provide material for the more rigorous investigation of propagation requirements; material of each was planted in the stock plant area.

Tests of cutting survival and rooting ability carried out in this project focused on *Clethra occidentalis, Vaccinium meridionale* and *Juniperus leucayana*. In factorial experiments with single-node cuttings, the effect of cutting length (long, short), leaf area (large, small), and the hormone level (4000, 8000) supplied in a commercial rooting powder ‘Stimroot’ were tested. Complex interactions have been found for *C. occidentalis* and *V. meridionale* between cutting length, leaf area, IBA hormone-treatment and species (Figures 18, 19 and 20). No cuttings of *Juniperus* rooted successfully.

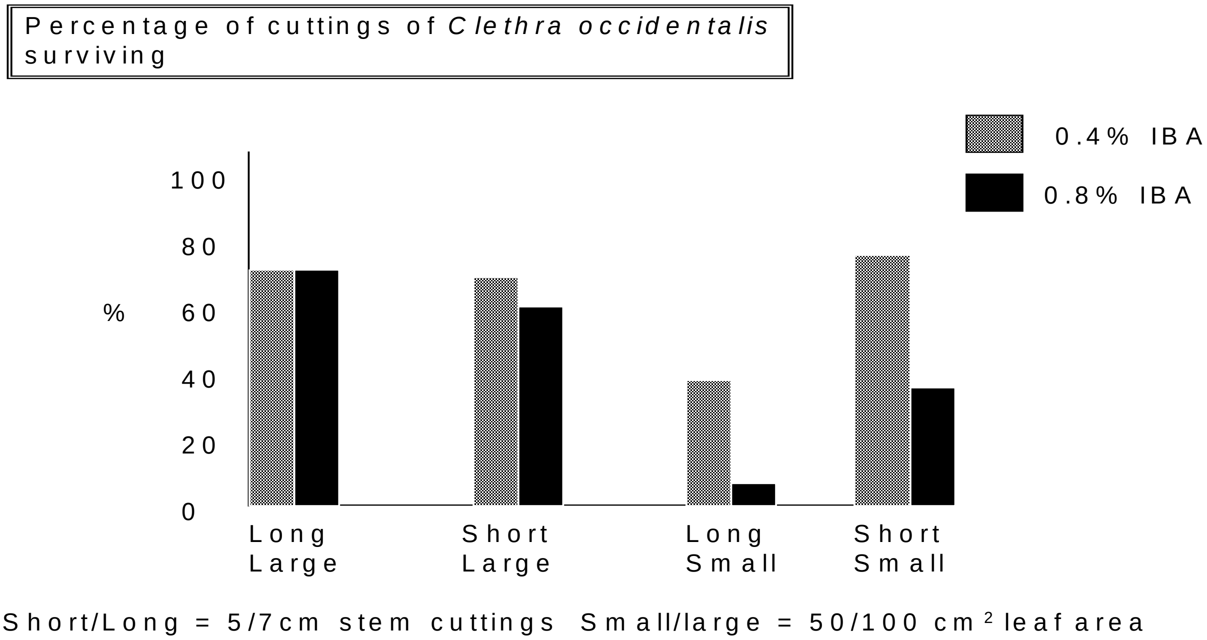

Figure 18 Survival of cuttings of *Clethra occidentalis.*

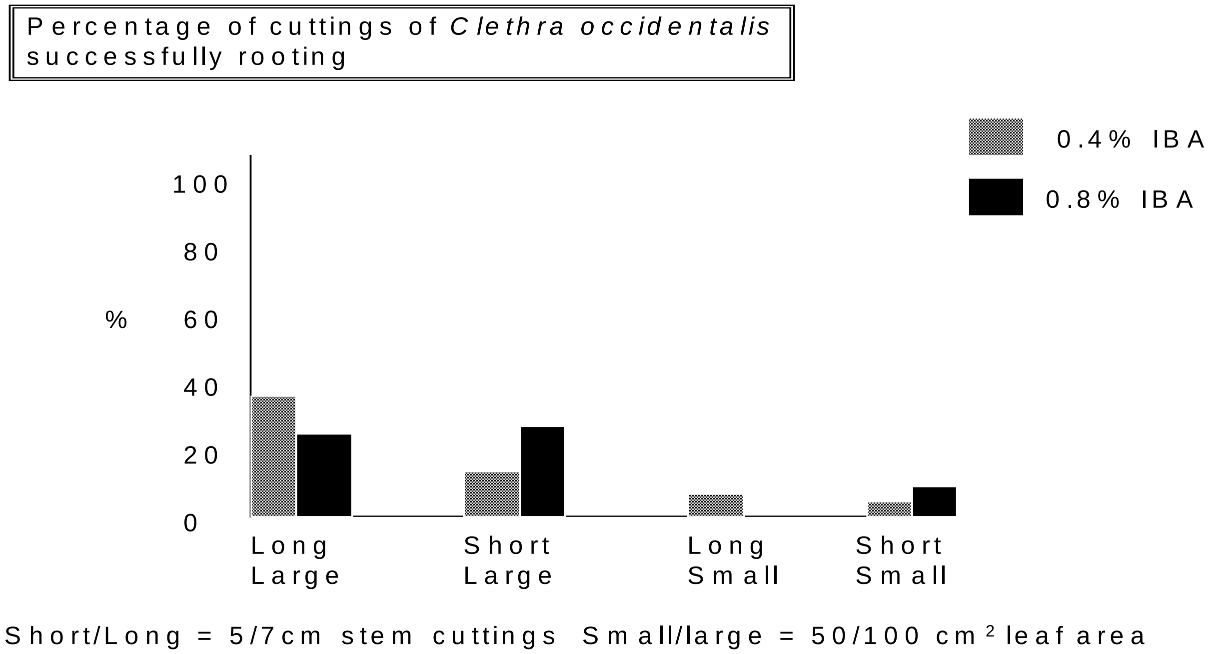

Figure 19 Rooting of cuttings of *Clethra occidentalis.*

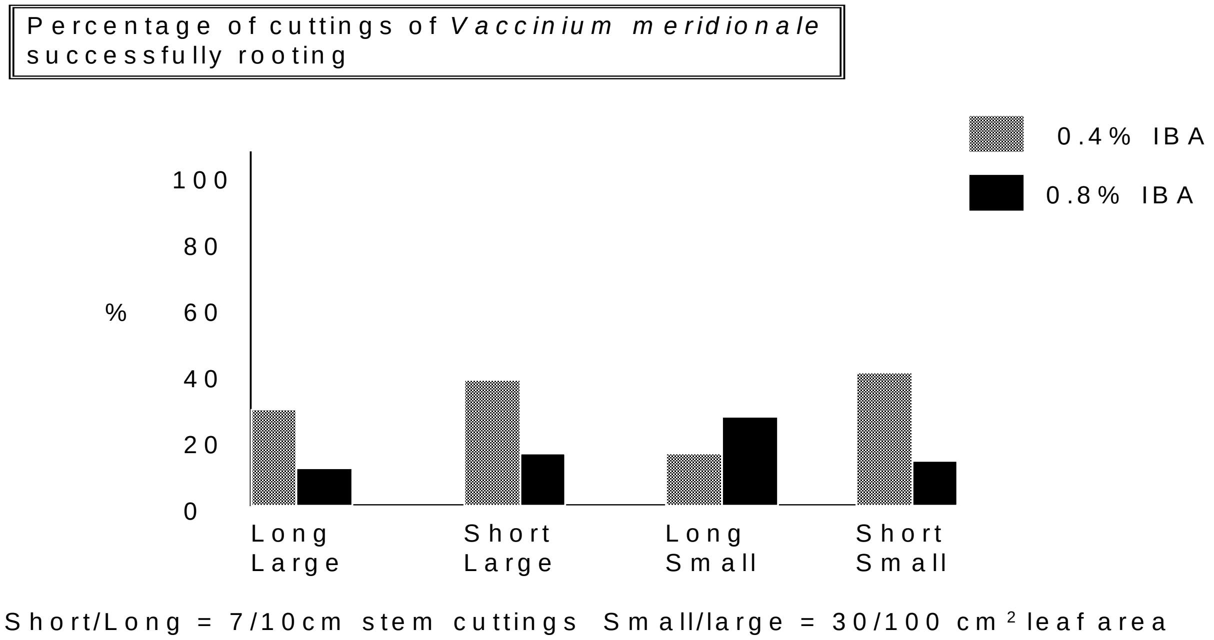

Figure 20 Rooting of cuttings of *Vaccinium meridionale.*

Plate 10 One of the non-mist propagators in the project's nursery at Cinchona Botanic Garden used for rooting cuttings following different experimental treatments.

4.5.4 DISCUSSION

Despite considerable trial and error experimentation, rooting percentages for the tested species remained very low (below 40%). This indicates the severe problems (and significant resource requirements in terms of staff time) in developing this technology for previously untested species. Nonetheless, the project has left a significant legacy for the Public Gardens Division of the Jamaican Ministry of Agriculture and Mines, including a thriving stock plant area, nursery shade house and non-mist propagators. The staff of the division trained by the project are now carrying on the work of developing and testing propagation methods for the nine established stock species, and incremental improvements in success rates can be anticipated over time.

Plate 11 The stock plant collection at Cinchona Botanic Garden includes a variety of native species (the intervening *Calliandra calothyrsus* hedgerows are used for mulch).

4.6 DISSEMINATION OF PROJECT OUTPUTS AT THE LOCAL LEVEL AND THOUGHOUT THE CARIBBEAN REGION

Purpose 4: To increase the awareness of local community and extension officers towards the benefits of trees in farming systems and appropriate agroforestry techniques

Purpose 5: To disseminate outputs throughout the Caribbean region.

4.6.1 METHODS

Ten principal promotion pathways were used to disseminate the projects outputs at the local level and throughout the Caribbean region. (Figure 21). These were based on our socio-economic surveys of the local farming community (e.g. the survey commissioned from Joy Douglas which was reported in Appendix 1 of the 1995-1996 project annual report) and experience of rural development and land use issues in Jamaica and the Caribbean region, and close contacts with relevant national and regional institutions.

The first pathway was realised via the development of the technology in partnership with the farmers most actively involved in the project. Successful development led to their acceptance, uptake and subsequent diffusion of the technology to other farmers in the district by observation, and informal conversation at rural 'one-stops' (community bar/meeting place), markets and at social gatherings such as weddings and funerals (pathway 2). Every year, Dr McDonald took groups of farmers to the annual Denbigh Agricultural Show to facilitate this. The project also ran six trips to visit farmers and projects in other parishes, and three training workshops for farmers from three parishes at the project sites at Cinchona (one being a two-day residential workshop, funded by the FAO of the UN). The first of these workshops was conducted by members of the local farming community after training from project staff.

Project R6290 was formulated partly at the request of the Blue Mountains/John Crow Mountains National Park management, who were involved from the outset. This ensured the third pathway - their involvement in the iterative testing and development of extension material. The leaflets produced by the project on Farm Forestry Recommendations and Tree Planting Recommendations were prepared for the park’s community outreach personnel and were distributed at regular Local Advisory Committee meetings held in the communities in the park. This ensured continuity (pathway 4) and dissemination to the wider farming communities of the Blue and John Crow Mountains region.

Pathway 5 was achieved through personnel from a range of land-use organisations operating in Jamaica visiting the project’s research sites. These personnel included representatives of the, Canadian International Development Agency (CIDA), Caribbean Agricultural Research and Development Institute (CARDI), Food and Agriculture Organisation (FAO), Forest Department, Protected Areas Resource Conservation Project (PARC), and European Union (EU). In addition, information sessions were conducted with the Caribbean Conservation Society (CCS), European Union (EU), Inter-American Development Bank (IDB), Inter-American Institute for Co-operation in Agriculture (IICA), the Watershed Donor’s Committee (IDB, CIDA, EU, USAID, FAO) and UWI (Trinidad campus). CARDI, CIDA, EU and FAO all have field based projects operating in Jamaica, and all groups are transferring the contour hedgerow technology to their projects. This successful implementation of pathway 5, has lead directly to the achievement of pathway 6 as these organisations have transfered the project’s outputs to the training and activities of their research staff.

Many of these institutions have a mandate which extends throughout the Caribbean. IICA has offices in all the Caribbean countries and co-ordinates both forestry and agricultural development; CARDI is involved in agroforestry in several Caribbean countries; BDDC obviously has regional responsibilities; CCS is a regional society with headquarters in Barbados; FAO and CIDA have, at various times, projects running in several Caribbean countries. The project’s outputs are being disseminated within all of these organisations at both country and regional levels. This process has been facilitated by the project through visits made by project staff to key institutions in the Caribbean and correspondence with them (see, details in the 1995-1996 and 1996-1997 project annual reports and information on the recent visit in Appendix 5 of this report). This has ensured progress with pathway 7, and feedback received by project staff during these liaison visits give grounds for optimisim that, the ultimately pathway 8 (leading to uptake by farmers in the Eastern Caribbean) will occur once sufficient time has elapsed for this wide geographical dissemination of the innovations communicated in the project outputs.

The Life Sciences Department of the University of the West Indies at Mona, Jamaica, started a new undergraduate course BT33A in Applied Ecology, Agroforestry and Sustainable Development in 1992. Dr McDonald was instrumental in developing the curriculum and the teaching of this course, and additional inputs were made by Dr Healey, Dr Adrian Newton, Dr Robert Brook and Dr Fergus Sinclair in visits to Jamaica facilitated by the project (but paid for from other sources). By 1996, Dr McDonald was solely responsible for the coordination of the content and delivery of this course, bringing about pathway 9. Three Caribbean national graduate students in the Life Sciences Department are currently carrying out research degrees in forestry in topics related to the project's objectives under the supervision of project staff, after completing the undergraduate course in Forest Ecology. The teaching materials provided by staff of project R6290 (a copy of the course curriculum has already been sent to FRP) have given staff of the Life Sciences Department of UWI the capacity to undertake the development of this important course. During the project graduates of the Life Sciences Department have obtained employment in the PARC project, the Forest Department and the Natural Resources Conservation Authority which is important for promotion of the project's outputs. The shortage of trained and knowledgeable staff for development projects has, in the past, been a barrier to the implementation of successful research project outputs. Augmentation of professional staff in the development field will be crucial to the organisations' ability to further their development work without extensive expatriate support.

The project has been instrumental in UWI (Mona) seeking to fulfill the objectives of pathway 10 to a far higher standard than achieved previously at a regional Caribbean and national level, through the introduction of a proposed new MSc course in Rural Development Forestry. This will provide a professional training to complement the diploma in Forestry offered by ECIAF (East Caribbean Institute for Agriculture and Forestry) in Trinidad.

BDDC	British Development Division in the Caribbean (ODA)
BJCMNP	Blue and John Crow Mountains National Park
CARDI	Caribbean Agricultural and Research Development Institute
CCS	Caribbean Conservation Society
CDC	Conservation Data Centre, Jamaica
CIDA	Canadian International Development Agency
ECIAF	East Caribbean Institute for Agriculture and Forestry
EU	European Union
FAO	Food and Agriculture Organisation
FRP	Forestry Research Programme of the ODA
HAP	Hillside Agriculture Project
IDB	Inter-American Development Bank
IICA	Inter-American Institute for Cooperation in Agriculture
JCDT	Jamaica Conservation and Development Trust
JET	Jamaica Environment Trust
NGO	Non-Governmental Organisation
NRCA	Natural Resources Conservation Authority, Jamaica
ODA	Overseas Development Administration
PARC	Protected Areas Resource Conservation Project, Jamaica
UNDP	United Nations Development Programme
UWA	Underground Water Authority, Jamaica
UWB	University of Wales Bangor
UWI	University of the West Indies

Plate 12 Final year undergraduate students from the University of the West Indies taking the module: 'Forest Ecology, Agroforestry and Sustainable Development' developed under R6290 on a field visit to the project research area.

4.6.2 RESULTS

4.6.2.1 ON-FARM TRIALS AND DEMONSTRATIONS

As a result of the close collaborative work with members of the local farming community there was a continuous increase in interest in agroforestry and an increase in demand for planting material of a variety of native and naturalised species from the project's nursery. Sixty-four local farmers participated in establishing demonstration plots of hedgerows and other agroforestry systems.

In total, the project set up new demonstration plots on the farms of 40 farmers (three female), involving 2044 tree seedlings from the project's nursery. The HAP has taken a further 1800 seedlings from our nursery; their activities involve up to 620 individual farmers. In addition, CARDI took 3500 *Calliandra* seedlings from our nursery for use in our joint research and to use in setting up demonstration hedgerow plots on farmers' land. The National Park has established *Calliandra* hedgerows with plants from the nursery on four farms.

Together these activities have involved the establishment of trials/demonstrations with a wide variety of species: *Cedrela, Grevillia, Calliandra, Sapium, Persea* (avocado), *Syzgium* (Otaheite Apple), *Hibiscus*, *Alchornea*, *Cinnamomum*, *Myrsine*, *Podocarpus* and Christmas trees. They have involved the establishment of trials/demonstrations of a range of management techniques: trees planted as lines, borders, shade for coffee, windbreaks and hedges.

The farmers managing the research plots also established hedgerows of a number of species on their own farms. This proved a valuable means of dissemination of the technology to other community members, as the participating farmers were all well respected within the community (Mr Sheraton Walker is a lay preacher with the Westphalia Church of God of Phrophecy - he also arranged a slide show to members of that church by Morag McDonald and Anna Hofny-Collins), and their systems were copied by neighbouring farmers. Mr Roy Bryan established hedgerows of *Calliandra calothyrsus*, *Cupressus lusitanica* and peach (*Prunus persica*) on his farm which was 'en route' for most farmers with land in the Green River Valley and as such provided a highly visible demonstration.

In 1997, a charge was imposed on tree seedlings of the species under heaviest demand (principally *Cedrela*, *Calliandra* and Christmas Trees). The total number of tree sold after the charge was imposed was 2507 (in addition to those quantified above in the establishment of the demonstration plots). The revenues were used in support of the under-resourced Cinchona Botanic Garden which has provided the project with field station and nursery facilities. The sales were advertised in local communities at "one-stops", schools and churches (Appendix IV). These arrangements were reached following discussions with the Public Gardens Division of the Jamaican Ministry of Agriculture and Mining.

Figure 21 Promotion pathways within the Caribbean region.

Plate 13 A variety of agroforestry systems were employed in on-farm demonstrations (Mr Sheraton Walker establishing a boundary of *Cedrela odorata*).

4.6.2.2 COLLABORATION WITH ENVIRONMENTAL NGOS

Amongst the collaborative links established with NGOs which were described in the methods section above, Dr McDonald has been appointed to the board, and project management committee, of the National Arboretum Foundation, an NGO with responsibility for the establishment of a Jamaican Plant Conservation Centre (National Arboretum Foundation/Ministry of Agriculture and Mining). Project R6290 has already taken concrete steps towards the establishment of this centre by providing planting material of endemic montane forest tree species to augment the existing collections of Hope Gardens (Jamaica's premier botanic garden). Dr McDonald was also appointed to the board, and the project sub-committee, of the Caribbean Conservation Area Management Foundation, an NGO recently awarded the mandate to manage the newly declared protected area of the South Coast of Jamaica by the Natural Resources Conservation Authority. She was also appointed in the capacity of scientific advisor to the board of the Negril Royal Palm Reserve, a private sector development consortium committed to opening the reserve as an eco-tourism resort, and to establish an ecological research station within the resort for use by the University of the West Indies, and international universities. This resort will provide valuable employment income for the depressed region of Sheffield on the north coast of Jamaica, as well as increasing awareness of environmental issues both locally, and internationally. The project has arranged the transfer of its output “a Database of the Woody Plant Species of the Blue Mountains of Jamaica” to the JCDT who manage the BJCMNP.

Plate 14 Mr Lloyd Stamp (Foreman, Cinchona Botanic Garden and nursery supervisor) in the project's nursery at Cinchona. The nursery is run by local community members, and revenues from tree sales are used to support the under-resourced garden.

4.6.2.3 COLLABORATION WITH JAMAICAN GOVERNMENT DEPARTMENTS

Dr McDonald has contributed to a Natural Resources Conservation Authority workshop on "Environmental Management of Watersheds - Development of Institutional Capabilities”. The project has collaborated closely with the BJCMNP and the HAP through a series of liaison meetings and collaborative activities. Dr McDonald assisted in the preparation of the BJCMNP five-year development plan (1997-2001) and the three-year action plan (1997-1999). She was appointed to the Scientific and Technical Advisory Committee of the BJCMNP. The research outputs of R6290 are being taken up and promoted by the extension officers of the FAO/Jamaica Forest Department Agroforestry Development Project in Portland, Jamaica and of the EU-funded Yallahs/Morant Agricultural Development Programme operating in two Jamaican watersheds, as well as the other government agencies listed in the Methods section above.

The project has left a significant legacy of infrastructure, trained expertise and experience for the Public Gardens Division of the Jamaican Ministry of Agriculture and Mining, including a thriving stock plant area, nursery shade house and non-mist propagators. The staff of the division trained by the project are now carrying on the work of developing and testing propagation methods for the nine established stock species, and incremental improvements in success rates can be anticipated over time.

4.6.2.4 DISSEMINATION OF RESULTS TO UNDERGRADUATE UNIVERSITY STUDENTS

Dr McDonald delivered a second year University of West Indies undergraduate course in Ecology taken by 92 Caribbean national students and the final year course on ‘Forest Ecology, Agroforestry and Sustainable Development’ to a total of 35 Caribbean national students of the Life Sciences Department over the project period. One UWI student completed his honours project on "The effect of gap size on forest regeneration a dry limestone forest" carried out in collaboration with R6290.

4.6.2.5 INTERACTION WITH RESEARCH STUDENTS IN JAMAICA

Ms Thera Edwardes is completing her MPhil thesis on research into disturbance effects on Blue Mountain forests carried out in collaboration with R6290 and under Dr McDonald’s co-supervision.

Plate 15 Ms Donna Lowe, an M.Phil. student at the University of the West Indies is studying the efficacy of contour hedgerows of a number of different species on-farm in collaboration with the CARDI, and within the framework of the European Union Yallahs/Morant Agricultural Development Project.

Donna Lowe, is registered at UWI under the joint supervision of Dr McDonald, Dr Joe Lindsay (CARDI) and Dr Jane Cohen (Department of Life Sciences, UWI) and is carrying out on-farm research on the efficacy of a number of different species as contour hedgerows, within the framework of the EU Agricultural Development Project and in collaboration with R6290. She is expected to complete her thesis in September, 1998.

A UWI graduate, Kurt McLaren, has commenced his work on the impact of charcoal burning on the structure and composition of natural forest in collaboration with R6290. He has received a Cheavening Award from the British Council to register as a postgraduate research student of the University of Wales Bangor; he is jointly supervised by Dr McDonald and Dr Peter Vogel of the Department of Life Sciences, UWI.

Ms Lois Morgan will begin her postgraduate research on the propagation requirements of montane forest species in January, 1999. This work will follow on from the propagation research initiated in R6290 and will utilise the stock plants established at Cinchona Botanic Garden. Ms Morgan was to have started the research in September, 1998, but was unable to do so for health reasons. However, she will be supervised by Dr Jane Cohen of the Department of Life Sciences, and Dr McDonald will continue to have a supervisory input.

Collaborative links have been developed with other visiting researchers at UWI in Jamaica (including two NERC-funded researchers from the University of Cambridge).

4.6.2.6 OTHER DISSEMINATION OF RESULTS AT A CARIBBEAN AND WIDER INTERNATIONAL LEVEL

The methods section above listed the links established with institutions in the Caribbean region. The mechanisms through which project outputs have been disseminated via these links include a series of conference papers and other seminar presentations made in the region, as listed in the section “Contribution of Outputs” (below). In addition, collaborative links have been established with CIAT (Colombia), STRI, IDIAP and INRENARE (Panama) and CATIE (Costa Rica).

A liaison visit was made to the Eastern Caribbean by Morag McDonald to make final plans for dissemination of the project's outputs with key institutions (including NGOs) there. During this Dr McDonald met staff of BDDC and UWI in Barbados; three government forestry/agroforestry staff in Trinidad; and attended a Community Forestry Review Workshop in St Lucia at which ten government agriculture and forestry staff, NGO representatives and private sector personnel. She then had meetings with four St Lucian government forestry staff and one farmer; and three NGOs. In

Dominica Dr McDonald had meetings with three government agriculture staff and four forestry staff, three individual farmers, and two NGOs. Further details of this visit are provided in Appendix V.

The dissemination of 300 copies of the manual is specified in the "Contribution of Outputs" section below. This has exhausted the initial print run, however if significant requests for more copies of the manual are received UWB will organise reprinting and dissemination (and seek support from funding agencies to enable this).

Together these results have concluded a successful exit strategy for the Eastern Caribbean, as well as Jamaica.

The results of the project have been disseminated in a wider international context through the presentation of papers at a range of conferences and the publication of journal papers, book chapters and reports in newsletters/professional journals (further information is given in the "Contribution of Outputs" section below).

5. CONTRIBUTION OF OUTPUTS

At the time of the start of the project the fundamental aim of the ODA was "the promotion of sustainable economic and social development in order to improve the quality of life and reduce poverty, suffering and deprivation in low income countries" (August 1995 FRP brochure).

By the end of the project DFID had revised its objectives thus: "the elimination of world poverty in poorer countries. In land use sectors, including forestry, this aim will be achieved by enhancing productive capacity on a socially, economically and environmentally sustainable basis" (April 1998 FRP brochure).

5.1 IMPLICATIONS OF RESULTS

5.1.1 The project has obtained good evidence that the disturbed, buffer-zone of secondary forest on steep hillslopes is well buffered against surface water runoff and erosion losses: water runoff was consistently less than 0.2% of rainfall in all major rain events, and sediment yield was consistently less than 500 kg ha^{-2} yr^{-1} over the five year period of observations). This shows that, even if human disturbance has caused forest to loose its biodiversity, and other indicators of "naturalness", it can still have great value for water yield regulation and soil conservation. This has major implications for land-use policy showing the importance of protecting these buffer zone forests to meet these objectives.

5.1.2 Where farming is carried out on steep hillslopes, this study provided scientific evidence (of international quality) of the effectiveness of a low input agroforestry contour tree hedgerow technology in soil and water conservation and in enhancing components of agricultural productivity. On slopes of a range of angles from 24 - 32º, with shallow acidic clay loam soil, from the second year after forest clearance and the start of cultivation, water run-off was significantly lower in the cultivated plots with contour hedgerows ("agroforestry") than those just cultivated (agriculture). By the fifth year the level was 2.5 times lower. In addition, in four years out of the five (in which rainfall varied from 2203 to 3465mm) the agroforestry plots had lower rates of erosion than those under agriculture. By the fifth year this difference was significant (erosion in the agroforestry plots was only 45% of that in the agricultural plots). Young (1997b) indicated that on steep slopes greater than 25% (14°), such as those studied in R6290, effective erosion control can only be achieved either by hedgerows being used in conjunction with other soil conservation structures such as terraces, bunds or grass strips, or by the use of much closer inter-hedgerow spacing than those used in R6290. However, we consider that these recommendations are much less likely to be acceptable to farmers because so much more of the field area will be made unavailable for cropping, and significantly greater inputs will be required. In fact, when we established our experiment, the spacing of 5 m was the minimum that the collaborating farmers considered acceptable, in spite of the fact that the researchers proposed a significantly closer spacing. Instead, we have demonstrated that, even on steep slopes in an area subject to intensive rainfall, a significant incremental improvement in runoff and erosion control can be achieved by a much less intensive, lower input system, that is much more likely to be adopted by farmers.

5.1.3 The importance of these results for resource-poor farmers themselves was supported by the results of the *Zea mays* field bioassay which showed higher yields (cob and grain weights up to 45% and 63% higher per plant respectively) from the alleys between the agroforestry hedgerows than those obtained from the agricultural plots. Although the difference in total yield per area between the agroforestry and agriculture plots is not significant due to the loss of planted area caused by the presence of the hedgerows, the differences in yield per plant may be of as much importance to farmers in many environments where: (a) available land area is not the primary limiting factor in their total production (a number of limiting inputs may be linked more to number of plants than to land area); (b) they may obtain valuable products or services from the harvesting of the hedgerow trees. I.e. by using this system farmers can gain the benefits of products and services provided by the hedgerow trees without experiencing any significant reduction in agricultural crop yield.

5.1.4 The project's evidence of the effects of on-farm tree hedgerows on crop growth and yield, including the significant impact of distance from hedgerow, are of great significance for the planning of contour hedgerow planting designs, e.g. so that quantitative assessment can be made of the potential impact of inter-hedgerow spacing on crop yield, as well as on runoff and erosion levels.

5.1.5 The project's research into the mechanisms of these effects through the impact of the experimental treatments on the physical and chemical properties of the plot soils (assessed by laboratory analyses and a greenhouse bioassay) and the rate of nitrogen mineralisation, indicates the complexity of the processes concerned. This indicates the caution that must be expressed in extrapolating such results to a wide range of other environments. We are very concerned that individual technologies should not be promoted and extended without adequate information about the conditions under which they are appropriate. Therefore, it is important that the results of this research are published in international scientific journals where the full environmental context of this study can be presented (erosivity of rainfall; erodibility of substrate: slope angle, soil type, specific land use (crops grown, timing and amount of tillage, level of weed cover etc.) so that other technical experts can relate our results to their own environments, and make informed decisions about their relevance.

5.1.6 The results of our survey of farmer's indigenous knowledge of the ecology and utilisation of trees native to the forests of the Blue Mountains confirmed the expectation that research and development work to meet local people's needs for improved information on agroforestry (tree species selection and research, and on-farm tree management techniques) should encompass a wider range of tree products and benefits than just erosion control. In addition, it has indicated the low level of existing indigenous knowledge of native tree species amongst most members of the farming community (a result readily explicable as a consequence of Jamaica's history). This is an important piece of counter-evidence to the view sometimes expressed that local people's indigenous ecological knowledge is adequate for their needs and always more useful than that which can be provided by scientific approaches. Therefore, it has demonstrated the real need in Jamaica for the project's research work to improve the available information on the ecological characteristics of selected native tree species, and enhance local knowledge on their suitability for on-farm forestry and other forms of afforestation.

5.1.7 Our assessment of the ecological characteristics of native species has demonstrated that, despite the small area of the natural montane forests of the Blue Mountains, there is a massive range in the ecological characteristics of the native species. This is true in terms of their response to variation in substrate, light level and various forms of exposure and disturbance, and in terms of their differential response of survival rate, growth rate and form to these environmental variables. These differences are readily explicable on account of the wide range of environmental conditions (in both space and time) experienced within the Blue Mountain forest mosaic. This between species variation is of profound importance in selecting species for planting on the basis of their suitability for different purposes in different environments. These conclusions will apply to other environments where there is a similar complexity of topography, climate and forest disturbance; existing biogeographical knowledge indicates that these conditions hold in the Eastern Caribbean, in much of Central America and in other DFID target areas such as SW Cameroon, Nepal etc.

5.1.8 The results of our species elimination trial indicate that whilst tree species relative establishment success in a farm environment are partly as predicted from their within-forest ecology, there is a considerable deviation between observed and expected results (some species predicted to do well have not, whilst others have performed much better than predicted). As expected significant differences were found in species performance between the two contrasting farm environments (valley bottom and ridge top), though, again, the interaction between species and environment did not always conform to predictions. These results demonstrate the importance of conducting experiments to test important applied questions directly, rather than relying solely on extrapolation from other existing data. The results also indicate the value in farmers conducting their own trial and error tests of different potential species on their own farms.

5.1.9 The project's distribution of seedlings, on demand, to local farmers has provided valuable "market information" about farmer decision-making over tree species choice (to supplement that obtained from our "ethnobotanical survey" within the local community). Together these have demonstrated the great importance of local people's perception of the value of products that can be obtained from tree species in making their species choice. This decision will have a significant impact on ways in which farmers adapt agroforestry techniques for their own purposes. Too often, past development projects have failed to recognise the great importance of the existing knowledge and requirements held by rural communities and have failed to successfully incorporate it in the project process.

5.1.10 Before the installation of our *Calliandra calothyrsus* provenance trial, there was little local knowledge in the Caribbean of variation within this species (e.g. in Jamacia germplasm from only a narrow range of sources had been introduced). The large level of variation in performance between the *C. calothyrsus* provenances that we found as early as six months into the trial demonstrates the value of this work in improving knowledge about the range of different material potentially available to farmers. The results of this trial show the lack of genetic correlation of the different observed traits for this multipurpose tree species. This indicates the importance, for such previously locally little-known agroforestry species, of such on-farm trials to enable farmers to select genotypes that best match their individual needs.

5.1.11 The experience of our propagation experimentation indicates the significant amount of work that is required to develop such technology for many species/environments. The costs of this must not be underestimated. For farm forestry/afforestation projects (particularly those at a small scale), success may often depend on the availability of alternative methods of producing planting stock (the ready availability of large quantities of viable seed has probably been a major factor in the over-reliance on a limited number of exotic species for such projects). Where there is a need or commitment to use local/under-utilised species, our results demonstrate the vital importance of the retention of protected forest areas in which these species naturally regenerate in sufficient quantities to provide a sustainable source of wildings (or seed) for farm forestry/afforestation. Depending on the geographical scale of the area under consideration/the access to transport/the nursery infrastructure, it may be vital that these source areas for wildings are within walking distance of local people. Once the first generation of planted trees are established, provided that the farm/plantation environment does not prove a serious barrier to their reproduction, then farmers/local people should be able to harvest sufficient seeds from these trees for future planting needs.

5.2 DISSEMINATION AND UPTAKE OF RESULTS

Dissemination of results was a major component of this adaptive project and, as described in section 4.5, this was carried out successfully with individual farmers, local communities, NGOs, the private sector and government agencies. The conclusions drawn from the project's research about the best design of appropriate agroforestry practices for the Caribbean region have been synthesised and interpreted in our widely distributed manual and via numerous links through the participating community, workshops and training mechanisms. More detailed technical background information has been made publicly available through a database, published bibliography, and six papers prepared for journal publication, three book chapters and 12 conference/seminar presentations.

There is strong evidence of present and forthcoming uptake of the project's results by various target audiences and beneficiaries.

5.2.1 In his recent reviews Young (1997a, b) has noted that contour hedgerow agroforestry could not yet be recommended for steep slopes (greater than 20% (11°)) because of a lack of research results quantifying its impact and effectiveness under these conditions; he advocated the need for further research. R6290 goes a substantial way towards meeting this need. Specifically its results will make a major contribution of high quality data to parameterise for steeper slopes the agroforestry models currently under development (e.g. Young *et al.*, in press). The results of R6290 are complementary to those of ICRAF in Kenya (on shallower slopes) (Kiepe and Young, 1992; Kiepe, 1995) and to those collected by a subsequent FRP-funded project in Honduras (on steeper ones) (Hellin and Larrea, 1997). In reviewing the huge range of erosion rates reported from the middle hills of Nepal, Gardner and Mawdesley (1997) accounted for this by the wide variation in the measurement methods used, and in the land use system. Across the range of measurement methods used, those in project R6290 were amongst the most rigorous, with direct measurement of all runoff water and eroded sediment after all major rainfall events (> 25 mm); and the land-use system has been carefully documented and quantified.

5.2.2 The project's extensive links with national and Caribbean regional target institutions and beneficiaries through the numerous meetings and visits attended by Dr McDonald, has established clearly the favourable conditions and great interest in uptake of the project's results in the region.

Fujisaka (1977) has proposed that contour hedgerows are only liable to be adopted by farmers in conditions where: most agricultural lands are sloping and soil erosion rates are high, population is high and the land frontier is closed, and where native soil and land productivity are at least moderate. He presents evidence that, where these conditions do not hold, promotion of this technology has failed to lead to farmer adoption. However, in the relatively young volcanic/uplift upland topography of much of the Caribbean region (as in the Jamaican Blue

Mountains), his conditions do apply. Because, in the past, low population densities and little restriction on movement by farmers into natural forest areas meant that land/soil was not a seriously limiting resource, little tradition of soil conservation practices has developed in these areas. This context, in combination with the results of R6290, does indicate the value in contour hedgerow technology now being actively promoted amongst the relevant farming communities.

Independently, project R6290 has determined that the applicability of contour hedgerow agroforestry technologies to sustainable development and poverty elimination throughout the Caribbean, and in other low income countries, depends on three main factors:

(a) The significance of soil degradation on hillslope lands as a constraint on the economic condition of farmers and to wider sustainable development in the land use sector. This is substantiated in the background section of this report.

(b) The cost-effectiveness of these technologies, compared with alternatives, for soil conservation in these lands. This is dependent on the relative technical efficiency of the alternative technologies under local environmental conditions (see the reviews by Young (1997a,b) and others cited in this report), and their relative costs (in time and resources both for establishment and maintenance).

(c) The willingness of farmers to adopt this technology and then to adapt it to their particular needs.

For both (b) & (c) the socio-economic context is critical, including: land tenure, farmer/household livelihoods, willingness to invest labour and other costs, and other related historical/psychological factors. Market information is also vital, including: costs of various alternative inputs, value of various potential outputs - agricultural crops, tree products etc. In addition, the institutional context plays a significant factor on farmer decision making and willingness to adopt and adapt new innovations in the Caribbean: sources of information, advice, pressure etc. A number of unpublished reports by the CARDI, support the conclusions of R6290's own participatory research, that these factors do make contour hedgerow agroforestry an appropriate technology to meet the needs of many farmers in the Caribbean region. In many Caribbean countries, a large number of upland farmers who had previously been able to carry out quite extensive shifting-cultivation, are now having to adjust rapidly to new restrictions on this practice: whilst the land frontier has not yet been closed everywhere, increased protected area legislation is increasingly restricting farmer's ability to extend their agriculture into forest areas. Together with rapid rates of population increase, this means that whilst shifting cultivation may still be possible in places, it is becoming increasingly problematic. The farmers are now experiencing an urgent need to increase the sustainable productivity of the land that they already occupy.

5.3 DIRECT IMPACT OF THE PROJECT

5.3.1 In Jamaica, we have gather evidence that agroforestry techniques are acceptable to resource poor farmers: the project has caused a significant change in attitude by farmers on steep hillslopes towards the value of farm forestry practices for soil conservation and wood production, as follows.

Before the start of the project, in the farming practices of the steeply sloping upper watersheds of the Blue Mountains of Jamaica:

(a) previous attempts at promoting soil conservation by the creation of physical barriers had failed;

(b) trees were rarely planted on farms;

(c) and cultivation shifted repeatedly from place to place.

From this very low starting point the project had an increasing impact:

(a) the project demonstrated to farmers the positive impact of on-farm tree hedgerows on soil conservation;

(b) the project demonstrated to farmers the absence of any significant negative effect of on-farm tree hedgerows on crop yield;

(c) farmers requested tree seedlings from the project's nursery at a rapidly increasing rate, by the end 64 farmers were participating in the project's informal network of on-farm trials;

(d) project staff were invited to enthusiastic local community and NGO meetings to describe farm forestry techniques;

(e) there was a big growth in demand for the project's extension leaflets from extension officers and NGOs.

(f) the project provided regular employment for seven local community members, and up to 40 others on a casual basis (making a significant positive impact on reduction of poverty in the local community which suffers from low rates of employment and income).

5.3.2 The project has also had a major impact on the key government institutions:

(a) it has been instrumental in ensuring that the BJCMNP has begun to promote farm forestry as a central component of forest buffer zone management and community outreach.

(b) it has re-invigorated the work of the Jamaican Forestry Department on assessment of native Jamaican species for forestry and agroforestry applications: the Department is now maintain the project's species elimination trials, and is expected to develop them;

(c) through the provision of advice, training, infrastructure and leadership it has contributed substantially to a new joint initiative between the Jamaican Ministry of Agriculture and Mining, Public Gardens Division and a Jamaican NGO to extend the Division's activities to *ex situ* conservation of Jamaican tree species and provision of planting material to individual farmers and other organisations in tree nursery and propagation techniques.

These developments are contributing to the significant increase in demand for trained personnel to manage such forestry/agroforestry development initiatives throughout the Caribbean. The project has made an important contribution to the training of the next generation of land-use/conservation professionals who will have to deal with these issues through its close collaboration with the major training institution in the region, the University of the West Indies. The project's activities were the major factor leading to a significant recent increase in postgraduate student registration for research projects in this field, and for the University of the West Indies making firm proposals for a new MSc in Rural Development Forestry in Jamaica.

5.3.3 R6290 has made an active contribution to the success of the international *Calliandra* provenance trial network run by the Oxford Forestry Institute. We have managed one of the trial field sites (with five experimental blocks), reported results on germination, seedling survival and growth; and supplied seed of the local Jamaican provenance to the network project.

5.4 CONSEQUENCES FOR DFID OBJECTIVES

The project has and will have a significant impact on the reduction of poverty of a number of impoverished social groups.

Amongst marginalised hillside farmers it has demonstrated, tested and disseminated a technology that is enabling them to increase the productive capacity of their farm-land on a socially, economically and environmentally sustainable basis. The technology does not disrupt existing social or tenure patterns; indeed, by enabling farmers to continue cultivating the same area of land for longer, it contributes positively to their security of tenure. The technology itself requires only low levels of inputs, reduces the inputs that farmers have to make in clearing new farm land and enhances the diversity of valuable products obtained by the farmer, thus increasing profit and reducing economic risk. The technology enhances environmental sustainability, by reducing the negative environmental consequences of current practice (on both existing fields, and by reducing the rate of forest clearance for new fields).

Recent research results show the difficulty in demonstrating the positive impact of such improvements in the environmental sustainability of hillside agriculture, and reduction in deforestation rates, because of the complexity of the linkage between processes at a plot, and a catchment scale (e.g. Bruijnzeel, 1990). However, there is good evidence of the importance of upper catchment hillslopes, and the dynamics of the forest-agriculture buffer-zone interface, in such processes. Therefore, depending on the dynamics of water and sediment transfer in any given catchment, the outputs of this project are of great potential significance for poverty reduction amongst those dependent on catchment services (especially regulation of water yield, and water quality). These include the people dependent on fisheries, those involved in downstream agriculture dependent on river water for irrigation (these include many poor plantation workers); and those whose water supplies (or even power generation) depend on the flow of river water into reservoirs. In the Caribbean region, as in many other poorer countries, the latter include a high proportion of the urban poor population.

The project has provided very strong evidence of the importance of protection of forest cover for soil and water conservation and it is expected that these will contribute significantly towards a strengthening of policies and actions by Caribbean governments to achieve this. Other important consequences will flow from this, including improved conservation and enhancement of other forest services such as biodiversity and biomass. The consequences of this will contribute significantly to poverty reduction through enhanced employment in ecotourism, positive climatic impacts from reduced carbon dioxide emissions etc. Ecotourism is an important source of income in the Caribbean; as well as positive impacts on terrestrial ecotourism, the improvement in protection of catchments resulting from this project will contribute significantly to marine ecotourism which is being harmed in places by the damage caused to coral reefs by drift of sediment discharges from rivers.

5.5 LIST OF PUBLICATIONS AND OTHER DISSEMINATION METHODS

5.5.1 EXTENSION MATERIALS

1. McDonald, M.A. & Evans, P.T. (1998). *Agroforestry practices for smallholder farmers in the Caribbean: an extension manual*. School of Agricultural and Forest Sciences Publication Number 10, University of Wales, Bangor. 36 pp.

   Three hundred copies of this manual have been distributed to organisations in five Caribbean countries:

   Jamaica: The BJCMNP extension service; the Government Forest Department; Caribbean Agricultural Research and Development Institute (CARDI); agricultural development projects funded by the European Union and the Food and Agricultural Organisation of the United Nations via a number of government departments.

   St. Lucia: The Government Forest and Lands Department; the Caribbean Natural Resources Institute (NGO)

   Trinidad: the Government Forestry Division

   Dominica: the Ministry of Agriculture; the Government Forestry and Wildlife Division; the Dominica Conservation Association (NGO)

   Grenada: the Government Forest Department (via a DFID bilaterally-funded programme)

2. McDonald, M A & Evans, P T (1996a). *Tree planting recommendations: an extension leaflet*. School of Agricultural and Forest Sciences, University of Wales, Bangor. 6 pp. *

3. McDonald, M A & Evans, P T (1996b). *Farm forestry recommendations: an extension leaflet*. School of Agricultural and Forest Sciences, University of Wales, Bangor. 6 pp. *

   *These leaflets were distributed in Jamaica by the extension staff of the Blue and John Crow Mountains National Park (BJCMNP) via their Local Advisory Committee (LAC) meetings held by the communities of the park.

5.5.2 TRAINING MATERIALS

1. McDonald, M.A. (1998). Curriculum, BSc final year course BT33A Forest Ecology, Agroforestry and Sustainable Development, Department of Life Sciences, University of West Indies, Mona, Kingston, Jamaica. 200 pp.

   The curriculum is deposited with the Department of Life Sciences of UWI and is being extended to the University of Guyana via a DFID funded bilateral programme.

5.5.3 DATABASE AND BIBLIOGRAPHY FOR PRACTITIONERS AND RESEARCHERS

1. Goodland, T.C.R., Bellingham, P.J., Healey, J.R. & Tanner, E.V.J. (1998). *The woody plant species of the Blue Mountains of Jamaica. A database.* School of Agricultural and Forest Sciences, University of Wales, Bangor. A printed outputs of the database (260 pp.) has been produced.

   Transfer of the database has been arranged to The Jamaica Conservation and Development Trust (the NGO which manages the Blue and John Crow Mountains National Park), which has agreed to host and maintain the database in Jamaica from now on. Copies of the 260 page printed output of the database are being disseminated to all interested organisations (including the Forestry Department and University of the West Indies in Jamaica). Arrangements have been made for continued UWB input into the enhancement and development of the database, in collaboration with JCDT.

2. Pitcher, M. (1995). *A bibliography of soil erosion and soil conservation research in the Caribbean*. Natural Resources Institute. 103 pp. Project R6290 contributed to the production of this bibliography in collaboration with its main sponsors, NFI FRP Project R5809).

5.5.4 WORKSHOPS/TRAINING

1. The project sponsored (with the Department of Botany, University of the West Indies) a one day workshop on "Forestry Research on Jamaica". in which results from project R6290 were presented. 80 attendees represented a range of organisations including the Forest Department, CARDI, IICA, IDB, CIDA, JET, JCDT, BMJCMNP, NHS, UWA and UWI.

2. A presentation of results from project R6290 was made by Dr McDonald to 40 attendees from local community organisation at a workshop organised by IICA and CATIE. Dr McDonald was on the organising committee for this workshop.

3. The project held two training workshops for 10 local community members and extension staff associated with other watershed management programmes. Local community members associated with R6290 attended a reciprocal training day organised by an FAO project. Further details are given in section 4.5 (above). 7 farmers from the Cinchona area attended this training day.

4. Dr McDonald delivered a second year University of West Indies undergraduate course in Ecology taken by 92 students and the final year course on 'Forest Ecology, Agroforestry and Sustainable Development' to a total of 35 students over the project period. These have proved to be a valuable means of disseminating the project's results. Further details are given in section 4.5 (above).

5. Dr McDonald is supervising the work of four post-graduate students and one under-graduate student, who are carrying out research related to the project. Further details are given in section 4.5 (above).

6. The project has provided on-going training to four members of staff of the Jamaican Ministry of Agriculture and Mining, Public Gardens Division in tree nursery and propagation techniques.

7. Nine seminar presentations on the work of the project were made to: the Faculty of Natural Sciences, UWI; the Jamaica Natural History Society; the Inter-American Institute for Co-operation in Agriculture; CARDI; the Jamaican Rural Development Advisory Authority; extension staff of the EU Development Programme; the Jamaican Natural Resources Conservation Authority; North Carolina State University and the watershed sub-committee of the international donor group (CIDA, USAID, EU, UNDP, UNEP); University of Wales, Bangor.

5.5.5 JOURNAL PAPERS

1. McDonald, M.A. & Healey, J.R. (2000). Nutrient cycling in secondary forests in the Blue Mountains of Jamaica. *Forest Ecology and Management*, **139**, 257-278.

2. McDonald, M.A., Healey, J.R. & Jones, M. (2000). Sources of variation and phenotypic correlation of above- and below-ground growth attributes in a provenance trial of *Calliandra calothyrsus* in the Blue Mountains of Jamaica. *Agroforestry Systems*, **50**, 293-314.

3. McDonald, M.A., Stevens, P.A., Healey, J.R. & Devi Prasad, P.V. (1997). Maintenance of soil fertility on steeplands in the Blue Mountains of Jamaica: the role of contour hedgerows. *Agroforestry Forum*, **8 (4)**, 21-25.

4. McDonald, M.A., Healey, J.R. & Stevens, P.A. (2000). The effects of secondary forest clearance and subsequent land use on erosion losses and soil properties in the Blue Mountains of Jamaica. Paper submitted to *Agriculture Ecosystems and Environment*.

5. McDonald, M.A., Healey, J.R., Hofny-Collins, A. & Goodland, T.C.R. (2000). Evaluation of trees indigenous to the montane forests of the Blue Mountains, Jamaica for reforestation and agroforestry. Paper to be submitted to *Forest Ecology and Management*.

6. McDonald, M.A., Healey, J.R. & Stevens, P.A. (2000). Bioassasys of soil fertility and nitrogen availability on steeplands under bush fallows in the Blue Mountains of Jamaica. Paper to be submitted to *Agriculture Ecosystems and Environment*.

5.5.6 BOOK CHAPTERS

1. McDonald, M.A., Healey, J.R., Stevens, P.A. & Devi Prasad, P.V. (2000). Improved agroforestry systems for steeplands in the Caribbean. In Price, M.F. and Butt, N. (eds*.). Forests in sustainable mountain development: a state of knowledge report for 2000*. CABI, Wallingford, UK, pp. 287-293.

2. McDonald, M.A. & Healey, J.R. (2000). Evaluation of trees indigenous to the montane forests of the Blue Mountains, Jamaica for reforestation and agroforestry. In Price, M.F. and Butt, N. (eds.). *Forests in sustainable mountain development: a state of knowledge report for 2000*. CABI, Wallingford, UK, pp. 293-295.

3. McDonald, M.A., Stevens, P.A., Healey, J.R. & Devi Prasad, P.V. (1999). Maintenance of soil fertility on steeplands in the Blue Mountains of Jamaica: the role of contour hedgerows. In Price, M. (ed.) *Global Change in the Mountains*, Parthenon, New York, pp. 193-196.

5.5.7 CONFERENCE PAPERS

1. McDonald, M.A., Stevens, P.A. & Healey, J.R. (1999). Contour hedgerows of *Calliandra calothyrsus* Meissn. for soil and water conservation in the Blue Mountains of Jamaica. Paper presented at *the Tenth International Soil Conservation Organization Conference "Sustaining the global farm, local action for land stewardship"*, Purdue University, Indiana, USA, 23-28 May 1999.

2. McDonald, M.A., Stevens, P.A., Healey, J.R. & Devi Prasad, P.V. (1997). The role of contour hedgerows in soil conservation on steeplands in the Blue Mountains of Jamaica: the role of contour hedgerows. Abstracts of *the European Conference on Environmental and Societal Change in Mountain Regions*, University of Oxford, 18-20 December 1997.

3. Lindsay, J. I., Campbell, V. & McDonald, M.A. (1996). Successes in the use of vegetative barriers for improved sloping land husbandry in Jamaica. *Proceedings of the 9th Conference of the International Soil Conservation Organisation (ISCO)*, Bonn, Germany, 26-30 August, 1996.

4. Ahmad, R., Manning, P., McDonald, M., Clark, J. & Hellin, J. (1996). Bio-engineering for prevention of landslides on Jamaican roads. In Ahmed, R. *et al.* (eds), *Proceedings of the second Caribbean Conference on Natural Hazards and Disasters*.

5. Healey, J.R., McDonald, M.A. & Devi Prasad, P.V. (1996). On-farm research for the development and promotion of improved methods for agroforestry on steeplands in the Caribbean. Paper presented at the annual *Plant Sciences Wales Conference* (University of Wales, Bangor, December 1996).

6. McDonald, M.A., Healey, J.R. & Devi Prasad, P.V. (1995). The effects of forest clearance on soil and water resources and an investigation of the use of contour hedgerows for soil conservation in the Blue Mountains of Jamaica. Abstracts of the Agroforestry programme (P1.15-00) of the *IUFRO XX World Congress* 8-11 August, 1995, Tampere, Finland.

5.5.7 REPORTS IN NEWSLETTERS/PROFESSIONAL JOURNALS

1. The University of the West Indies, Faculty of Natural Sciences, Mona, Newsletter, volume 8, number 4 (May 1995) pubished an article about the work of the project entitled 'Agroforestry and watershed management project' (p. 21).

2. Agroforestry Forum, Volume 6 number 1 (June 1995), published an article about the work of the project in its 'Systems Analysis and Modelling' section (p. 29).

3. The Edinburgh Centre for Tropical Forests Newsletter, Volume 5 number 2 (August 1995), published an article about the work of the project entitled 'Reforestation in Jamaica'.

5.5.8 DEGREE DISSERTATIONS

1. Ferguson, C.E. (1996). Rooting patterns of five native tree species being considered for use in agroforestry systems in the Blue Mountains of Jamaica. BSc Honours dissertation, Department of Animal and Plant Sciences, University of Sheffield.

2. Price, R. (1997). The effect of gap size on forest regeneration in dry limestone forest. BSc Honours dissertation, Department of Botany, University of West Indies, Mona, Jamaica.

3. Rowden, A. (1998).Characterisation of the seedling shoot architecture of eight native tree species being considered for use in agroforestry systems in the Blue Mountains of Jamaica. Appendix to BSc Honours dissertation, School of Agricultural and Forest Sciences, University of Wales, Bangor.

5.5.9 TECHNICAL REPORTS

1. R4611 ‘’The protection role of Jamaican catchment forest and their resistance to and recovery from the impact of Hurricane Gilbert’’ project final report, submitted to FRP, pp. 26 + appendices.
2. R6290 1995 calendar year report, submitted to FRP, pp. 2.
3. R6290 1995/6 annual report, submitted to FRP, pp. 18 + appendices.
4. R6290 summary of outcomes (September 1996), submitted to FRP on request for inclusion in a report to the ODA, and subsequently in the ODA publication “ODA Natural Resources Research Working for Development ‘Making a difference’”, pp. 37-38.
5. R6290 1996/7 calendar year report, submitted to FRP, pp. 4.
6. R6290 1996/7 annual report, submitted to FRP, pp. 27 + appendices.
7. R6290 1997/8 annual report, submitted to FRP, pp. 2.

6. REFERENCES

Adams, C.D. (1972). *Flowering Plants of Jamaica*. University of the West Indies, Mona, Jamaica, 848 pp.

Agus, F., Cassel, D.K. & Garrity, D.P. (1997). Soil-water and soil physical properties under contour hedgerow systems on sloping Oxisols. *Soil Till. Res*. **40**, 185-199.

Agus, F., Garrity, D.P. & Cassel, D.K. (1999). Soil fertility in contour hedgerow systems on sloping oxisols in Mindanao, Philippines. *Soil Till. Res*. **50**, 159-167.

Alegre, J.C. and Cassel, D.K. (1996). Dynamics of soil physical properties under alternative systems to slash-and-burn. *Agric. Ecosyst. Environ*. **58**, 39-48.

Alegre, J.C. and Rao, M.R. (1996). Soil and water conservation by contour hedging in the humid tropics of Peru. *Agric. Ecosyst. Environ.* **57**, 17-25.

Allen, S.E. (Ed.) (1989) *Chemical Analysis of Ecological Materials*. 2nd Ed. Blackwell Scientific, Oxford.

Anderson, J.M. and Ingram, J.S.I. (1993). *Tropical Soil Biology and Fertility. A Handbook of Methods*. 2nd Edition. CAB International, Wallingford.

Andriesse, J.P. and Schelhaas, R.M. (1987). A monitoring study on nutrient cycles in soils used for shifting cultivation under various climatic conditions in tropical Asia. III. The effects of land clearing through burning on fertility level. *Agric. Ecosyst. Environ*. **19**, 311-332.

Badola, R. (1998). Attitudes of local people towards conservation and alternatives to forest resources: a case study form the lower Himalayas. *Biodiv. Conserv*. **7**, 1245-1259.

Baker, J.L. (1997). Poverty reduction and human development in the Caribbean: a cross-country study. *World Bank Discussion Papers* **336.**

Barker, D. and McGregor, D.F.M. (1988). Land degradation in the Yallahs Basin, Jamaica: historical notes and contemporary observations. *Geography* **73**, 116-24.

Barnett, W.L. (1936). Wynne Grass. *J. Ja. Agric. Soc.* **40**, 119-120.

Baxter, A.E. (1975). The diffusion of innovations: soil conservation techniques in the Yallahs Valley, Jamaica. *Jamaica J.* **9**, 51-6.

Bazzaz, F.A. (1991). Regeneration of tropical forests: physiological responses of pioneer and secondary species. In: Goméz-Pompa, A., Whitmore, T.C. & Hadley, M. (eds) *Rain forest regeneration and management*. Parthenon Publishing. pp. 91-118.

Bellingham, P.J. (1993). *The effects of a hurricane on Jamaican montane rain forests*. PhD dissertation, University of Cambridge.

Bellingham, P.J., Kapos, V., Varty, N., Healey, J.R., Tanner, E.V.J., Kelly D.L., Dalling, J.W. Burns, L.S., Lee, D. & Sidrak, G. (1992). Catastrophic disturbance need not cause high mortality: the effects of a major hurricane on forests in Jamaica. *J. Trop. Ecol*. **8**, 217-223.

Bellingham, P.J. and Tanner, E.V.J. (2000). The influence of topography on tree growth, mortality and recruitment in a tropical montane forest. *Biotropica*, **32**, 378-384.

Bellingham, P.J., Tanner, E.V.J. & Healey, J.R. (1995). Damage and responsiveness of Jamaican montane tree species after disturbance by a hurricane. *Ecology* **76**, 2562-80.

Bowen, G.D. (1985). Roots as a component of tree productivity. In: Cannell, M.G.R. and Jackson, J.E. (eds) *Attributes of Trees as Crop Plants*, pp. 303-315. ITE, Abbots Ripton, UK.

Brand, J. and Pfund, J.L. (1998). Site and watershed-level assessment of nutrient dynamics under shifting cultivation in eastern Madagascar. *Agric. Ecosyst. Environ*. **71**, 169-183.

Brown, R.B., Cutshall, N.H. & Kling, G.F. (1991a). Agricultural erosion indicated by Cs-137 redistribution: I. Level and distribution of Cs-137 activity in soils. *Soil Sci. Soc. Amer. J*. **45**, 1184-1190.

Brown, R.B., Kling, G.F. & Cutshall, N.H. (1991b). Agricultural erosion indicated by Cs-137 redistribution: II. Estimates of erosion rates. *Soil Sci. Soc. Amer. J*. **45**, 1191-1197.

Brown, S. and Lugo, A.E. (1990). Tropical secondary forests. *J. Trop. Ecol*. **6**, 1-32.

Bruijnzeel, L. A. (1990). *Hydrology of moist tropical forests and effects of conversion: A state of knowledge review*. UNESCO, Paris.

Bruijnzeel, L.A., Waterloo, M.J., Proctor, J., Kuiters, A.T. & Kotterink, B. (1993). Hydrological observations in montane rain forests on Gunung Silam, Sabah, Malaysia, with special reference to the 'Massenerhebung' effect. *J. Ecol*. **81**, 145-167.

Burghouts, T., Ernsting, G., Korthalis, G. & de Vries, T. (1992). Litterfall, leaf litter decomposition and litter invertebrates in primary and secondary logged dipterocarp forest in Sabah, Malaysia. *Phil. Trans. Roy. Soc. Lond. B.* **335**, 407-416.

Busacca, A.J., Cook, C.A. & Mulla, D.J. (1993). Comparing landscape-scale estimation of soil erosion in the Palouse using Cs-137 and RUSLE. *J. Soil Water Conserv*. **48**, 361-367.

Butterfield, R P. (1995). Promoting biodiversity: advances in evaluating native species for reforestation. *For. Ecol. Manage*. **75**, 111-121.

Butterfield, R.P. (1996). Early species selection for tropical reforestation: a consideration of stability. *For. Ecol. Manage*. **81**, 161-168

Butterfield, R.P. and Espinoza, C.M. (1995). Screeing 14 tropical hardwoods with an emphasis on species native to Costa Rica: fourth year results. *New For*. **9**, 135-145.

Butterfield, R.P. and Fisher, R.F. (1994). Untapped potential: native species for reforestation. *J. For*. **92**, 37-40.

Cannell, M.G.R. (1985). Dry matter partitioning in tree crops. In: Cannell M.G.R. and Jackson J.E. (eds) *Attributes of Trees as Crop Plants*, pp. 160-193. ITE, Abbots Ripton, UK

Cavelier, J., Solis, D. & Jaramillo, M. (1996). Fog interception in the montane forests across the Central Cordillera of Panamá. *J. Trop. Ecol*. **12**, 357-369.

Cavelier, J., Jaramillo, M., Solis, D. & de León, D. (1997). Water balance and nutrient inputs in bulk precipitation in tropical montane cloud forest in Panama. *J. Hydrol*. **193**, 83-96.

Chamberlain, J.R. (1998). Isozyme variation in *Calliandra calothyrus* (Leguminosae): its implications for species delimitation and conservation. *Am. J. Bot*. **85**, 37-47.

Chamberlain, J.R. and Hubert, J.D. (2000). Molecular analyses of variation. In: Chamberlain J.R. (ed.) Calliandra calothyrsus*: an Agroforestry Tree for the Humid Tropics*. Tropical Forestry Paper No. 40, Oxford Forestry Institute, Oxford, UK

Champion, H.G. (1966). *Report on soil erosion in the Mahogany Vale catchment and its control with special reference to sedimentation in the future reservoir*. London: Howard Humphries and Sons, 52 pp.

Clark, K.L., Nadkarni., N.M., Schaefer, D. & Gholz, H.L. (1998). Atmospheric deposition and net retention of ions by the canopy in a tropical montane forest, Monteverde, Costa Rica. *J. Trop. Ecol*. **14**, 27-45.

Collins, A. and McDonald, M.A. (1997). Farmer knowledge and use of trees indigenous to the montane forests of the Blue and John Crow Mountains National Park, Jamaica. In: Healey, J.R., McDonald, M.A., Devi Prasad, P.V. (Eds.), *On-farm Research for the Development and Promotion of Improved Agroforestry Systems for Steeplands in the Caribbean: 1996-1997 Annual Report of ODA Forestry Research Project R6290*, School of Agricultural and Forest Sciences, University of Wales, Bangor, U.K., pp. 28-52.

Condit, R., Hubbell, S.P. & Foster, R.B. (1993). Identifying fast-growing native tress from the Neotropics using data from a large, permanent census plot. *For. Ecol. Manage*. **62**, 123-143.

Cramb, R.A., Garcia, J.N.M., Gerrits, R.V. and Saguiguit, G.C. (1999). Smallholder adoption of soil conservation technologies: evidence from upland projects in the Philippines. *Land Degrad. Devel*. **10**, 405-423.

Cross, A.F., and Schlesinger, W.H. (1995). A literature review and evaluation of the Hedley fractionation: applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma* **64**, 197-214.

Dalling, J.W. (1994). Vegetation colonization of landslides in the Blue Mountains, Jamaica. *Biotropica* **26**, 392-399.

Dalling, J.W. and Tanner, E.V.J. (1995). An experimental study of regeneration on landslides in montane rain forest in Jamaica. *J. Ecol*. **83**, 55-64.

Dantas, M. and Philipson, J. (1989). Litterfall and litter nutrient content in primary and secondary Amazonian 'terra firme' rain forest. *J. Trop. Ecol*. **5**, 27-36.

Davidson, R., Gagnon, D., Maufette, Y., Hernandez, H. (1998). Early survival, growth and foliar nutrients in native Ecuadorian trees planted on degraded volcanic soil. *For. Ecol. Manage*. **105**, 1-19.

de Graaff, J. (1996). The price of soil erosion. *Mansholt Studies* **3**, Wageningen Agricultural University.

Dharmasena, P.B. (1995). Conservation farming practices for small reservoir watersheds: a case study from Sri Lanks. *Agrofor. Syst.* **28**, 203-212.

Douglas, J.E. (1995). On-farm research for the development and promotion of improved agroforestry systems for steeplands in the Caribbean: Ethnobotanical survey. In Healey, J.R., McDonald, M.A. & Devi Prasad, P.V. (eds) *1995-1996 Annual Report of ODA Forestry Research Project R6290*, School of Agricultural and Forest Sciences, University of Wales, Bangor, U.K., 32pp.

Duguma B. and Mollet M. (1998). Early growth of *Calliandra calothyrsus* (Meissner) provenances in the acid soils of southern Cameroon. *Agrofor. Syst.* **40**, 283-296

Elwell, H.A. and Stocking, M.A. (1976). Vegetative cover to estimate soil erosion hazard in Rhodesia. *Geoderma* **15**, 61-70.

Evans, D.O. (ed.) (1996). *Proceedings of an International Workshop on the Genus* Calliandra. Winrock International, Morrilton, USA.

Evans, J. (1992). *Plantation forestry in the Tropics*, 2nd edn., Clarendon Press, Oxford.

Ewel, J.J. (1976). Litterfall and leaf decomposition in a tropical forest succession in eastern Guatemala. *J. Ecol*. **64**, 293-308.

Eyre, L.A. (1987). Fire in the tropical environment. *Jamaica J.* **20**, 10-16.

FAO. (1999). *State of the world's forests 1999*, Food and Agriculture Organisation of the United Nations, Rome, Italy, 155 pp.

FAO-UNESCO. (1975). *Soil Map of the World. Volume III*. Mexico and Central America. UNESCO, Paris.

Finch, T. (1952). *Soil survey of the area administered by the Yallahs Valley Land Authority, Jamaica*. Trinidad: Imperial College Tropical Agriculture.

Fielding, W.J. and Sherchan, D.P. (1999). The variability of level and sloping terraces in Eastern Nepal and the implications for the design of experiments. *Exp. Agric*. **35**, 449-459.

Floyd, B. (1970). Agricultural innovation in Jamaica: the Yallahs Valley Land Authority. *Economic Geography* **46**, 63-67.

Floyd, B. (1979). *Jamaica - an island microcosm*. London, Macmillan.

Fujisaka, S. (1989). The need to build upon farmer practices and knowledge: reminders from selected upland conservation projects and policies. *Agrofo. Syst.* **15**, 51-63.

Fujisaka, S. (1993). A case of farmer adaptation and adoption of contour hedgerows for soil conservation. *Exp. Agric.* **29**, 97-105.

Fujisaka, S. (1997). Sense and nonsense: contour hedgerows for erosion control. *Agrofor. Forum* **8 (4)**, 8-11.

Fujisaka, S., Jayson, E. & Dapasula, A. (1994). Trees, grasses and weeds: species choices in farmer-developed contour hedgerows. *Agrofor. Syst.* **25**, 13-22.

Funakawa, S., Tanaka, S., Shinjyo, H., Kaewkhongkha, T., Hattori, T. & Yonebayashi, K. (1997). Ecological study on the dynamics of soil organic matter and its related properties in shifting cultivation in Northern Thailand. *Soil Sci. Pl. Nutr*. **43**, 681-693.

Gales, K. (1979). Effects of water supply on partitioning of dry matter between roots and shoots in *Lolium perenne*. *J. Appl. Ecol*. **16**, 54-63

Gardner, R. and Mawdesley, K. (1997). Soil erosion in the Middle Mountains of Nepal. *Agrofor. Forum* **8 (4)**, 25-29.

Garrity, D.P. (1996). Tree-soil-crop interactions on slopes. In: Ong, C.K. and Huxley, P. (eds) *Tree-Crop Interactions*. CAB International, Wallingford, pp. 299-318.

GOJ/UNDP/FAO. (1982). *Development plan for the Upper Yallahs*. Project working paper WP/23.

González, J.E. and Fisher, R.F. (1994). Growth of native forest species planted on abandoned pasture land in Costa Rica. *For. Ecol. Manage*. **70**, 159-167.

Goodland, T.C.R., Bellingham, P.J., Healey, J.R. & Tanner, E.V.J. (1998). *The woody plant species of the Blue Mountains of Jamaica: a database*. School of Agricultural and Forest Sciences, University of Wales, Bangor.

Goodland, T.C.R. and Healey, J.R. (1995). Monitoring the effect of an invasive tree, *Pittosporum undulatum*, on the biodiversity of the Blue Mountains of Jamaica. In: *Abstracts of Measuring and Monitoring Forest Biological Diversity*. International Symposium organised by the Smithsonian Institution / Man and the Biosphere Biodiversity Program, Washington D.C., 23-25 May 1995.

Goodland, T.C.R. and Healey, J.R. (1998). Seedling identification notes: upper montane forest – Jamaican Blue Mountains. In: Healey, J.R., McDonald, M.A. & Devi Prasad, P.V. (eds). *On-farm research for the development and promotion of improved agroforestry systems for steeplands in the Caribbean*. DFID Forestry Research Programme R6290 Final report, 79 pp + appendices.

Grubb, P.J. and Tanner, E.V. J. (1976). The montane forests and soils of Jamaica: a reassessment. *J. Arn. Arb.* **57**, 313-368.

Gumbs, F.A. (1992). *Integrating soil conservation into farming systems in the Commonwealth Caribbean*. Status report and components of a regional programme. Commonwealth Secretariat, London.

Gumbs, F.A. (1994). *Farmers and soil conservation in the Caribbean*. Commonwealth Secretariat, London.

Habeck, J.R. (1958). White cedar ecotypes in Wisconsin. *Ecology* **39**, 457-463.

Hafkenscheid, R.L.L.J. (2000). *Hydrology and biogeochemistry of tropical montane rain forests of contrasting staturein the Blue Mountains, Jamaica*. PhD thesis, Vrije Universiteit, Amsterdam.

Hafkenscheid, R.L.L.J., Bruijnzeel, L.A. & de Jeu, R.A.M. (1998). Estimates of fog interception by montane rain forest in the Blue Mountains of Jamaica. In: Schemenauer, R.S., Bridgman, H.A. (eds.), *Proceedings of the First International Conference on Fog and Fog Collection*, Vancouver, Canada, 19-24 July 1998, pp. 33-36.

Haggar, J.P., Bufird Briscoe, C. & Butterfield, R.P. (1998). Native species: a resource for the diversification of forestry production in the lowland humid tropics. *For. Ecol. Manage*. **106**, 195-203.

Harcombe, P.A. (1977). The influence of fertilization on some aspects of succession in a humid tropical forest. *Ecology* **58**, 1375-1383.

Healey, J.R. (1989). A bioassay study of soils in the Blue Mountains of Jamaica. In: Proctor, J. (ed.) *Mineral nutrients in tropical forest and savanna ecosystems*. Special publication number **9** of the British Ecological Society, Blackwell Scientific Publications, Oxford, pp. 273-88.

Healey, J.R., Goodland, T.C.R., Binggeli, P. & Hall, J.B. (1995). *The Impact on Forest Biodiversity of an Invasive Tree Species and the Development of Methods for its Control*. Final Report of ODA Forestry Research Project R4742, School of Agricultural and Forest Sciences, University of Wales, Bangor.

Healey, J.R., Goodland T.C.R., Hall, J.B. & Devi Prasad, P.V. (1992). *The impact on forest biodiversity of an invasive tree species and the development of methods for its control*. Annual Report of ODA Forestry Research Project R4742, School of Agricultural and Forest Sciences, University of Wales, Bangor, pp36.

Healey, J.R., Hall J.B., Goodland T.C.R. & Devi Prasad, P.V. (1993). *The impact on forest biodiversity of an invasive tree species and the development of methods for its control.* Annual Report of ODA Forestry Research Project R4742, School of Agricultural and Forest Sciences, University of Wales, Bangor.

Healey, J.R., McDonald M.A. & Devi Prasad, P.V. (1994). *The protection role of Jamaican catchment forests and their resistance to and recovery from the impact of Hurricane Gilbert*. Annual Report of ODA Forestry Research Project R4611, School of Agricultural and Forest Sciences, University of Wales, Bangor.

Healey, J.R., McDonald, M.A. & Devi Prasad, P.V. (1998). On-farm Research for the Development and Promotion of Improved Agroforestry Systems for Steeplands in the Caribbean. Final report of DFID Forestry Research Project R6290, School of Agricultural and Forest Sciences, University of Wales, Bangor, UK, 89 pp.

Hegarty, E.E. (1991). Leaf production by lianes and trees in a sub-tropical Australian rain forest. *J. Trop. Ecol*. **7**, 201-214.

Hellin, J. and Larrea, S. (1997). Live barriers on hillside farms: are we really addressing farmers' needs. *Agrofor. Forum* **8 (4)**, 17-20.

Henrot, J. and Robertson, G.P. (1994). Vegetation removal in two soils of the humid tropics: effects on microbial biomass. *Soil Biol. Biochem*. **26**, 111-116.

Herbohn, J.L.and Congdon, R.A. (1993). Ecosystem dynamics at disturbed and undisturbed sites in north Queensland wet tropical rain forest: II litterfall. *J. Trop. Ecol*. **9**, 365-380.

Holscher, D., Ludwig, B., Moller, R.F. & Folster, H. (1997). Dynamic of soil chemical properties in shifting agriculture in the Eastern Amazon. *Agric. Ecosyst. Environ*. **66**, 153-163.

Huxley, P.A. (1985). The basis of selection, management and evaluation of multipurpose trees – an overview. In: Cannell, M.G.R. and Jackson, J.E. (eds) *Attributes of Trees as Crop Plants*, ITE, Abbots Ripton, UK pp. 13-35.

ICRAF. (1994). International Centre for Research in Agroforestry, Nairobi. *Annual report* **1994** 208 pp.

Jones, M., Sinclair, F.L. & Grime, V. (1998). Effect of tree species and crown pruning on root length and soil water content in semi-arid agroforestry. *Plant Soil* **201**, 199-210.

Jordan, C.F. (1985). *Nutrient Cycling in Tropical Forest Ecosystems: Principles and Their Application in Management and Conservation.* Wiley, Chichester.

Jordan, C.F. (ed.) (19890. *An Amazonian Rain Forest: the Structure and Function of a Nutrient Stressed Ecosystem and the Impact of Slash-and-burn Agriculture*. UNESCO, Paris.

Juo, A.S.R. and Kang, B.T. (1989). Nutrient effects of modification of shifting cultivation in West Africa. In: Proctor, J. (ed.), *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*. Blackwell Scientific Publications, Oxford, pp. 289-300.

Juo, A.S.R.and Manu, A. (1996). Chemical dynamics in slash-and-burn agriculture. *Agric. Ecosyst. Environ*. **58**, 49-60.

Kang, B.T. (1993). Alley cropping: past achievements and future directions. *Agrofor. Syst.* **23**, 141-155.

Kang, B.T., Grimme, H. & Lawson, T.L. (1985). Alley cropping sequentially cropped maize and cowpea with Leucaena on sandy soil in southern Nigeria. *Plant Soil* **85**, 264-277.

Kang, B.T. and Ghuman, B.S. (1991). Alley cropping as a sustainable system. In: Moldenhauer, W.C., Hudson, N.W., Sheng, T.C. & Lee, S.W. (eds.), *Development of Conservation Farming on Hillslopes*, Soil and Water Conservation Society, Ankeny, Iowa, USA, pp. 172-184.

Kang, B.T., Reynolds, L. & Atta-Krah, A.N. (1990). Alley farming. *Adv. Agron.* **43**, 315-359.

Kellman, M.C. (1970). *Secondary plant succession in tropical montane Mindanao*. Publication BG/2, Research School of Pacific Studies, Australian National University, Canberra, Australia.

Kellman, M. and Tackaberry, R. (1997). *Tropical Environments: the Functioning and Management of Tropical Ecosystems*. Routledge, London.

Kerr, R. *et al.* (1991). *Blue Mountains and John Crow Mountains National Park draft management plan.* NRCA, Kingston, Jamaica.

Kiepe, P. (1995). Effect of *Cassia siamea* hedgerow barriers on soil physical properties. *Geoderma* **66**, 113-120.

Kiepe, P. and Young, A. (1992). Soil conservation through agroforestry: experience from four years of demonstrations at Machakos, Kenya. In: Hurni, H. and Tato, K. (eds) *Erosion, conservation and small-scale farming*. Geographica Bernsia, Berne, pp. 303-312.

Kleinman, P.J.A., Bryant, R.B. & Pimentel, D. (1996). Assessing ecological sustainability of slash-and-burn agriculture through soil fertility indicators. *Agron. J*. **88**, 122-127.

Knowles, O.H. and Parrotta, J. A. (1995). Amazonian forest restoration: an innovative system for native species selection based on phenological data and field performance indices. *Comm. For. Rev*. **74**, 230-243.

Lal. R. (1989a). Potential of agroforestry as a sustainable alternative to shifting cultivation: concluding remarks. *Agrofor. Syst.* **8**, 239-242.

Lal, R. (1989b). Agroforestry systems and soil surface management of a tropical alfisol. 2. Water runoff, soil erosion and nutrient loss. *Agrofor. Syst.* **8**, 97-111.

Lal, R. (1989c) Agroforestry systems and soil surface management of a tropical alfisol. 3. Changes in soil chemical properties. *Agrofor. Syst.* **8**, 113-132.

Lal, R. (1996). Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. II. Soil chemical properties. *Land Degrad. Devel*. **2**, 87-98.

Lal, R. (1997). Soil degradative effects of slope length and tillage methods on Alfisols in western Nigeria. I. Runoff, erosion and crop response. *Land Degrad. Devel*. **8**, 201-219.

Leach, M. and Mearns, R. (1996). *The lie of the land: challenging received wisdom on the African environment*. London: International African Institute, with J. Correy and Heinemann.

Ledig, F.T. (1983). The influence of genotype and environment on dry matter distribution in plants. In: Huxley, P.A. (ed) *Plant Research and Agroforestry,* ICRAF, Nairobi, Kenya, pp. 427-454.

Lugo, A.E. (1992). Comparison of tropical tree plantations with secondary forests of similar age. *Ecol. Monogr*. **62**, 1-41.

Lundgren, L. (1980). Comparison of surface runoff and soil loss from runoff plots in forest and small-scale agriculture in the Usambara Mts., Tanzania. *Geografiska Annaler* **62A**, 113-148.

Maass, J.M., Jordan, C.F. & Sarukhan, J. (1988). Soil erosion and nutrient losses in seasonal tropical agroecosystems under various management techniques. *J. Appl. Ecol.* **25**, 595-607.

McDonald, M. and Brown, K. (2000). Soil and water conservation projects and rural livelihoods: options for design and research to enhance adoption and adaptation. *Land Degrad. Devel*. **11**, 343-361.

McDonald, M.A. and Healey, J.R. (2000). Nutrient cycling in secondary forests in the Blue Mountains of Jamaica. *For. Ecol. Manage*. **139**, 257-278.

McGregor, D.F.M. (1988). An investigation of soil status and landuse on a steeply sloping hillside, Blue Mountains, Jamaica. *Singapore J. Trop. Geog*. **9**, 60-71.

McGregor, D.F.M., Barker, D. & Miller, L.A. (1985). Land resources and development in the Upper Yallahs Valley, Jamaica: a preliminary assessment. *Papers in Geography* **18** Bedford College, University of London.

MacQueen, D.J. (1992). *Calliandra calothyrsus*: implications of plant taxonomy, ecology and biology for seed collection. *Comm. For. Rev.* **71**, 20-34.

MacQueen, D.J. (1993). Calliandra *series* Racemosae*: taxonomic information; OFI seed collections; trial design*. Oxford Forestry Institute, Department of Plant Sciences, University of Oxford, 157 pp.

Montagnini, F. and Sancho, F. (1994). Net nitrogen mineralization in soils under six indigenous tree species, and abandoned pasture and a secondary forest in the Atlantic lowlands of Costa Rica. *Plant Soil* **162**, 117-124.

Montagnini, F., Fanzeres, A. & da Vinha, S.G. (1994). Studoes on restoration ecology in the Atlantic forest region of Bahia, Brazil. *Interciencia* **19**, 323-330.

Montagnini, F., Gonzalez, E., Porras, C. & Rheingans, R. (1995). Mixed and pure forest plantations in the humid neotropics: a comparison of early growth, pest management and establishment costs. *Comm. For. Rev*. **74**, 306-314.

Morellato, L.P.C. (1992). Nutrient cycling in two south-east Brazilian forests. I. Litterfall and litter standing crop. *J. Trop. Ecol*. 8, 205-215.

Morgan, R.P.C. (1979). Soil Erosion. Longman, New York.

Morgan, R.P.C. (1986) *Soil erosion and conservation*. Longman Scientific and Technical, UK.

Morikawa, B., Lantagne, D.O., Gold, M.A., Krecik, S. & Roshetko, J.M. (1995). Management of *Calliandra calothyrsus* for fodder production in Jamaica. *Trop. Grassl*. **29**, 236-240.

Mueller-Harvey, I., Juo, A.S.R. & Wild, A. (1989). Mineralization of nutrients after forest clearance and their uptake during cropping. In: Proctor, J. (ed.) *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*. Blackwell Scientific Publications, Oxford, pp. 315-324.

National Academy of Sciences. (1980). *Firewood Crops: Shrub and Tree Species for Energy Production*. National Academy of Sciences, Washington, D.C.

National Research Council. (1983). Calliandra*: a versatile small tree for the humid tropics*. National Academy Press, Washington, D C.

Njoroge, M. and Rao, M.R. (1995). *Barrier hedgerow intercropping for soil and water conservation on sloping lands*. ICRAF, Nairobi, 28 pp.

Nortcliff, S., Ross, S.M. & Thornes, J.B. (1990). Soil moisture, runoff and sediment yield from differentially cleared tropical rain forest plots. In: Thornes, J.B. (ed.) *Vegetation and Erosion*. Wiley, Chichester, pp. 419-436.

Nye, P.H. and Greenland, D.J. (1960). *The soil under shifting cultivation.* Tech. Comm. No. 51, Commonwealth Bureau of Soils, Harpenden, UK.

Nye, P.H. and Greenland, D.J. (1964). Changes in soil after clearing a tropical forest. *Plant Soil* **21**, 101-112.

Ong, C. (1994). Alley cropping - ecological pie in the sky? *Agrofor. Today* **6(5)**, 8-10.

Ongprasert, S. and Turkelboom, F. (1996). Twenty years of alley cropping research and extension in the slopes of northern Thailand. In: Turkelboom, F., van Look-Rothschild, K. & van Keer, K. (eds.) *Highland Farming: Soil and the Future*? Proceedings of a Conference, Chiang Mai, Thailand, 21-22 December, 1995, pp. 55-71.

Owino, F. (1996). Selection and adaptation in multipurpose trees and shrubs for production and function in agroforestry systems. *Euphytica* **92**, 225-234.

Palm, C.A., Swift, M.J. & Woomer, P.L. (1996). Soil biological dynamics in slash-and-burn agriculture. *Agric. Ecosyst. Environ*. **58**, 61-74.

Palmer, B., MacQueen, D.J. & Gutteridge, R.C. (1994). *Calliandra calothyrsus* – a multipurpose tree legume for humid locations. In: Gutteridge, R.C., Shelton, H.M. (eds.) *Forage Tree Legumes in Tropical Agriculture*. CAB International, Wallingford, pp. 65-74.

Palo, M. and Mery, G. (1996). Transition from deforestation to sustainable forestry – a distant dream? In: Palo, M and Mery, G. (eds) *Sustainable forestry challenges for developing countries*. Environmental Science and Technology Libraray Volume 10. Kluwer Academic Publishers, The Netherlands, pp. 1-15.

Paningbatan, E.P. Jr (1990). Alley cropping for managing soil erosion in sloping lands. *Transactions 14th ISSS Congress, Kyoto, Japan*, **Vol VII**, 376-377.

PARC. (1994). *Protected Areas Resources Conservation Project: Blue and John Crow Mountains National Park* Management Plan, Kingston, Jamaica.

Parker, G.G. (1983). Throughfall and stemflow in the forest nutrient cycle. *Adv. Ecol. Res*. **13**, 57-133.

Pellek, R. (1992). Contour hedgerows and other soil conservation interventions for hilly terrain. *Agrofor. Syst.* **17**, 135-152.

Pendry, C.A. and Proctor, J. (1996). The causes of altitudinal zonation of rain forests of Bukit Belalong, Brunei. *J. Ecol.* **84**, 407-418.

Pickup, G. (1985). The erosion cell – a geomorphic approach to landscape classification in range assessment. *Aust. Rangel. J*. **7**, 114-121.

Pottinger, A. (1996). The international calliandra network coordinated by the Oxford Forestry Institute. In: Evans, D.O. (1996). *International workshop on the Genus* Calliandra. Proceedings of a workshop held January 23-27, 1996, in Bogor, Indonesia. Forest, Farm, and Community Tree Research Reports (Special Issue). Winrock International, Morrilton, Arkansas, USA. pp. 97-101.

Poudel, D.D., Midmore, D.J. & West, L.T. (1999). Erosion and productivity of vegetable systems on sloping volcanic ash-derived Philippine soils. *Soil Sci. Soc. Am. J*. 63, 1366-1376.

Pretty, J.N. (1995). *Regenerating agricultural: policies and practice for sustainability and self-reliance*. Earthscan Publications Ltd., London.

Proctor, J. (1983). Tropical forest litterfall II: the data set. In: Chadwick, A.C., Sutton, S.L. (eds*.) Tropical Rain-Forest: the Leeds Symposium*. Leeds Philosophical and Literary Society Ltd., Leeds, pp. 83-113.

Ramakrishnan, P.S. (1990). Agricultural systems of the northeastern hill region of India. In: Gliessman, S.R. (ed.) *Agroecology*. Springer-Verlag, New York, pp. 251-274.

Ramakrishnan, P.S. and Toky, O.P. (1981). Soil nutrient status of hill agro-ecosystems and recovery pattern after slash and burn agriculture (jhum) in northeastern India. *Plant Soil* **60**, 41-64.

Rao, M.R., Nair, P.K.R. & Ong, C.K. (1998). Biophysical interactions in tropical agroforestry systems. Agrofor. Syst. **38**, 3-50.

Richardson, J.H. (1982). Some implications of tropical forest replacement in Jamaica. *Z. Geomorph*. **11**, 107-118.

Riha, S.J. and McIntyre, B.D. (1999). Water management with hedgerow agroforestry systems. In: Buck, L.E., Lassoie, J.P. & Fernandes, E.C.M. (eds) *Agroforestry in Sustainable Agricultural Systems*. CRC Press, Boca Raton, Florida, pp. 47-66.

Roder, W., Phengchanh, S. & Maniphone, S. (1997). Dynamics of soil and vegetation during crop and fallow period in slash-and-burn fields of northern Laos. *Geoderma* **76**, 131-144.

Roshetko, J.M., Lantagne, D.O., Gold, M.A., Morikawa, B. & Krecik, S. (1996). Recommendations for establishing and managing *Calliandra calothyrsus* as a fodder resource in Jamaica. In: Evans, D.O. (ed) *International Workshop on the Genus* Calliandra. Proceedings of a workshop held January 23-27, 1996, in Bogor, Indonesia. Forest, Farm, and Community Tree Research Reports (Special Issue). Winrock International, Morrilton, Arkansas, USA, pp. 168-179.

Salcedo, I.H., Tiessen, H. & Sampaio, E.V.S.B. (1997). Nutrient availability in soil samples from shifting cultivation in the semi-arid Caatinga of NE Brazil. *Agric. Ecosyst. Env*. **65**, 177-186.

Samsuzzaman, S., Garrity, D.P. & Quintana, R.U. (1999). Soil property changes in contour hedgerow systems on sloping land in the Philippines. *Agrofor. Syst*. **46**, 251-272.

Sanchez, P.A. (1976). *Properties and Management of Soils in the Tropics*. John Wiley, New York.

Sanchez, R.G. and Alvarez-Sanchez, J. (1995). Litterfall in primary and secondary tropical forests of Mexico. *Trop. Ecol*. 36, 191-201.

Sanchez, P.A., Palm, C.A., Davey, C.B., Szott, L.T. & Russell, C.E. (1985). Trees as soil improvers in the humid tropics? In: Cannell, M.G.R. and Jackson, J.E. (eds.) *Attributes of Trees as Crop Plants*. Institute of Terrestrial Ecology, Abbots Ripton, pp. 327-358.

Scatena, F.N., Moya, S., Estrada, C. & Chinea, J.D. (1996). The first five years in the reorganisation of aboveground biomass and nutrient use following Hurricane Hugo in the Bisley experimental watersheds, Luquillo Experimental Forest, Puerto Rico. *Biotropica* **28**, 424-440.

Scherr, S.J. (ed.) (1991). On-farm agroforestry research. *Agrofor. Syst.* **15**, 91-302.

Schroth, G. (1995). Tree root characteristics as criteria for species selection and systems-design in agroforestry. *Agrofor. Syst*. **30**, 125-143.

Scott, D.A., Proctor, J. & Thompson, J. (1992). Ecological studies on a lowland evergreen rain forest on Maraca Island, Roraima, Brazil. II. Litter and nutrient cycling. *J. Ecol.* **80**, 705-717.

Shang, C. and Tiessen, H. (1997). Organic matter lability in a tropical Oxisol: evidence from shifting cultivation, chemical oxidation, particle size, density, and magnetic fractionations. *Soil Sci*. **162**, 795-807.

Shaxton, T.F., Tiffen, M., Wood, A. & Turton, C. (1997). *Better land husbandry: re-thinking approaches to land improvement and the conservation of water and soil*. ODI Natural Resource Perspectives 19.

Sheng, T.C. (1972). A treatment-oriented land capability classification scheme for hilly marginal lands in the humid tropics. *J. Sci. Res. Council Jamaica* **3**, 93-112.

Sheng, T.C. (1981). The need for soil conservation structures for steep cultivated slopes in the humid tropics. In: Lal, R. and Russell, E.W. (eds) *Tropical Agricultural Hydrology*. Chichester: John Wiley, pp. 357-372.

Shreve, F. (1914). *A montane rain forest*. Carnegie Institute of Washington Publication 119, pp. 110.

Sillitoe, P. and Shiel, R.S. (1999). Soil fertility under shifting and semi-continuous cultivation in the Southern Highlands of Papua New Guinea. *Soil Use Manage*. **15**, 49-55.

Sinclair, F.L., Verinumbe, I. & Hall, J.B. (1994). The role of domestication in agroforestry. In: Leakey, R.R.B. and Newton, A.C. (eds) *Tropical Trees: the Potential for Domestication and the Rebuilding of Forest Resources*. ITE, Penicuik, UK, pp. 124-136.

Skalar Analytical. (1993). *The SANplus Segmented Flow Analyzer and its Applications*. Skalar Analytical B.V., De Breda.

SPSS. (1988). *SPSS/PC+ V2.0 Base Manual*. Marija J. Norusis/SPSS Inc., Chicago, Il.

STATIN. (1991). *Jamacia Population Census*, Statistical Institute of Jamaica, Kingston, Jamaica.

Stocker, G.C., Thompson, W.A., Irvine, A.K., Fitzsimon, J.D. & Thomas, P.R. (1995). Annual pattern of litterfall in lowland and tableland rainforest in tropical Australia. *Biotropica* **27**, 412-420.

Stocking, M.A. and Elwell, H.A. (1973). Prediction of subtropical storm losses from field plot studies. *Agric. Met.* **12**, 193-201.

Stromgaard, P. (1985). Biomass, growth, and burning of woodland in a shifting cultivation area of South Central-Africa. *For. Ecol. Manage*. **12**, 163-178.

Stromgaard, P. (1992). Immediate and long-term effects of fire and ash fertilization on a Zambian Miombo woodland soil. *Agric. Ecosyst. Env*. **41**, 19-37.

Suah, J.R.R. and Nicholson, D.P. (1992). The role of agroforestry in Jamaica. In: Thompson, D.A., Bretting, P.K. & Humphreys, M. (eds) *Forests of Jamaica*. Jamaican Society of Scientists and Technologists, pp. 107-111.

Swabey, C. (1940). *Lumber on crown lands*. Extract from the Proceedings of the Jamaica Agricultural Society, for February, 1940.

Swabey, C. (1941). *The principal timbers of Jamaica*. Department of Science and Agriculture, Jamaica. Bulletin 29, 37 pp.

Swabey, C. (1945). *Forestry in Jamaica*. Forestry Bulletin 1, Jamaica Department of Forestry.

Swaine, M.D. and Whitmore, T.C. (1988). On the definition of ecological species groups in tropical rain forests. *Vegetatio* **75**, 81-86.

Szott, L.T., Palm, C.A. & Sanchez, P.A. (1991). Agroforestry in acid soils of the humid tropics. *Adv. Agron*. **45**, 275-301.

Tacio, H.D. (1993). Sloping Agricultural Land Technology (SALT); a sustainable agroforestry scheme for the uplands. *Agofor. Syst.* **22**, 145-152.

Tanner, E.V.J. (1977a). Four montane rain forests of Jamaica: a quantitative characterisation of the floristics, the soils and the foliar mineral levels, and a discussion of the interrelations. *J. Ecol.* **65**, 573-588.

Tanner, E.V.J. (1977b). Mineral Cycling in Montane Rain Forests in Jamaica. Ph.D. dissertation, University of Cambridge.

Tanner, E.V.J. (1980a). Studies on the biomass and productivity in a series of montane rain forests in Jamaica. *J. Ecol.* **68**, 573-588.

Tanner, E.V.J. (1980b). Litterfall in montane forests of Jamaica and its relation to climate. *J. of Ecolog*, **68** 833-848.

Tanner, E V J (1981) The decomposition of leaf litter in Jamaican rain forests. *J. Ecol.* **69**, 263-275.

Tanner, E.V.J. (1985). Jamaican montane forests: nutrient capital and cost of growth. *J. Ecol*. **73**, 553-568.

Tanner, E.V.J. (1986). Forests of the Blue Mountains and the Port Royal Mountains of Jamaica. In: Bretting, P.K., Thmpson, D.A. & Humphries, M. (eds.) *Forests of Jamaica*. Jamaican Society of Scientists and Technologists, Kingston, pp. 15-30.

Tanner, E.V.J., Kapos V., Freskos S., Healey J.R. & Theobald, A.M. (1990). Nitrogen and phosophorus fertilization of Jamiacan montane forest trees. *J. Trop. Ecol.* **6**, 231-238.

Tanner E.V.J., Vitousek P.M. & Cuevas E. (1998). Experimental investigation of nutrient limitation of forest growth on wet tropical mountains. *Ecology* **79**, 10-22.

Tennant, D. (1975). A modified line intercept method for estimating root length. *J. Ecol.* **63**, 995-1001.

Thaiutsa, B., Suwannapinunt, W. & Kaitpraneet, W. (1978). *Preliminary study of production and chemical composition of forest litter in Thailand*. Forest Research Bulletin 52, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.

Thompson, D.A. (1986). Leucaena leucocephala *and other fast growing trees*. Institute of Jamaica Publications, Kingston, Jamaica.

Tiessen, H., Cuevas, E. & Chacon, P. (1994). The role of soil organic matter in sustaining soil fertility. *Nature* **371**, 783-5.

Tiessen, H., Salcedo, I.H. & Sampaio, E.V.S.B. (1992). Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agric. Ecosyst. Env*. **38**, 139-151.

Tulaphitak, T., Pairinatra, C. & Kyuma, K. (1985). Changes in soil fertility and tilth under shifting cultivation. 2. Changes in soil nutrient status. *Soil Sci. Pl. Nutr*. **31**, 239-249.

Turkelboom, F., Poesen, J., Ohler, I., van Keer, K., Ongprasert, S. & Vlassak, K. (1997). Assessment of tillage erosion rates on steep slopes in northern Thailand. *Catena* **29**, 29-44.

UNESCO. (1978). Tropical forest ecosystems. UNESCO, Paris.

van Noordwijk, M., van Roode, M., McCallie, E.L. & Lusiana, B. (1998). Erosion and sedimentation as multiscale, fractal processes: implications for models, experiments and the real world. In: Penning de Vries, F.W.T., Agus, F. & Kerr, J. (eds) *Soil erosion at multiple scales: principles and methods for assessing causes and impacts*. CAB International, Wallingford, UK, pp. 223-253.

Veneklaas, E.J. (1991). Litterfall and nutrient fluxes in two montane tropical rain forests, Colombia. *J. Trop. Ecol*. **7**, 319-336.

Vitousek, P.M. (1984). Litterfall, nutrient cycling, and nutrient limitation in tropical forests. *Ecology* **65**, 285-298.

Vitousek, P.M. and Reiners, W.A. (1975). Ecosystem succession and nutrient retention: a hypothesis. *Bioscience* **25**, 376-381.

Vitousek, P.M. and Sanford, R.L. Jr (1986). Nutrient cycling in moist tropical forests. *Ann. Rev. Ecol. Syst.* **17**, 137-167.

Vitousek, P.M., Gerrish, G., Turner, D.R., Walker, L.R. & Mueller-Dombois, D. (1995). Litterfall and nutrient cycling in four Hawaiian montane rainforests. *J. Trop. Ecol*. **11**, 189-203.

Walker, L.R., Zimmerman, J.K., Lodge, D.J. & Guzmán-Grajales, S. (1996). An altitudinal comparison of growth and species composition in hurricane-damaged forests in Puerto Rico. *J. Ecol*. **84**, 877-889.

Weaver, P.L. and Murphy, P.G. (1990). Forest structure and productivity in Puerto Rico's Luquillo Mountains. *Biotropica* **22**, 69-82.

Westoby, M. (1987). Soil erosion, as a landscape ecology phenomenon. *Trends Ecol. Evol*. **2**, 321-322.

Wiersum, K.F. (1984). Surface erosion under various tropical agroforestry systems. In: O'Loughlin, C.L. and Pearce, A.J. (eds) *Symposium on effects of forest land use on erosion and slope stability*. Honolulu, Hawaii, USA: East-West Centre, pp. 231-239.

Wiersum, K.F. (1994). Farmer adoption of contour hedgerow intercropping, a case study from east Indonesia. *Agrofor. Syst.* **27**, 163-182.

Young, A. (1989). *Agroforestry for soil conservation*. CAB International, UK.

Young, A. (1993). Agroforestry as a viable alternative for soil conservation. *Entwicklung und Landlicher Raum* **27(5)**, 3-7.

Young, A. (1997a). *Agroforestry for soil management* (second edition). CAB International, Wallingford.

Young, A. (1997b). The effectiveness of contour hedgerows for soil and water conservation. *Agrofor. Forum* **8 (4)**, 2-4.

Young, A., Murraya, P., Menz, K. & Smith, C.R. (in press). *SCUAF Version 4: a model to compare soil changes under agriculture, forestry and agroforestry*. ACIAR Canberra.

Zobisch, M.A., Klingspor, P. & Odour, A.R. (1996). The accuracy of manual runoff and sediment sampling from erosion plots. *J. Soil Water Conserv*. **51**, 231-233.

Zou, X., Zucca, C.P., Waide, R.B. & McDowell, W.H. (1995). Long-term influence of deforestation on tree species composition and litter dynamics of a tropical rain forest in Puerto Rico. *For. Ecol. Manage*. **78**, 147-157.

7. LIST OF APPENDICES

I Core questions addressed in the semi-structured interviews

II Seedling identification notes

III Sketch of *Calliandra calothyrsus* provenance trial site

IV Trees for sale

V Itinerary of Eastern Caribbean liason trip by Dr Morag McDonald

Table 24 Tree species identified as useful by members of the farming community.

Species	Common name	Family	Timber	Furniture	Fuelwood	Charcoal	Sticks	Fence Posts	Live Fence Posts	Poles	Tool Handles	Shade	Other
Acacia mearnsii De Wild.	Black Boy	Mimosaceae	x	o	xx	xx	xx	xx	o	xx	x	x	Fodder, tannins
Alchornea latifolia Sw.	Woman wood	Euphorbiaceae	o	o	o	o	o	o	o	o	oo	x	
Baccharis scoparia (L.) Sw.	Bitter Broom	Compositae	o	o	xxx	xxx	x	x	o	x			Brooms
Bambusa vulgaris Schrad. Ex Wendl.	Bamboo	Poaceae	oo	x	x	oo	xxx	x	oo	xxx	oo	o	Craft, instruments
Bursera simaruba (L.) Sarg.	Red Birch	Burseraceae	o	o	x	o	xxx	xxx	xxx	x	oo	x	
Byrsonima coriacea (Sw.) DC.	Locust	Malpighiaceae	o	o	x	o	xx	xx		xo	o	xx	Fruit, colour pigment
Calliandra calothyrsus Meissner	Calliandra	Mimosaceae	o	o	xx	x	x	x	x	x		xxx	Fodder, soil fertility
Camellia sinensis (L.) Kuntze	Green Tea	Theaceae	oo	oo	x	o	o	o	o	o	o		Drink from leaves
Cecropia schrieberiana Miq.	Trumpet Tree	Moraceae	o	o	o	o	o	o	o	o	oo		Coffins
Cedrela odorata L.	Cedar	Meliaceae	xxx	xxx	xx	o	xx	xx	x	xx	x	xx	
Cinnamomum montanum (Sw.) Bercht. & Presl.	Black Wattle	Lauraceae	oo	oo	xxx	xxx	xx	xx	o	xx	x	x	
Cinchona officinalis L.	Cinchona	Rubiaceae	oo	oo	xo	o	o	o	o	o	oo	o	Medicine
Clethra occidentalis (L.) Kuntze	Soapwood	Clethraceae	xxx	xx	xxx	xx	xxx	xxx	o	xxx	xxx	xx	
Clusia havetioides (Griseb.) Plancd. & Triana	Wild Mango	Clusiaceae	o	o	xxx	xxx	x	x	o	o	x		
Coccoloba zebra Griseb.	Mountain Grape	Polygonaceae	o	o	xx	xx	x	x	o	x	x		
Comocladia pinnatifolia L.	Maiden Plum	Anancardiaceae	oo	oo	x	o	xxx	xxx	xxx	xx	o	o	Fruit
Cordia gerascanthus L.	Spanish Elm	Boraginaceae	x	x	x	x	x	x	o	x	xxx		
Cupressus lusitanica Mill.	Christmas tree	Cupressaceae	x	o	x	o	x	x	o	x	o	xxx	Christmas trees, windbreak
Daphnopsis americana (Mill.) J.R. Johnston ssp. *cumingii*	Burn Nose	Thymelaeaceae	oo	oo	oo	oo	x	x	o	xo	o	x	String
Dendropanax arboreus (L.) Decne & Planch.	Man-jack	Araliaceae	oo	oo	xx	o	xxx	x	x	x	oo	x	
Esenbeckia pentaphylla (Macf.) Griseb.	Wild Orange	Rutaceae								xx			
Eucalyptus spp.	Eucalyptus	Myrtaceae	x	x	x	x	xx	xxx	o	xxx	x	x	Medicine
Eugenia spp.	Rodwood	Myrtaceae	xo	o	xxx	xxx	xx	xx	o	xx	xxx	x	
Ficus spp.	Fig	Moraceae	x	x	xo	o	x	x	o	x	o		

Gliricidia sepium (Jacq.) Kunth ex Griseb.	Quickstick	Papilionaceae	oo	oo	x	o	xx	xx	xxx	o	oo	x	Fodder
Gordonia haematoxylon Swartz	Bloodwood	Theaceae	o	o	x	x	x	x	o	x	x	x	
Grevillea robusta A. Cunn.	Silky Oak	Proteaceae	xxx	xx	xx	x	xx	xx	o	xx	x	xx	
Haematoxylum campechianum L.	Logwood	Caesalpinaceae	o	o	xx	xx	xx	xxx	o	xx	x		
Hernandia catalpifolia Britton & Harris	Water Mahoe	Hernandiaceae	o	o	xo	o	xo	o	o	o	o	x	
Hevea brasiliensis (Kunth) Müll. Arg.	Rubber	Euphorbiaceae	o	o	x	o	o	o	o	o	o	x	
Hibiscus elatus Sw.	Blue Mahoe	Malvaceae	xxx	xxx	xx	xx	x	xx	o	xx	xx	xx	Crafts
Hibiscus rosa-sinensis *L.*	Shoe Black	Malvaceae	oo	oo	x	o	xx	xx	xx	o	oo		Hedging, ornamental
Ilex macfadyenii *(Walp.) Rehder*	Black Tea	Aquifoliaceae	o	o	xxx	xxx	xx	xx	o	xx	xo	x	
Juniperus lucayana Britton	Juniper	Cupressaceae	xxx	xxx	x	o	xxx	xxx	o	xxx	xx	xx	
Leucaena leucocephala (Lam.) De Wit.	Leucaena	Mimosaceae	o	o	xx	x	xx	x	x	x		xx	Soil fertility
Linociera domingensis (Lam.) Knobl.	Ironwood	Oleaceae	x	o	xxx	xxx	x	x		xx	x		
Lyonia jamaicensis (Sw.) D. Don	Beefwood	Ericaceae	xo	o	xxx	xxx	xxx	xxx	o	xxx	x	x	
Myrica cerifera L.	Waxwood	Myricaceae	oo	oo	xxx	xxx	xx	xx	o	o	x	x	
Ocotea, Nectandra spp.	Sweetwood	Lauraceae	x	x	xxx	xxx	x	x	o	x	x		
Persea alpigena (Sw.) Spreng.var. harrisii	Wild Pear	Lauraceae	o	xo	xx	x	x	x		x	x		
Picramnia antidesma Sw.	Bitterwood	Simaroubaceae	x	x	x	o	xx	xx	o	xx	x	x	Medicine, bitters
Pimenta jamaicensis (Britton & Harris) Proctor	Wild Pimento	Mytraceae	o	o	x	x	x	x		x	xxx		
Pinus caribaea	Pine	Pinaceae	xxx	xxx	xo	oo	xx	xx	o	xx	o	x	
Pittosporum undulatum Vent.	Wild Coffee	Pittosporaceae	xo	o	xxx	xxx	xx	xx	x	xx	x	x	
Podocarpus urbanii Pilger	Yacca	Podocarpaceae	xx	x	xx	o	x	x	o	x	x	x	
Prunus occidentalis Sw.	Pruan, prune	Rosaceae	x	o	xx	xx	xx	xx		xx	x	o	Drink from bark
Psidium montanum Sw.	Mountain Guava	Myrtaceae	o	o	x	x	x	x	o	x	xx		Fruit, bird traps
Sapium jamaicense Sw.	Milkwood	Euphorbiaceae	o	o	xx	xx	x	x	o	xx	o	x	
Schefflera sciadophylum (Sw.) Harms	Aralia	Araliaceae	oo	oo	xo	oo	xx				oo		Hedging
Sideroxylon montanum (Swartz) Pennington	Mountain Bullet	Sapotaceae	xx	xx	xxx	xxx	xx	xx	o	xxx	xxx	x	

Spondias mombin L.	Hog Plum	Anacardaceae	oo	oo	x	o	xxx	xxx	xxx	o	o	x	Fruit
Swietenia macrophylla G. King	Mahogany	Meliaceae	xxx	xxx	xx	xx	x	xx	o	xx		xx	
Syzygium jambos (L.) Alston	Rose Apple	Myrtaceae	o	o	x	xo	x	x	o	x	x		Fruit, rat poison
Tamarindus indica L.	Tamarind	Caesalpinaceae	o	o	xx	xx	x	x	o	x	o	x	
Terminalia latifolia Sw.	Broad leaf	Combretaceae	o	o	x	o					o		
Turpinia occidentalis (Sw.) G. Don	Candlewood	Celastraceae	x	o	xxx	xxx	xx	xx	o	xx	o		
Vaccinium meridionale Sw.	Bilberry	Ericaceae	oo	oo	xx	x	x	x	o	x	x	x	Fruit
Unknown	Bird Feeding Stick		o	o	xx	xx	xx	xx	o				
Unknown	Redwood		xo	o	x	x	x	x	o	xx	xxx	x	
Unknown	Soldier Wisp		o	o	x	xo	x	xx	o	xx	xx		Gigs
Unkown	White Coal		oo	oo	xxx	xxx	x	xx	o	xx			
Unknown	Yellow Wisp		oo	oo	o	o	x	x	xx	x	o		

xxx = excellent xx = good x = reasonable xo = not ideal, but reasonable o = not suited oo = completely unsuited

Table 25 Ecological characteristics of montane forest species identified as useful by members of the farming community.

Species	Regeneration type [1]classification certain [2]less certain [3]speculative	Maximum height (m)	Maximum DBH (cm)	Maximum tree density (trees ha^{-1})	Maximum basal area dominance (m^2 ha^{-1})	Growth rate a) 1984-89 b) 1989-94 (m^2 m^{-2} yr^{-1})	Average annual mortality (%) a) 1974 -1989 b) 1989 - 1994	Wood density (Mg kg^{-3})
Acacia mearnsii De Wild.	Pioneer of disturbed ground [2]	20	NI	NI	NI	NI	NI	0.52-0.65
Alchornea latifolia Sw.	Near pioneer [1]	NI	72	1100	19.45	a) 0.014 b) 0.054	a) 0.012 b) 0.015	0.28-0.51
Baccharis scoparia (L.) Sw.	Slow growing pioneer [2]	3	NI	NI	NI	NI	NI	NI
Cinchona officinalis L.	Pioneer-gap benefiting [3]	NI	18	1950	5.25	NI	NI	NI
Cinnamomum montanum (Sw.) Bercht. & Presl.	Shade tolerant/(gap benefiting) [2]	25	68	208	10.26	a) -0.005 b) 0.001	a) 0.07 b) 0	0.61
Citharexylum caudatum L.	Strongly gap-benefiting[3]	15	37	583	11.74	a) 0.008 b) 0.019	a) 0.016 b) 0	0.66 – 0.98
Clethra occidentalis (L.) Kuntze	Near pioneer [1]	NI	73	1750	25.68	a) 0.005 b) 0.017	a) 0.009 b) 0.033	0.60-0.74
Clusia havetioides (Griseb.) Plancd. & Triana	Shade tolerant [1]	NI	28	1200	10.61	a) 0.014 b) 0.018	a) 0.006 b) 0.048	NI
Coccoloba zebra Griseb.	NI	10	NI	NI	NI	NI	NI	NI
Cyrilla racemiflora L.	Slow-growing pioneer[1]	30	62	1167	41.97	a) 0.001 b) 0.011	a) 0.01 b) 0.033	0.53 – 1.02
Daphnopsis americana (Mill.) J.R. Johnston ssp. *cumingii*	Seedlings very rare	20	NI	NI	NI	NI	NI	NI
Dendropanax arboreus (L.) Decne & Planch.	Gap benefiting [3]	6	NI	400	22.28	NI	NI	NI
Eugenia monticola (Sw.) DC var. monticola	Shade tolerant[2]	12	31	1917	5.72	a) 0.006 b) 0.028	a) 0.019 b) 0.014	1 – 1.03
Eugenia virgultosa (Sw.) DC var. virgultosa	Shade tolerant [1]	15	20	3472	5.59	a) 0 b) 0.03	a) 0.005 b) 0.021	0.88-1.04
Gordonia haematoxylon Swartz	Gap benefiting/strongly gap benefiting [3]	28	56	206	9.19	a) 0.005 b) 0.009	a) 0.015 b) 0.009	NI
Guarea glabrs Vahl	Shade tolerant[1]	20	73	1651	19.45	a) 0.001 b) 0.033	a) 0.002 b) 0.005	0.67-0.79
Haenianthus incrassatus (Sw.) Griseb.	Strongly gap-benefiting[1]	NI	61	300	32.75	a) 0.008 b) 0.017	a) 0.009 b) 0.032	NI
Ilex macfadyenii (Walp.) Rehder	Strongly gap-benefiting [3]	NI	27	1917	11.46	a) 0.005 b) 0.033	a) 0.037 b) 0.065	0.78
Juniperus lucayana Britton	Near pioneer [3]	15	75	1000	44.06	a) 0 b) –0.001	a) 0 b) 0	NI
Linociera domingensis (Lam.) Knobl.	Seedlings very rare	16	33	NI	NI	NI	NI	NI
Lyonia jamaicensis (Sw.) D. Don	Slow-growing pioneer [2]	13	7	167	0.59	NI	NI	NI
Maytenus jamaicensus Krug & Urban	Shade tolerant[1]	22	44	762	5.79	a) –0.006 b) 0.028	a) 0 b) 0	0.87
Myrica cerifera L.	Pioneer of disturbed ground [3]	22	51	417	5.26	a) 0.045 b) 0.066	a) 0 b) 0.066	NI
Myrsine coriacea (Sw.) R. Br. ex Roem. & Schult.	Strongly gap-benefiting[1]	13	27	649	1.79	a) 0.012 b) 0.041	a) 0.008 b) 0.047	0.70
Ocotea, Nectandra spp.	Gap benefiting/shade tolerant	20 [1]	33	347	1.56	a) 0.002 b) 0.056	a) 0.092 b) 0.032	0.85
Picramnia antidesma Sw.	Strongly gap benefiting/shade tolerant [3]	6	8	278	0.59	NI	NI	NI
Pittosporum undulatum Vent.	Gap benefiting/strongly gap	22	66	3056	20.76	NI	NI	0.93-1.04

	benefiting [1]							
Podocarpus urbanii Pilger	Gap benefiting [2]	16	58	1800	20.83	a) 0.003 b) 0.023	a) 0.009 b) 0.013	0.62
Prunus occidentalis Sw.	Gap benefiting/shade tolerant [2]	5	17	208	0.28	NI	NI	0.90-1.05
Psidium montanum Sw.	NI	20	NI	NI	NI	NI	NI	NI
Sapium jamaicense Sw.	Seedlings very rare	25	52	100	4.92	NI	NI	NI
Schefflera sciadophylum (Sw.) Harms	Seedlings very rare	15	27	833	3.25	a) 0.003 b) 0.059	a) 0.028 b) 0.031	NI
Sideroxylon montanum (Swartz) Pennington	Gap benefiting [1]	25	71	500	15.04	a) –0.003 b) 0.022	a) 0.006 b) 0	NI
Solanum punctulatum Dunal	Gap-benefiting[1]	18	102	500	12.66	a) 0.003 b) 0.011	a) 0.003 b) 0.039	0.62
Syzygium jambos (L.) Alston	Gap benefiting/shade tolerant [2]	NI	NI	NI	NI	NI	NI	0.70
Turpinia occidentalis (Sw.) G. Don	Strongly gap benefiting [1]	28	79	833	25.06	a) 0.003 b) 0.022	a) 0 b) 0.092	NI
Vaccinium meridionale Sw.	Slow growing pioneer [1]	22	57	3264	18.14	a) 0.005 b) 0.02	a) 0.021 b) 0.022	0.73-0.76
Viburnum alpinum Macf. ex Britton	Near pioneer/gap-benefiting[2]	15	34	625	5.66	a) 0.009 b) 0.005	a) 0.004 b) 0.066	NI

[1] (*O. patens* (Sw.) Nees)

Table 26 Survival of montane forest species in the species elimination trial; MAP = months after planting.

Species	Survival (%) 1 MAP Ridge-top	Survival (%) 1 MAP Valley-bottom	Survival (%) 12 MAP Ridge-top	Survival (%) 12 MAP Valley-bottom
Alchornea latifolia Sw.	100	100	20	80
Cedrela odorata L.	95	100	25	55
Cinnamomum montanum (Sw.) Bercht. & Presl.	95	95	80	65
Citharexylum caudatum L.	100	100	21	65
Clethra occidentalis (L.) Kuntze	100	100	55	75
Cyrilla racemiflora L.	85	100	35	10
Dendropanax arboreus (L.) Decne & Planch.	95	95	50	35
Eugenia monticola (Sw.) DC var. *monticola*	80	90	50	35
Gordonia haematoxylon Swartz	70	80	19	16
Grevillea robusta A. Cunn.	100	100	40	75
Guarea glabra Vahl	85	100	20	35
Haenianthus incrassatus (Sw.) Griseb.	100	85	0	0
Ilex macfadyenii (Walp.) Rehder	65	55	40	53
Juniperus lucayana Britton	100	95	45	75
Lyonia jamaicensis (Sw.) D. Don	95	100	48	76
Maytenus jamaicensus Krug & Urban	95	100	70	33
Myrica cerifera L.	85	90	30	45
Myrsine coriacea (Sw.) R. Br. ex Roem. & Schult.	90	95	55	70
Ocotea, patens (Sw.) Nees	85	80	20	25
Podocarpus urbanii Pilger	75	90	50	55
Prunus occidentalis Sw.	100	100	35	85
Sideroxylon montanum (Swartz) Pennington	70	75	41	22
Solanum punctulatum Dunal	70	95	10	30
Turpinia occidentalis (Sw.) G. Don	95	95	65	65
Vaccinium meridionale Sw.	70	95	12	25
Viburnum alpinum Macf. ex Britton	95	95	80	80

Table 27 Productivity of montane forest species in the species elimination trial; MAP = months after planting.

Species	Basal diameter increment 6 MAP (cm) Ridge-top	Basal diameter increment 12 MAP (cm) Ridge-top	Basal diameter increment 42 MAP (cm) Ridge-top	Height increment 6 MAP (cm) Ridge-top	Height increment 12 MAP (cm) Ridge-top	Height increment 42 MAP (cm) Ridge-top	Basal diameter increment 6 MAP (cm) Valley-bottom	Basal diameter increment 12 MAP (cm) Valley-bottom
Alchornea latifolia Sw.	0.45	0.75	5.03	28.86	30.35	198.20	0.43	1.30
Cedrela odorata L.	0.46	1.41	4.56	8.44	45.36	225.78	0.40	1.75
Cinnamomum montanum (Sw.) Bercht. & Presl.	0.28	0.70	3.76	13.44	33.00	219.07	0.25	0.66
Citharexylum caudatum L.	0.33	0.66	3.14	17.50	36.60	169.55	0.17	0.54
Clethra occidentalis (L.) Kuntze	0.41	1.07	4.66	15.75	48.08	215.84	0.40	1.21
Cyrilla racemiflora L.	0.17	0.67	2.51	7.88	29.37	91.65	0.13	0.36
Dendropanax arboreus (L.) Decne & Planch.	0.27	0.82	3.31	12.17	39.62	143.10	0.31	1.18
Eugenia monticola (Sw.) DC var. *monticola*	0.05	0.14	1.87	3.07	7.67	89.77	0.02	0.06
Gordonia haematoxylon Swartz	0.15	0.44	3.34	5.01	14.99	154.70	0.08	0.30
Grevillea robusta A. Cunn.	0.46	0.89	6.54	6.34	28.45	324.83	0.37	1.32
Guarea glabra Vahl	0.01	0.27	1.65	8.85	10.55	74.80	0.05	0.11
Haenianthus incrassatus (Sw.) Griseb.	-	-	-	-	-	-	-	-
Ilex macfadyenii *(Walp.)* Rehder	0.21	0.49	2.58	10.26	25.67	106.44	0.25	0.49
Juniperus lucayana Britton	0.20	0.48	4.54	11.68	34.38	192.67	0.18	0.63
Lyonia jamaicensis (Sw.) D. Don	0.26	0.45	1.69	10.66	19.57	58.80	0.22	0.74
Maytenus jamaicensus Krug & Urban	0.15	0.26	1.41	6.89	16.56	51.83	0.09	0.20
Myrica cerifera L.	0.28	0.28	2.07	12.38	14.68	99.00	0.21	0.72
Myrsine coriacea (Sw.) R. Br. ex Roem. & Schult.	0.23	0.71	3.60	11.05	26.44	173.52	0.32	1.04
Ocotea, patens (Sw.) Nees	0.09	0.24	1.01	3.90	20.08	29.90	0.12	0.23
Podocarpus urbanii Pilger	0.13	0.41	2.29	8.72	20.66	83.65	0.10	0.27
Prunus occidentalis Sw.	0.23	0.69	2.62	10.85	28.31	125.88	0.23	0.65
Sideroxylon montanum (Swartz) Pennington	0.07	0.20	1.01	3.73	11.21	29.90	0.10	0.17
Solanum punctulatum Dunal	0.07	0.42	4.41	1.73	13.65	125.88	0.22	0.57
Turpinia occidentalis (Sw.) G. Don	0.34	1.12	5.08	15.65	46.36	241.94	0.47	1.03
Vaccinium meridionale Sw.	0.01	0.08	-	5.40	8.80	-	0.03	0.12
Viburnum alpinum Macf. ex Britton	0.41	0.94	2.83	23.26	63.57	154.18	0.35	1.31

Table 28 Crown and stem form of, and incidence of damage to, montane forest species in the species elimination trial 42 months after present.

Species	Crown form Ridge-top	Crown diameter (cm) Ridge-top	Stem form Ridge-top	Weather damage Ridge-top	Insect damage Ridge-top	Crown form Valley-bottom	Crown diameter (cm) Valley-bottom	V
Alchornea latifolia Sw.	3	134	3	4	5	2.43 (0.2)	70.06 (20.39)	
Cedrela odorata L.	3.2 (0.2)	63.70 (7.03)	3.6 (0.25)	3.4 (0.4)	5	3.29 (0.29)	83.71 (8.65)	
Cinnamomum montanum (Sw.) Bercht. & Presl.	3.67(0.22)	91.08 (11.36)	3.00 (0.26)	4.00 (0.26)	4.5 (0.22)	3.5 (0.29)	80.2 (18.97)	
Citharexylum caudatum L.	3 (0.22)	149.86 (25.75)	3.14 (0.34)	4.71 (0.29)	4.71 (0.29)	3.33 (0.33)	66.25 (10.05)	
Clethra occidentalis (L.) Kuntze	2.75 (0.45)	85.75 (16.83)	2.89 (0.42)	4.22 (0.15)	4.89 (0.11)	2.83 (0.17)	63.29 (11.48)	
Cyrilla racemiflora L.	1.83 (0.47)	50.60 (8.31)	2.17 (0.31)	4 (0.26)	4.67 (0.21)	-	-	
Dendropanax arboreus (L.) Decne & Planch.	2.25 (0.37)	57.88 (5.31)	3.13 (0.13)	3.38 (0.38)	4.5 (0.27)	3 (0)	74 (27.83)	
Eugenia monticola (Sw.) DC var. *monticola*	2 (3)	33 (5)	2.37 (0.67)	4 (0.58)	4.33 (0.33)	-	-	
Gordonia haematoxylon Swartz	3	63	4	4	4	3	63	
Grevillea robusta A. Cunn.	3 (0.22)	149.86 (25.75)	3.14 (0.34)	4.71 (0.29)	4.71 (0.29)	3.33 (0.33)	66.25 (10.05)	
Guarea glabra Vahl	3.5 (0.5)	24.5 (5)	2.5 (0.5)	3.5 (0.5)	5 (0)	-	-	
Haenianthus incrassatus (Sw.) Griseb.	-	-	-	-	-	-	-	
Ilex macfadyenii (Walp.) Rehder	2.33 (1.20)	54.25 (19.75)	2.67 (0.33)	4.67 (0.33)	4.33 (0.67)	3 (0)	36 (8.5)	
Juniperus lucayana Britton	3.43 (0.37)	86.93 (7.57)	3.14 (0.14)	4.86 (0.14)	5 (0)	3 (0.19)	60.69 (11.86)	
Lyonia jamaicensis (Sw.) D. Don	2	36	4	5	4	2.83 (0.17)	44.42 (13.19)	
Maytenus jamaicensus Krug &Urban	2.33 (0.67)	50.33 (9.16)	2.67 (0.88)	4 (0.58)	4.33 (0.33)	-	-	
Myrica cerifera L.	2.33 (0.88)	52.67 (22.51)	1.33 (0.33)	5 (0)	5 (0)	2 (0)	90.25 (9.25)	
Myrsine coriacea (Sw.) R. Br. ex Roem. & Schult.	3.8 (0.2)	79.3 (15.98)	2.67 (0.33)	3.33 (0.21)	4.5 (0.35)	3.11 (0.20)	78.75 (11.29)	
Ocotea, patens (Sw.) Nees	2.5 (0.5)	70.5 (43)	2.5 (0.5)	4 (0)	5 (0)	-	-	
Podocarpus urbanii Pilger	2.75 (0.45)	73.57 (9.63)	3 (0.33)	4.63 (0.18)	5 (0)	3.6 (0.25)	43.6 (5.59)	
Prunus occidentalis Sw.	3 (0)	68 (12.87)	2.6 (0.25)	3.2 (0.2)	4.8 (0.2)	3.14 (0.26)	86.56 (15.62)	
Sideroxylon montanum (Swartz) Pennington	2	20	4	5	5	-	-	
Solanum punctulatum Dunal	2	46	1	4	5	2	28	
Turpinia occidentalis (Sw.) G. Don	2.91 (0.21)	77.59 (13.10)	3.82 (0.18)	3.81 (0.23)	5 (0)	3.17 (0.40)	89.5 (22.19)	
Vaccinium meridionale Sw.	-	-	-	-	-	-	-	
Viburnum alpinum Macf. ex Britton	2 (0.46)	70.67 (9.04)	2.33 (0.17)	3.33 (0.33)	5 (0)	2.57 (0.20)	61 (12.38)	

DFID Forestry Research Project R6290

On-farm research for the development and promotion of improved agroforestry systems for steeplands in the Caribbean

School of Agricultural and Forest Sciences

University of Wales, Bangor

Plates for Final report

1 April 1995 - 31 March 1998

Plate 1: The steep slopes, high rainfall and poor soil management of many of the Caribbean islands has led to erosion, loss of soil productivity, and often invasion by exotic weeds which prevent forest regeneration

Plate 2: *Calliandra calothyrsus* is popular with the farming community for its fuelwood and fodder properties. It also fixes nitrogen and coppices readily

Plate 3: The natural vegetation of the Blue Mountains is montane rain forest

Plate 4: The experimental plots are located in the forest buffer-zone. These are blocks II and III, farmed by Mr Roy Bryan and Mr Sheraton Walker, respectively

Plate 5 Established *Calliandra calothyrsus* hedgerow in an agroforestry treatment plot after pruning [See front cover of report].

Plate 6: Spaced rows of *Zea mays* were planted as a bioassay in all of the project's farmed experimental plots to evaluate the effects of hedgerows on crop productivity

Plate 7: A native species elimination trial was established on the farm of Mr Sheraton Walker in a fallow area overgrown with *Melinis minutoflora*

Plate 8: Some of the wildings used in the establishment of the species elimination trial

Plate 9: A *Calliandra calothyrsus* provenance trial was established on the farm of Mr Roy Bryan

Plate 10: One of the non-mist propagators in the project's nursery at Cinchona Botanic Garden used for rooting cuttings following different experimental treatments

Plate 11: The stock plant collection at Cinchona Botanic Garden includes a variety of native species (the *Calliandra calothyrsus* is used for mulch)

Plate 12: Final year undergraduate students from the University of the West Indies taking the module: 'Forest Ecology, Agroforestry and Sustainable Development' developed under R6290 on a field visit to the project research area

Plate 13: A variety of agroforestry systems were employed in on-farm demonstrations (Mr Sheraton Walker establishing a boundary of *Cedrela odorata*)

Plate 14: Mr Lloyd Stamp (Foreman, Cinchona Botanic Garden and nursery supervisor) in the project's nursery at Cinchona. The nursery is run by local community members, and revenues from tree sales are used to support the under-resourced garden.

Plate 15: Ms Donna Lowe, an M.Phil. student at the University of the West Indies is studying the efficacy of contour hedgerows of a number of different species on-farm in collaboration with the CARDI, and within the framework of the European Union Yallahs/Morant Agricultural Development Project