PROCEEDINGS

OF THE

35TH ANNUAL MEETING

25-31 July 1999

Castries, St. Lucia, W.I.

Proceedings Edited
By
Wilfredo Colón

Published by the Caribbean Food Crops Society

Proceedings of the Caribbean Food Crops Society. 35:205-217. 1999

WATERSHED LAND CAPABILITY CLASSIFICATION AND CROP SUITABILITY MODELLING USING GEOGRAPHIC INFORMATION SYSTEMS (GIS)

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ABSTRACT. A geographic information system was used to demonstrate a methodology for assignment of best management practices that integrate land capability and crop suitability zoning on an agricultural watershed on St. Lucia. Primary parameters used in determining land capability included slope steepness and soil stability. Land capability classes were delineated, and recommended agricultural, agro-forestry and forestry prescriptions were assigned across the watershed. Crop suitability over the watershed was analyzed for selected tree crops, using fuzzy-set membership to represent variability in slope, rainfall and soil parameters in crop growth. The procedures developed in this study will contribute to a spatially-based decision support system toward conservation-oriented agricultural and forestry land planning on St. Lucia. The study demonstrates the effectiveness of GIS in the application of spatial modelling procedures in rapidly evaluating watershed management strategies.

INTRODUCTION

1.1 Land management issues on St. Lucia

St. Lucia is located in the Eastern Caribbean, at 14° N and 61 ° W. The island is 616 km^2 in area, approximately 45 km long by 23 km wide along its longest and widest axes respectively. The island is volcanic in origin and is dominated by a rugged topography with the tallest peaks in the south-central region exceeding 900 meters. St. Lucia's climate is tropical maritime, characterized by average day-time temperatures that range from 26 to 32 ° C, with the average relative humidity around 75%. The annual rainfall is relatively high, ranging from 1,500 mm in the dry coastal regions to 3,800 mm in the mountainous interior. The rainfall has a strong seasonal distribution, with most of the precipitation occurring between May and November.

Bananas are the most important export crop. Other major crops include coconuts, mangos, breadfruit, and citrus, along with a variety of vegetables and tuber crops. Approximately 55% of the total land area is under cultivation (Roche Lteé, 1992). Because of the steep terrain, flat arable land is limited to the lower floodplains of some of the major rivers and accounts for only 2% of the total land area. Consequently most cultivation takes place on hillslopes with a significant proportion of holdings located on excessively steep slopes, greater than 40% (Roche Lteé, 1992).

Soil conservation measures are generally lacking on farm holdings and is compounded by the fact that traditional crops such as bananas, tubers, and vegetables are shallow-rooted and provide little soil support. The result is acute surface erosion from steep slopes during heavy rains, which not only reduces soil productivity but also causes excessive sediment loading in streams draining agricultural areas. Heavy deposition of sediment within lower river reaches aggravates flooding in lowland areas. Marine ecosystems are also adversely affected by sediment discharge into coastal waters, and the recreational value of coastal waters for tourism-related activities is also impacted.

Poor agricultural land management has seriously affected fresh water resources on the island. Replacement of forest cover by short-term crops under poor agronomic management typically results in higher surface runoff rates, which tend to be more severe within steeply sloped watersheds. Loss of forest cover results in drier micro-climates, increased direct surface evaporation and rapid runoff, the net result being lower river recharge rates and declining baseflows. Siltation and agro-chemical pollution due to upstream agricultural activity are of particular concern at drinking water extraction points along rivers. Intake structures and pipelines often become choked by eroded material during heavy rains causing supply interruptions. Agro-chemical contamination from agriculture further degrades water quality and complicates treatment.

Land management on St. Lucia must be watershed-based in which the watershed is considered a management unit. A watershed master plan recommends a range of best management practices with the goal of conserving soil, water and ecological resources, while ensuring economic viability of stake-holders. While the watershed management plan will identify conservation requirements over the entire watershed, financial and human resource constraints will often limit management recommendations that can be implemented in the short-term. Consequently attention should first be given to implementation of conservation measures within priority management areas (PMAs). PMAs include riparian buffers, drinking water catchment areas, ecological reserves and areas of high erosion potential.

1.2 Computer-assisted watershed management planning

Design of a watershed management plan requires a myriad of spatial data attributes. Such a management plan will identify areas across the watershed to be managed for water conservation, erosion control, biodiversity conservation and regions for earmarked crop optimization. Hazard zones such as flood and landslide-prone areas should be identified for special remediation and mitigation measures. Data requirements for this type of exercise are often extensive and include soil parameters, land use patterns, topographic and hydrologic characteristics of the watershed.

Geographic information systems have become increasingly popular tools in watershed planning. GIS significantly reduces the time and effort required in the analysis of large spatial datasets for evaluating land management alternatives (Sheng *et al.*, 1997). The strength in GIS technology lies in the ability to store databases associated with thematic spatial data digitally, and the capacity to generate cartographic output for easy interpretation (Cox, 1997). The raster or grid-element data representation supported by most GIS software is ideally suited to representation of heterogeneity in landscape surfaces, and is useful in the manipulation of multiple datasets required in modelling applications.

There is a well-documented body of literature on the use of GIS in modelling for watershed management. The GIS is typically used to automate the process by which the input parameters are generated for models. The spatial analytical capabilities and cartographic utilities of the GIS allow for interactive exchange of data between the model and the GIS, and render the results as map output. Research in this area has led to interfacing of non-point source (NPS) pollution models with GIS platforms to evaluate watershed management recommendations (Chansheng *et al.*, 1993; Udoyara and Jolly, 1994; Srinivasan *et al.*, 1994; Mousavizadeh *et al.*, 1995). Mellerowicz *et al.*, (1994) and Fraser *et al.*, (1996) used GIS to extract parameters required for the Universal Soil Loss Equation to evaluate potential soil losses under various land management regimes. Cox and Madramootoo (1997) used a raster-based GIS to evaluate alternative management treatments and estimate corresponding erosion losses on two watersheds on St. Lucia.

1.3 Scope of study

This paper presents an application of GIS analytical tools in watershed management planning on the Marquis watershed on St. Lucia. Crop suitability across the watershed was analyzed for 5 economically important tree crops, and 'best' conservation-oriented management prescriptions were determined based on a land capability classification.

METHODS

2.1 Study area

The Marquis watershed is located in the northeast of the island (Figure 1). The watershed is 3,121 ha and is intensively cultivated, predominantly under bananas, monocropped on hillslope farms. Intensive agriculture accounts for approximately 39% of the total watershed area. Flat-land intensive banana agriculture along the river flood plain accounts for only 2% of the watershed area. Mixed agriculture, bananas intercropped with vegetables, tubers, coconuts and mangos account for 20% of the area. Some 615 ha of the upper reaches of the watershed are contained within the government forest reserve. Dry forest and littoral woodland dominates the lower reaches of the watershed, of which approximately 135 ha are contained within the forest reserve (Figure 1).

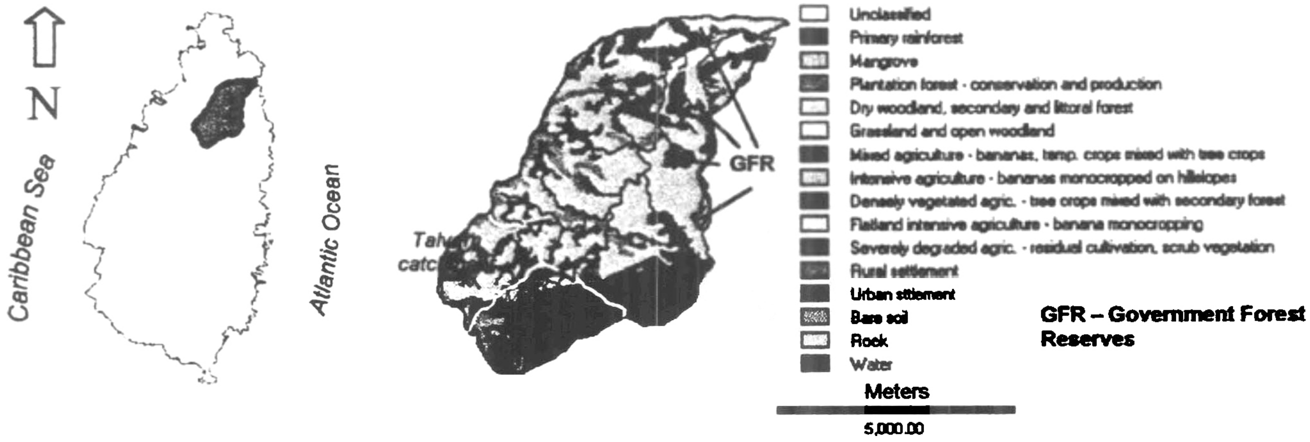


Figure 1. Location and land use on the Marquis watershed

The topography of the watershed is variable with most of the landscape falling into the 0-20% slope range (Figure 2). The flat areas are confined to the narrow Marquis river floodplain while the excessively steep areas in excess of 40% are found on the flanks of Piton Flore (563 m) and La Sourciere (670 m), and along the banks of the tributaries. Average annual precipitation across the watershed ranges from 1,700 mm in the coastal north-east to over 2,600 mm around the mountains in the upper reaches toward the south.

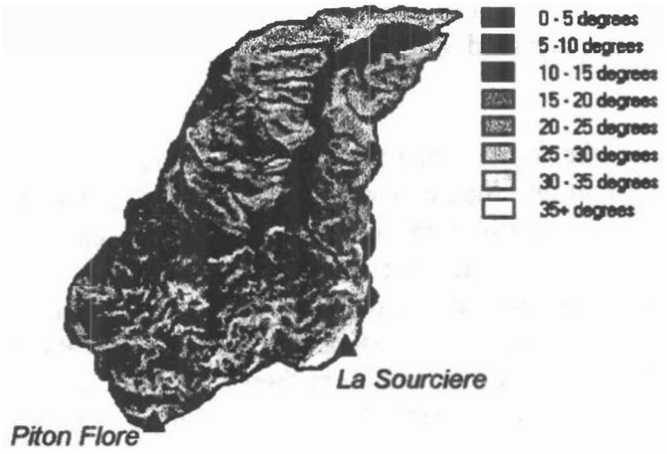


Figure 2. Slope classes

The soils within the watershed are all volcanic in origin, generally deeply weathered, acid-leached and predominantly clayey in texture. The soils in the lower reaches of the watershed are dominated by highly erodible vertisols such as Anse and Hardy clays while the soils in the upper parts of the watershed are predominantly stable inceptisols such as Garrand clay loam, Canelles clay and Marquis clay (Stark *et al.*, 1966). In terms of erosion stability, 33%, 45%, and 26% of the soils were classified as stable, less stable and fragile (Stark *et al.*, 1966; Ahmad, 1989; and Roche Lteé, 1992). The soil stability classes are shown in Figure 3.

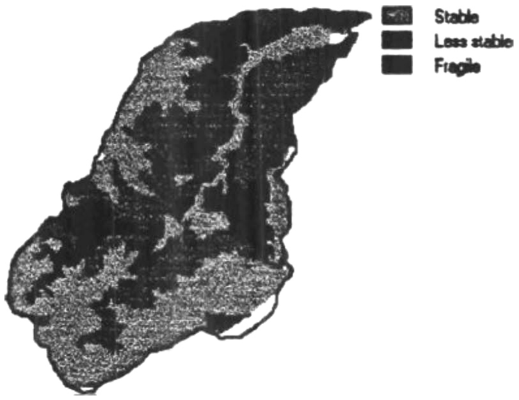


Figure 3. Soil stability classes

2.2 GIS Data

Digital data of the study area was acquired from St. Lucia's national GIS data archives. The archival data was created using SPANS™ GIS. Three primary data layers in raster (grid) format were used; soil type, land use and the digital elevation model (DEM). The soil type layer was digitized from the St. Lucia Soil Survey by Stark *et. al.*, (1966), the land use layer was digitized from the Forest Management Plan (Roche Lteé, 1992) and the DEM was generated from a digital scan of the 1:25,000 topographic map. The hydrologic network for the watershed was derived from the stream network vector (line-type) layer for the island.

For each thematic layer, the region corresponding to the watershed extents were *'windowed out'* of the island dataset and then converted to IDRISI ™ GIS format for use. IDRISI GIS software was used to perform all the spatial analyses and generate the results as map output. The vector-format hydrologic network was subsequently converted to a raster representation in IDRISI. The annual rainfall distribution was generated by 'on-screen' digitizing the rainfall islohyets in IDRISI using a hard-copy isohyetal map (OAS, 1987) as a reference. The isohyets in vector format were then rasterized, and a continuous surface created by interpolating between isohyets. The grid resolution of the raster layers selected in this study was 10 x 10 m.

From these primary data sources, intermediate data layers were generated to derive two final digital representations; (1) tree crop suitability (for major economic tree crops) and (2) recommended management prescriptions. The procedures for deriving these digital map layers are outlined below.

2.3 Tree Crop Suitability

Crop growth suitability over the watershed was analyzed for 5 tree crops with high economic value and importance in terms of agro-forestry-based soil conservation measures on sloped lands. The crops were cocoa, avocado, citrus, mango, and breadfruit. In this evaluation, crop productivity was assumed to be influenced by the interaction of three factors: soil fertility, rainfall and slope steepness. These factors were represented as three separate images (Figure 6). The combination of these factors to analyze spatial variation in suitability across the watershed was carried out in the GIS using a multiple criteria evaluation (MCE) tool. Areas excluded from analysis, included settlements and forest reserves, which were represented as separate '*constraint*' images.

The three suitability factor images were combined using a weighted linear combination (WLC) routine in IDRISI. Weighted linear combination is a procedure in which factors and constraints are combined in successive multiplicative overlays using importance weights that are assigned to each factor. The importance weights determine the degree to which factors can be traded off against others. The higher the importance weight, the greater influence the factor will have on the final suitability map (Eastman, 1997). In this analysis the factors were rated on a 9-point scale in a pairwise comparison where 9 suggests one factor *is 'extremely more important'* relative another factor, and 1/9 suggests that one factor is '*extremely less important*' relative to another factor. This routine was executed in IDRISI using a weighting module. In this analysis soil suitability was assumed to be *equally* important relative to rainfall for crop growth (rated '1'), slope *moderately less important* as rainfall (rated '1/3') and slope *less important* than soil suitability (rated '1/2').

Before the factor layers can be used in the WLC routine they were standardized to reflect suitability in terms of crop growth. Rainfall and slope are continuous variables and the degree of suitability of any pixel in the image was expressed within a range between 0 and 1 in a fuzzy membership set. Hence a pixel assigned a value of 0 indicated that suitability for crop growth at that location was nil; a pixel assigned a value of 1.0 indicated that suitability for crop growth at that location was high. The fuzzy set membership grade therefore represents the change from non-membership to complete membership (Eastman, 1997). A built-in module in the GIS software provided various membership-set functions that describe the nature of the membership relationship. Those used in this analysis were sigmoidal and J-shaped, based on the crop growth requirements summarized in Table 1.

Table 1. Growth requirements for some major tree crops.

Crop	Optimal annual rainfall range (mm)	Optimal soil requirements	Slope range
Cocoa	2000-3000	Moderately fertile soils	< 30°
Citrus	1750-3000	Moderate to high fertility	< 25°
Avocado	1750-3000	Poor to moderately fertile soils Best on well-drained soils	< 35°
Mango	1750-3000	Moderately fertile soils	< 30°
Breadfruit	1750-3000	Moderately fertile soils	< 35°

Source: St. Lucia Soil Survey (Stark *et al.*, 1966) and Watershed and Environment Project Report (Hunting Technical Services, 1997)

A symmetrical sigmoidal function was used to define rainfall suitability, the annual rainfall layer reclassified to reflect fuzzy set membership. In the case of avocado for example, where annual rainfall was less than 1,500 mm membership was 0, meaning that rainfall below this amount was unsuitable for the crop. As rainfall increased, membership approached 1, the optimal rainfall range for growth ranging between 2,000 and 2,500 mm. Rainfall above 2,500 mm was considered limiting for growth and accumulation above 3,500 mm was unsuitable for avocado (Figure 4).

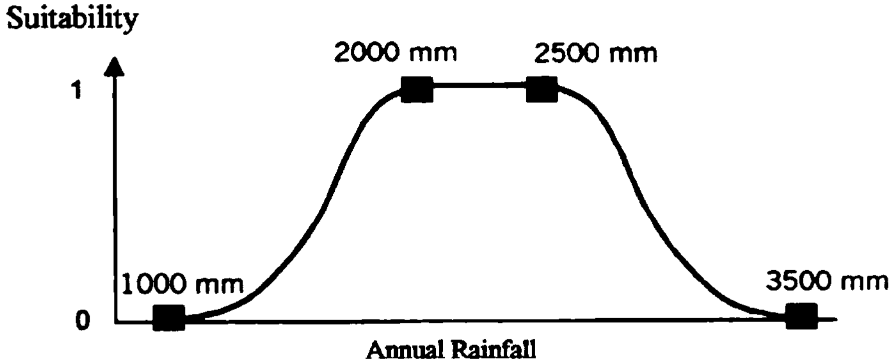


Figure 4. Rainfall suitability fuzzy membership function for avocado.

The DEM was used to derive a slope steepness layer from which the slope factor suitability layer was generated. Suitability was defined by a monotionically decreasing J-shaped function, in which high suitability corresponded to slopes of 0°, progressing to lower suitability on steeper slopes. In the case for avocado for example, at slopes above 35°, representing the inflection point on the function, suitability was assumed to decrease at a more rapid rate. (Figure 5).

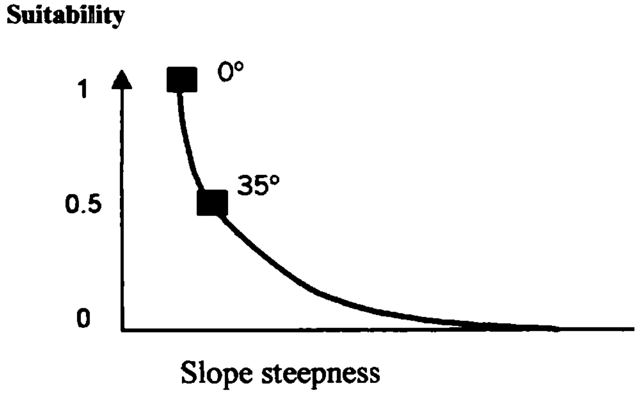


Figure 5. Slope suitability fuzzy membership function for avocado.

Since the soil series are discrete units, the soils layer was simply reclassified into 3 suitability classes. Soil suitability was characterized by parameters that included drainage, fertility, stoniness, and depth. The rating for each crop was derived from the St. Lucia Soil Survey (Stark *et al.*, 1966) and the soil analyses presented in the Watershed and Environment Report (HTS, 1997). For further details on multiple-critera evaluation procedures in IDRISI, consult Eastman (1997).

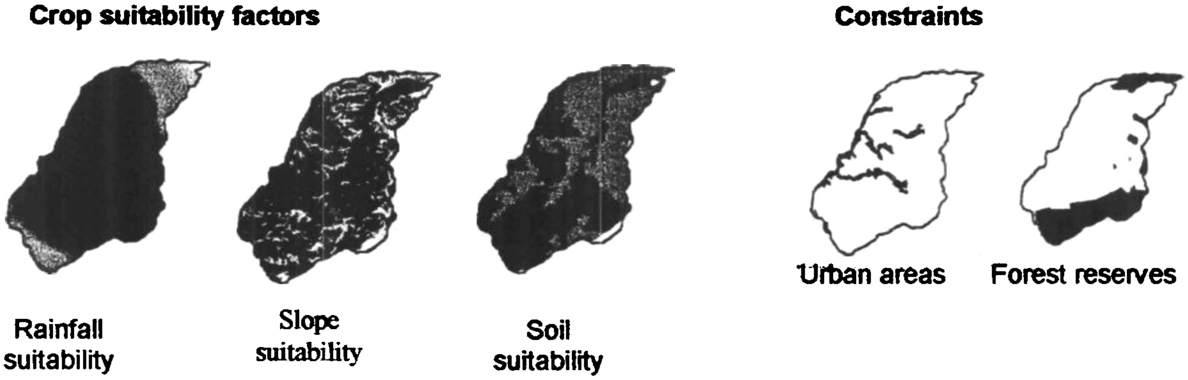


Figure 6. Crop suitability factors for avocado (dark shade represent high suitability, light shades represent low suitability) and constraints (areas excluded from analysis).

Suitability maps using MCE procedures generated for each of the five crops are shown in Figures 7a to 7d.

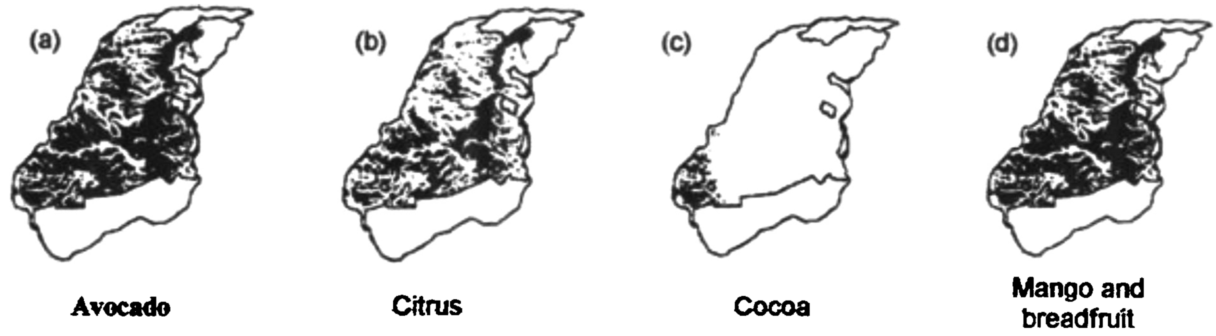


Figure 7. Tree crop suitability rating (dark shades represent high suitability, light shades represent low suitability.

2.4 Land capability and recommended land treatment assignment

To determine recommended conservation-oriented treatments a land capability classification was developed based on proposed classification schemes by Ahmad (1989) and Roche Lteé. (1992). Soil stability and slope steepness were the criteria which defined the capability classes, and were translated into a spatial representation in the GIS using the digital elevation model (DEM) and the soil type data layers. Slope steepness was generated from the DEM and subsequently reclassified into seven 5° slope categories (Figure 2). Soil series were grouped based on data from a soils database within the GIS, into three categories according to relative resistance to erosion (Ahmad, 1989; Roche Lteé, 1992). Most andisols, alfisols, some inceptisols, and mollisols were classified as stable, while soils classified as less stable included some inceptisols and most mollisols. Fragile soils were predominantly vertisols. Relative soil stability across the watershed is illustrated in Figure 3.

The slope steepness layer and soil stability layers were combined in a cross-classification operation in the GIS. Nine unique combinations or 'capability classes' with specific management prescriptions were defined. Management prescriptions for each of the nine combinations are contained in Table 2. On stable soils with flat to gentle slopes it was assumed that no special soil conservation measures were necessary, and the recommended treatment is intensive cultivation with bananas or other traditional crops. On steeper slopes with less stable soils, recommended treatments incorporated conservation measures such as contouring and strip-cropping. On very steep slopes, agro-forestry systems were recommended, in which traditional crops are alley-cropped with tree crops along the contour. On the steepest areas where the erosion risk was high, forestry-based systems were recommended.

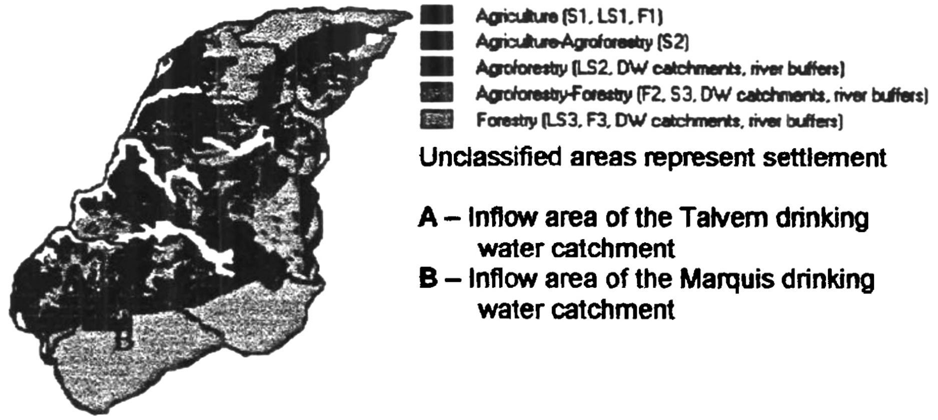
Within the watershed are two major catchment areas for extraction of drinking water. The Marquis Pumping station and the Talvern Pumping station located on two separate branches of the Marquis River, extract water for drinking supplies to nearby communities (Figure 1). Agro-forestry prescriptions were recommended for these areas to minimize soil and agro-chemical discharge into the rivers upstream of the water extraction points.

Table 2. Recommended conservation treatments and management prescriptions

Soil stability class	Slope class (degrees)	Capability class	Recommended treatment system	Management prescriptions		Conservation support practice
				Recommended main crops	Recommended secondary crops	
Stable	0-5 5-10 10-15 15-20	***S1***	**Agriculture**	Bananas, root crops, vegetables (100% coverage)	Tree crops optional	Contouring on gentle slopes
	20-25 25-30	***S2***	**Agriculture/ Agro-forestry**	Bananas, root crops, vegetables (60-80% coverage)	Scattered tree crops (20-40% coverage)	Strip cropping Alley cropping
	30+	***S3***	**Forestry**	Natural or plantation forest, pure tree crops	None	None
Less stable	0-5 5-10	***LS1***	**Agriculture**	Bananas, root crops, vegetables (100% coverage)	Tree crops optional	Contouring Strip cropping
	10-15 15-20	***LS2***	**Agro-forestry**	Bananas, root crops, vegetables (50-60% coverage)	Tree crops planted along contour (40 - 50% coverage)	Strip cropping/alley cropping Alley cropping
	20+	***LS3***	**Forestry**	Natural or plantation forest, pure tree crops	None	None
Fragile	0-5	***F1***	**Agriculture**	Bananas, root crops, vegetables (100% coverage)	Tree crops	Contouring
	5-10	***F2***	**Agro-forestry/ Forestry**	Natural or plantation forest, pure tree crops (80% coverage)	Limited temp. crops with high crown cover	Alley cropping
	10+	***F3***	**Forestry**	Natural or plantation forest, pure tree crops (100% coverage)	None	None

NOTE: Drinking water catchment areas were assigned agro-forestry treatments.
Forest reserves were assigned forestry treatments.
Source: Cox, 1997.

The spatial representation of the capability classification and recommended treatments across the watershed is illustrated in Figure 8.



Unclassified areas represent settlement

A – Inflow area of the Talvern drinking water catchment
B – Inflow area of the Marquis drinking water catchment

Figure 8. Recommended management prescriptions

RESULTS AND DISCUSSION

3.1 Crop suitability

Suitability for the crops evaluated was generally highest at locations that were characterized by flat to gentle slopes, moderate to high annual rainfall, and well-drained, fertile soils. Spatial variation in suitability for mangos and breadfruit was the same since the growth requirements were assumed to be identical. Based on the suitability model, these crops can be cultivated across most of the watershed except on the very steep slopes in the northwest and in the drier areas near the outlet of the watershed. Suitability for avocado across the watershed was similar to mango and breadfruit although there was a slight difference due to soil drainage requirements. Suitability for citrus was more restrictive in the watershed, optimal areas occurring on the gentler slopes within the river floodplain and in the central area of the watershed. Suitability for cocoa was optimal only in the southwest reaches of the watershed due to the high rainfall requirements for the crop (Figures 7a to 7d).

The suitability models generated through MCE can be useful in their application to determining crop zoning for other watersheds on St. Lucia. The model can be refined as crop growth parameters for individual crops are better understood. In addition, potential yields can be estimated based on relative growth suitability. This type of data can be valuable in guiding crop diversification strategies and prioritizing areas within watersheds for agricultural development.

The limitations of using such a procedure must be considered however. Three growth factors were considered in this analysis; slope steepness, soil suitability and rainfall. While these parameters may represent optimal growth and yield potential, other factors may affect the decision to recommend particular crops for given areas over the watershed. Proximity to vehicular access and irrigation sources, pest and disease risk for example, are other factors that can be considered. In addition, the precise relationships of the factors on crop growth as expressed in the fuzzy set membership functions need to be well understood before confidently applied.

Recommended Land Treatments

Assignment of land treatments depended on the land capability classification matrix (Table 2). Intensive agricultural management regimes were assigned to flat slopes with stable soils within the main river flood plain and over the western and south-central areas, and represented 769 ha of the watershed. Agro-forestry prescriptions were assigned to 1,068 ha of the watershed, predominantly in the steeper areas in the central areas of the watershed on the hillsides adjacent to the floodplain. Agro-forestry treatments were assigned to the sub-watersheds that drain into the drinking water extraction points (Talvern and Marquis pumping stations). The Talvern and Marquis catchments encompass 324 and 450 ha respectively. Currently the Talvern catchment is predominantly under intensive banana agriculture (Figure 1) and represents a high degree of conflictive land use, while the Marquis catchment remains mostly forested within the forest reserve. Forestry prescriptions were assigned to the steepest slopes underlain by erodible soils over two regions; the northwestern and southeastern areas of the watershed. The recommended prescriptions are illustrated in Figure 8.

Defining the spatial pattern of recommended management prescriptions over the watershed represent a first step in watershed planning. The next step would be evaluating these recommendations with respect to the current management practices at the farm scale to determine implementation strategies. The crop suitability evaluation can be integrated within the recommended management practices in terms of determining most suitable tree crops to integrate into agro-forestry prescriptions.

CONCLUSIONS

The procedures presented in this paper demonstrate the application of geographic information systems in spatial modelling and decision-support in watershed management planning on St. Lucia. The advantage of using a GIS is the ability to efficiently combine numerous data layers on the basis [illegible] decision criteria and rules to derive management recommendations. While the process may be achieved manually, the complexity of integrating multiple map layers within a decision rule base may make detailed analyses error-prone and subjective. The spatial representation of management recommendations over the watershed allows managers to easily visualize and quantify the scale and implications of management interventions.

Using GIS in watershed modelling has been a natural step in the evolution of sustainable management planning in many countries around the world. The same is now true for St. Lucia, with the availability of GIS data and the affordability of capable commercial GIS products. The challenge however is to ensure that input data is accurate and very importantly, up-to-date. This means that while a land manager may spend less time compiling and analyzing data, more time needs to be invested in maintenance of the databases.

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