Assessment of land suitability potential for selected field crops using GIS - based multi-criteria analysis :
Evaluating the case for Jaffna Peninsula, Sri -Lanka.

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ABSTRACT: Land evaluation using a scientific procedure is essential in assessing the potential and constraints of a given land parcel for agricultural purposes. Various approaches of land evaluation have been developed, and each has a specific methodological procedure. In contemporary land evaluation exercises, statistical and geospatial (such as Geographic Information System or GIS) tools are used to assess the land units and to present the results as suitability maps. In the last decade Multi-Criteria Analysis (MCA) has received renewed attention in the context of GIS- based decision-making. The purpose of this paper is to apply an integrated approach for evaluating potential land suitability for selected field crops in the Jaffna Peninsula, Northern Sri Lanka. This approach applies techniques such as GIS and MCA. According to the potential land suitability analysis, the study area was found to have a considerable amount of land (45%) which is marginally suitable for selected field crops. The next largest total land area was in the category of 'Most suitable' for crops, while there was relatively little land classified as least and not suitable. This study also provides us with an understanding of the potential and limitation to development of the land in the region. Land-use planners often make complex decisions within a short period of time when they must take into account sustainable development and economic competitiveness. A set of land-use suitability maps would be very useful in this respect.

Key Words: land evaluation; geographic information system (GIS); multi-criteria evaluation; jaffna peninsula; field crops.

Introduction

Decisions on the land use allocation for a specific location depend on the suitability of the land for a specific type of use. This can be assessed by a land suitability evaluation. The basic feature of land suitability evaluation is the comparisons of the requirements of land use with resources offered by the land. It integrates three factors of an area: location, development activities, and biophysical/environmental processes. The result is a measure of the suitability of each kind of land use for each kind of land and is used to guide strategic land use decisions (Rossiter, 1995). Land evaluation is formally defined by Food and Agricultural Organization (FAO, 1976) as 'the assessment of land performance when used for a specified purpose, involving the execution and interpretation of surveys and studies of land forms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation'. Carsjens and Knaap (2002) suggest that a land suitability evaluation predicts the potentials for the land and constraints on land for a defined use and provides objective data sets for these potentials and constraints, which influence any decisions on land use allocation.

Although traditional land evaluation approaches have been based primarily on soil surveys and land capability classifications, the first scientific land evaluation method, called "Framework for Land Evaluation", was proposed by FAO (1976). In this method, the concepts, principles and methodologies for land suitability evaluation have been described. Subsequent FAO guidelines on land evaluation involved detailed application of the Framework for land evaluation to several specific main land use types, namely, rain-fed agriculture, irrigated agriculture, livestock and forestry production (FAO, 1983, 1984, 1985, 1991 respectively). The principles of the FAO framework state that land should be evaluated with respect to its suitability for range of alternative land uses based on several criteria: the requirements of specific land uses, a comparative multi-disciplinary analysis of inputs and outputs, the physical, economic and social context, and potential environmental impacts and land sustainability (Dent & Young, 1981; George, 2002). The FAO approach has been applied extensively in projects supported by FAO in various countries immediately after the publications of Framework and Guidelines of land evaluation (e.g., FAO, 1980; Dimantha, 1980, 1986; Dimantha& De Alwis, 1981; Stamm, Gill, & Page, 1987; Somasiri, 1993; Chen, Messing, Zhang, Fu, &Ledin, 2003).

One of the most significant developments has been the advent of PC-based Geographic Information System (or GIS). GIS facilitate the storage and analysis of a wide range of spatial data and displaying topological interrelations of different spatial information. Computerized databases and modeling programs are now inter-faced with GIS in order to facilitate the computational intensive aspects of land evaluation, particularly in the stage of matching potential land utilization requirements with land qualities (George, 2002; Ekanayaki & Dayawansa, 2003). Thus, nowadays, GIS is used widely as an effective tool for land evaluation. This graphic capability of GIS allows for readily producible communication of the outcome of land-evaluation in formats useful for guiding decision making at all levels, such as maps.

The map-overlay approach has been typically implemented to land suitability in the form of Boolean operations or rule-based approach, whereby all criteria are reduced to logical statements of suitability and then combined by means of one or more logical operators such as intersection (AND) and union (OR). This method is easy to implement within the GIS environment using map algebra operations. The method is also easy-to-understand and spontaneously attractive to decision makers (Malczewski, 2004). Hence, a number of researchers applied the Boolean operations as a major methodological approach in GIS-based land suitability analysis (e.g., Beek, de Bie, & Driessen, 1997; Kaligorou, 2002;Suthakar, 2002;Bandyopad hyay, Jaiswal, Hegde & Jayaraman, 2009; Rasheed & Venugopal, 2009; Sathish & Niranjana, 2010).

However, the utility or GIS functionality in the land suitability analysis has been limited by the restrictions inherent in overlaying of digital information maps. Some of these restrictions are: (1) overlays are difficult to use when there are many underlying variables (more than 4), (2) the overlay procedure does not enable one to take into account that the underlying variables are not of equal importance (Janssen and Rietved, 1990; Silva and Blanco, 2002). The integration of Multicriteria Decision Making (MCDM) techniques with GIS has considerably advanced the conventional map overlay approaches to the land suitability analysis. Recently, thus, much attention has been paid to solving land suitability evaluation problems with MCDM techniques in a GIS environment. A well-established body of literature on GIS-based MCDM exists (e.g., Carver, 1991; Banai, 1993; Pereira & Duckstein, 1993; Eastman, McKendry, & Fulk, 1995; Eastman et al. 1998; Sharifi & Retsios, 2004; Silva & Blanco, 2003; Malczewski, 2006;Hossain & Das, 2010).

These two distinctive areas of research, GIS and MCDM, can benefit from each other. GIS techniques and procedures, data acquisition, storage, retrieval, manipulation and analysis, have an important role in decision problems. Indeed, GIS is often recognized as a decision support system involving the integration of spatially referenced data in a problem solving environment. On the other hand, MCDM provides a rich collection of techniques and procedures for structuring decision problems, and designing, evaluating and prioritizing alternatives decisions according to specified decision rules. In fact, in this process, multidimensional geographical data and value judgments (the decision-maker's preferences) can be combined into one-dimensional values to obtain information for decision making regarding land use allocation (Sharifi&Retsios, 2004; Malczewski, 2004, 2006).

Over the last decade, many MCDM approaches have received renewed attentionin the GIS environment for tackling land-use suitability problems including the weighted summation method (Mwasi, 2001; Silva & Blanco, 2003; Sharifi & Retsios, 2004), ideal point method (Cromley & Hanink, 2003; Pereira & Duckstein, 1993), outranking method (Joerin, Theriault, & Musy, 2001), ordered weighted averaging (Jiang & Eastman, 2000), Analytical Hierarchy Process method (Mendoza & Prabhu, 2000; Cengiz & akbulak, 2009; Yu, Chen, Wu & Khan, 2011), and Analytic Network Process (Pourebrahim, Hadipour & Mokhtar, 2011). Among these procedures, the weighted summation method is considered the most straightforward and the most often employed because it is very easy to implement within the GIS environment and also easy-to-understand and intuitively appealing to decision-makers. In weighted summation method, continuous criteria (factors) are standardized to a common numeric range, and then combined by weighted averaging.

Challenges towards land use objectives in the Jaffna Peninsula are increased farmers income, employment and labor productivity, stable food production and maintain the quality of natural resources and the reduced the environmental pollution and resolve potential conflict situations among various stakeholder groups of land use and resource use. Consequently, there is an increasing demand for land use planning tool that are flexible enough to contribute usefully to the task of allocating land use in a scientific ways. The prime objective of the Sri Lankan national land use policy is to guide the utilization of the limited land resources on a scientific basis and in a sustainable manner considering the needs of future generations (Land Use Policy Planning Division, 2003). However, in many areas, the miss- assignment of land use is such that as a result land is being visibly degraded. It is well understood by the land use planners that the present pattern of land use is not sustainable yet systematic information on land resources is scarcely used at any level of decision-making. Current evidence indicates that increasing areas are subject to land degradation and poor management, lessening the land available for agricultural uses. For instance, in the Jaffna Peninsula, more than 2,500 ha paddy land has been abandoned from cultivation due to the increase of salinity (Department of Agriculture, 2005). The Nitrate concentration of ground-water in some agricultural areas is beyond the limits of the safety level due to the indiscriminate use of chemical fertilizers for paddy cultivation (Navaratnarajah, 1994; Mikunthan, 2005). Moreover, intensified cash crop cultivation (double or triple cropping) in the Jaffna Peninsula has increased more than 80 kg Nitrogen/ha per crop; hence, irrigation losses through the thin permeable soils are primarily responsible for the unusually high groundwater nitrate concentration observed (Hiscok, 2000). Expansion of residential, commercial, mining and transportation activities into agricultural lands has been occurred indiscriminately since last few years. Furthermore, the problems regarding to the data use and analysis involve lack of knowledge of methods for analyzing and compiling information; heavy and complicated procedures of land evaluations and land use allocation, due to lack of modern computerized tools of map data storage and retrieval and spatial analysis.

The accurate identification and the characterization of current production areas and potential areas are essential to agricultural research and development. This use must be done only in suitable areas for this economic activity (Silva & Blanco, 2003). Suitable areas for agricultural use are determined by an evaluation of the climate, soil, and relief environment components, and the understanding of local biophysical restraints. In this kind of evaluation, many variables are involved and each one should be weighting according to their relative importance on the optimal growth conditions for crops. In this research, that issue was expressed as Multi-Criteria decision problem, because several criteria (with different relative importance) should be evaluated. In this context, MCA seems to be applicable to GIS-based land suitability analysis (Pereira and Duckstein, 1993) and help us to carry out the delineation of potential suitable areas for crops. In Jaffna Peninsula, Suthakar & Rajeswaran (1990) and Suthakar (2002) demonstrated the utility of the FAO and GIS based FAO approaches to determine the suitability of land for several crops. However, MCA-GIS integration has not been utilized in Jaffna Peninsula to solve problems related to agricultural topics, such as in the case of identifying potential suitable areas for specific crops. For this reason, the main goal of this research is to delineate the potential suitable areas for the paddy, chili, onion, tobacco and potato crops through the MCA technique within a GIS context.

Materials and Methods

Study Area

The study area, Jaffna Peninsula, is situated in the extreme north of Sri Lanka. It is bounded by northern latitudes between 9° 34' 01.41" and 9° 50' 0.7.46", and eastern longitudes between 79" 45' 42.01" and 80° 37' 14.58". The total area of the Peninsula is 1125.7 sq. km of which inland lagoons cover 45.7 sq. km. The Peninsula is about 64 kilometers long with a width of 6 to 22 kilometers. It is bound with Palk Strait on its western, northern and eastern sides and the Jaffna lagoon abounds in the south. The narrow neck of the Peninsula, occupied by the Chundikkulam bird sanctuary and by the Elephant Pass, connects it to the rest of Sri Lanka. Three inland lagoons divide the peninsula into four geographical sub-regions: Islands, Vadamarachchi, Thenmarachchi and Valikamam. The Jaffna Peninsula refers to a physical unit rather than an administrative unit and it has two district administrative divisions which include Jaffna District and part of Kilinochchi district. The study area covers the entire Jaffna administrative district and part of the adjoining Kilinochchi district and includes 16 divisional administrative divisions, 14 from Jaffna district, and one from Kilinochchi district (Figure 1). A small (47.16 sq.km) divisional administrative division of Jaffna district is excluded from the study.

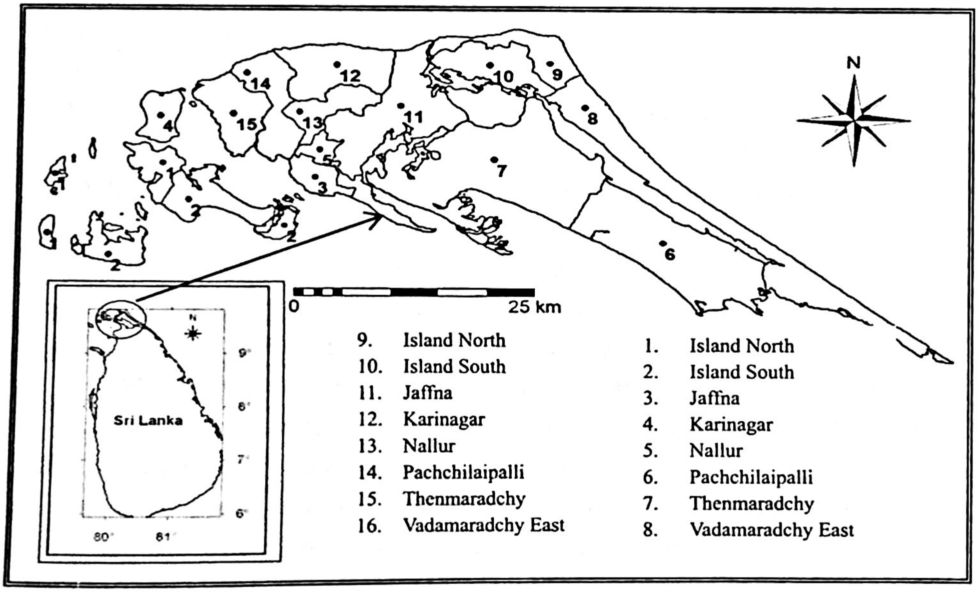

Figure 1. Study area and its local administrative divisions

Methods

The general procedure that followed in this paper outlined in Figure 2. This procedure is categorized as (i) structuring, (ii) standardization, (iii) weighting, and (iv) suitability assessment. The following sections explain all these steps in detail.

Structuring

Structuring refers to the identification of the main goal, sub-goals and the establishment of the criteria for evaluating the sub-goals and main goal (Figure 2). Main goal is here the land suitability evaluation. Land suitability evaluation has been made separately for each crop, because each crop has different requirements to meet a particular land. Therefore, suitability analysis for a particular crop is considered as sub-goal of the main goal of land suitability evaluation. Five field crops have been selected for land suitability assessment: paddy, chili, red onion, tobacco, and potato. Crops have been chosen on the basis of existing cultivation trends. Paddy is grown on small-holdings and mainly for domestic consumption. It is cultivated in rain-fed condition from October to March. Tobacco, red onion, chili and potato are the major commercial crops in this region. These crops are cultivated under small-holding with irrigation

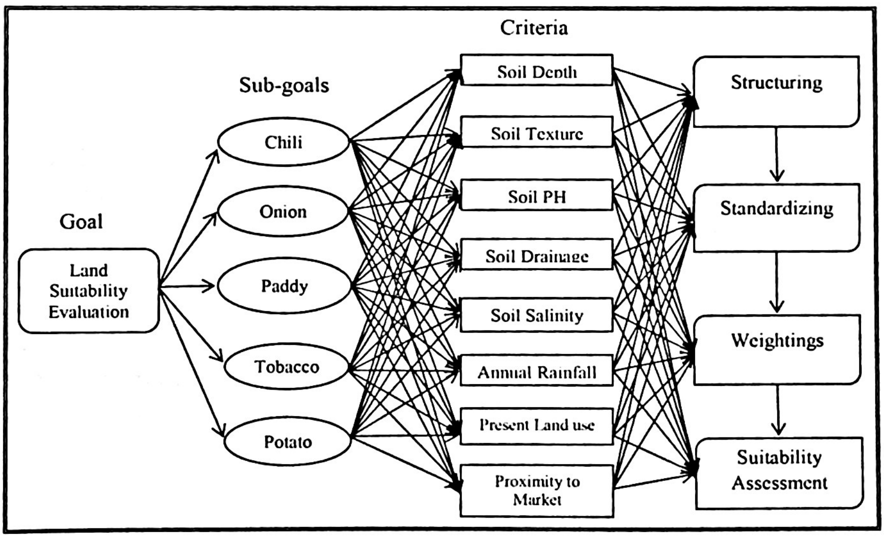

Figure 2.Procedural flow chart for land suitability evaluation through GIS based multi-criteria analysis:

Criteria are measurable based on which decisions about land quality and its suitability for a specified land use can be made. The eight criteria were identified as being relevant to the land suitability evaluation of selected field crops (Figure 2). Soil factors such as texture, depth, pH, and drainage significantly determine the growth, yield of the selected field crops and vary spatially in the study area. These factors were mapped from the soil map and its attributes (Irrigation Department, 1981). Although the spatial and temporal pattern of rainfall does not vary significantly, small variations affect cultivation of rain-fed crops, particularly the cropping calendar and yield. The spatial rainfall pattern was prepared from annual average rainfall data collected from available rainfall stations of the Jaffna Peninsula. Salinity is another important criterion which determines the crop activities greatly, particularly in coastal areas. Although soil salinity condition varies spatially and temporally, only an average pattern of salinity level was mapped. From a management point of view, suitable land uses should be made as close as possible to land with the same use; hence, present land use was considered as one of the criteria in this study and prepared from satellite images for the period of 2009(University of Maryland,2010). Proximity to market regulates agricultural activities in terms of site selection and prices of outputs of crops; hence it was selected as other criteria for suitability analysis. Proximity to market was modeled as a distance surface in GIS. Temperature is one of the determinant criteria for field crops; however, spatial variation in temperature in the study area is not significant to consider for analysis.

Standardizing the criteria

The values in the various criteria maps (factors) are expressed in different levels of measurement (e.g. nominal, interval, etc.). In order to compare criteria with each other in the multi-criteria process, all values need to be standardized, that is transformed to the same unit of measurement (from 0 to 1). Standardization is a measure of appreciation of the experts (partial attractiveness) for a particular crop with respect to each criterion. Linear Maximum standardization method was carried out for value maps (e.g., rainfall, proximity to market). However,for class maps, standardization was done by Pair-wise method.

Establishing the criteria weights

The next step was to establish a set of weights for each of the criteria. Different criteria usually have different level of importance. One of the most promising techniques for the development of weights is pair-wise comparisons developed by Saaty (2000) in the context of multi-criteria decision making process known as Analytical Hierarchy process (AHP). In the pair-wise comparison method, the analyst must indicate for each pair of criteria which criterion is the most important one for the stated crop. Subsequently analyst must indicate in qualitative terms to what extent a factor is more important than another. The pair-wise comparison method converts these comparisons of all pairs of criteria to quantitative weights for all criteria. It is also possible to determine the degree of coherence of the judgment of the comparisons, known as an inconsistency ratio which suggests whether to improve the judgment, by allowing the individual or the group to modify some of their estimates. Based on the relevant literatures (Dimantha, 1980; Dent & Ridgway, 1986; Deparment of Agriculture, 1990; Somasiri, 1993), a pair-wise comparison matrix was filled for each crop, according to the Saaty's rating scale (Saaty, 2000). The weighting was calculated at three different levels: between soil factors (depth, texture, drainage, and pH), between non-soil factors (rainfall, salinity, land use, and proximity to market), and between soil factors and non-soil factors. The table 1 shows, as example, the weight of the soil factors for paddy crops.

Table 1. Assessing weights for red onion by Pair-wise comparison method

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Soil factors	Depth	Texture	Drainage	pH	Normalized weight
Depth	1	3	5	1	0.091
Texture	1/3	1	3	1/5	0.279
Drainage	1/5	1/3	1	1/5	0.547
pH	1	5	5	1	0.082
Inconsistency ratio					0.040881

Suitability Assessment

The final step is to obtain the composite suitability map for selected crops. Weighted criteria are combined together to produce suitability map. This combination was carried out by Weighted Linear Combination (WLC) method. Consequently, the result is a continuous mapping of suitability to produce composite suitability map. The procedures of WLC are expressed by the following formula(Mendoza, 1997):

$$S = \sum w_i x_i * \prod c_j$$

Where, S= suitability; w= weight of factor i; x= criterion score of factor i; c = criterion score (false/true) of constraint j; and Π= product.

The composite suitability map has a value between 0 and 1. The values approaching 0 represents least suitable and values approaching 1 stands for most suitable for a particular crop in particular place. Once a composite suitability map has been prepared, it is necessary to undertake the ranking of suitability. The composite suitability maps were recalculated appropriately into five classes to understand easily: (i) most suitable, (ii) moderate suitable, (iii) marginal suitable, (iv) least suitable and not suitable.

Results

Potential Suitability of Field Crops

The potential land suitability maps for the crops resulting from GIS-based multi-criteria analysis in the Jaffna Peninsula are depicted in this section. The area of suitability for crop types is summarized in the Table 2. Maps in subsequent pages and Table 2 provide spatial and quantitative information regarding the potential land suitability of some selected field crops of the study area respectively. The suitability maps were prepared based on criteria associated with soil factors (depth, texture, pH, and drainage) and with non-soil factors (rainfall, salinity, land use, and proximity to market). Accordingly, this is essentially a physical suitability evaluation. The local administrative boundaries of the study area are overlaid on each suitability map which may provide more illustrative information for local level decision makers regarding potential suitable crops of their respective divisions. The following section describes the potential suitability of the present crop types spatially and quantitatively.

Table 2. Areas of potential land suitability for field crops (hectares)

Land use types	Suitability ranking class				
	Most suitable	Moderate suitable	Marginal suitable	Least suitable	Not suitable
Paddy	14,085	7,741	6,448	56	79,118
Chili	12,332	21,637	55,434	6,106	6,803
Red onion	15,893	22,467	42,926	14,283	6,803
Tobacco	25,202	11,132	45,899	13,336	6,803
Potato	12,160	11,223	56.658	15,542	6,803
Total	79,672	74,200	20,7365	49,323	106,330

The spatial pattern of the potential land suitability for paddy cultivation is displayed in Figure 3. Almost one fourth of the land in the Jaffna Peninsula (79,118 ha) appears to be not suitable for paddy cultivation (Table 2). Only 13 percent of the total land was ranked as 'most suitable' for paddy; however, another seven percent of land was assessed as 'moderately suitable' for paddy. The 'most suitable' areas for paddy are dominantly found in the Thenmaradchy administrative division (28%). Next to Thenmaradchy, 'most suitable' areas are assigned in the administrative divisions of Vadamaradchy South West, Island South and Valikamam West.

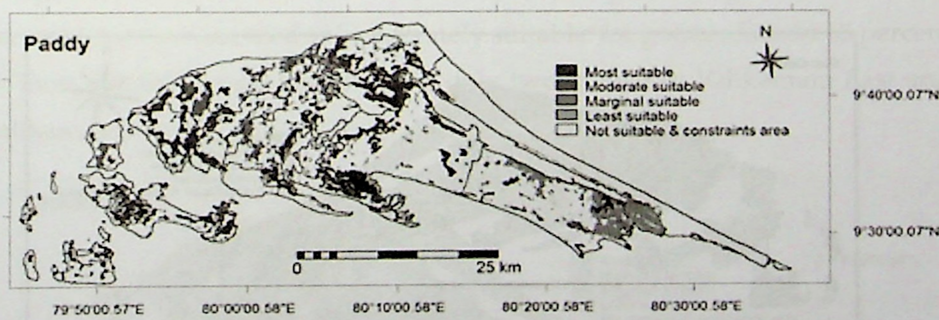

Figure3. Map of suitability for paddy in the Jaffna Peninsula.

The suitability map for chili (Figure 4) shows the different suitable classes spatially. Thirteen percent of the total land is potentially 'most suitable' for chili cultivation; however, more than half of the area of the Jaffna Peninsula was evaluated as 'marginal suitable' for chili. The 'most

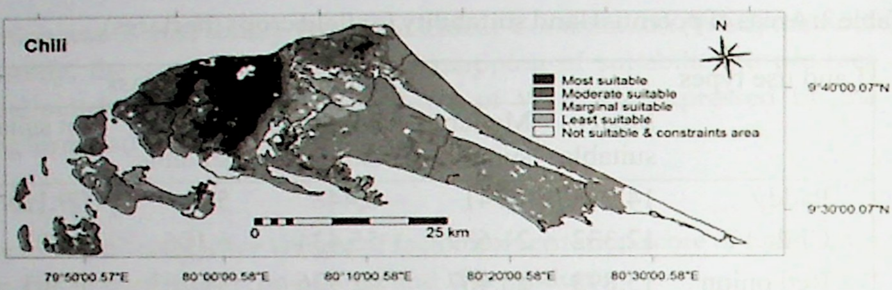

Figure4. Map of suitability for chili in the Jaffna Peninsula.

suitable' land is mostly concentrated on a few administrative divisions such as Valikamam North, Valikamam East and Valikamam South; indeed, more than eighty percent of the 'most suitable' lands are found in these administrative divisions.

The suitability map for red onion (Figure 5) indicates that about 15% of the study area was rated in 'most suitable' class and nearly 60% of area is found in the two lower classes (moderate suitable and marginal suitable). Almost seventy percent of the 'most suitable' land for red onion is found in only three administrative divisions of the Jaffna Peninsula (Figure 5): Valikamam North, Valikamam East and Valikamam South administrative divisions of the study area.

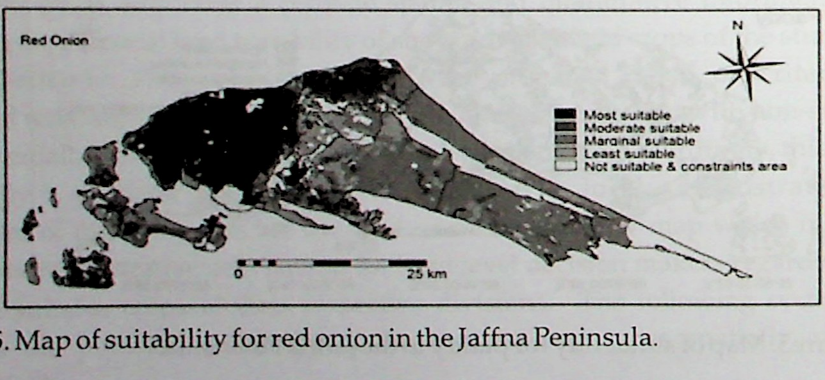

Figure5. Map of suitability for red onion in the Jaffna Peninsula.

Figure 6 shows the spatial pattern of potential suitable classes for the tobacco cultivation in each administrative divisions of the study area. The total area of 'most suitable' land is 25,202 hectares which is 25 percent of the study area. 'Most suitable' land for tobacco is found in many administrative divisions; however, Valikamam East and Valikamam north have the highest percentage, that is each division has 20 percent of most suitable land out of total most suitable land. Between 10 to 14 percent of the 'most suitable' lands are occupied in the divisions of Vadamardchi South west, Valikamam South, Valikamam South West and Valikamam West. 'Moderate' and 'marginal' suitable lands for tobacco are 11% and 45% of the total area respectively.

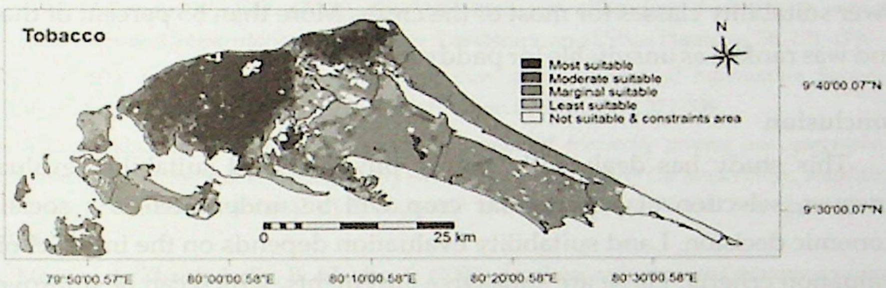

Figure 6. Map of suitability for paddy in the Jaffna Peninsula.

For potato cultivation, only 12 percent of total land is evaluated as 'most suitable'; however, more than 70 percent of total area is classified either 'marginal suitable' (55%) or 'least suitable' (15%) for potato (Figure 7). Another 11 percent land was assessed as 'moderately suitable' for potato. Almost 65 percent of 'most suitable' lands are found in only two divisions: Valikamam East and Valikamam North.

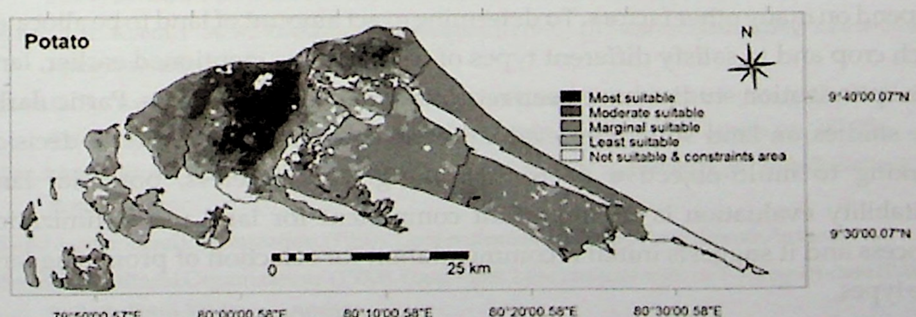

Figure 7. Map of suitability for potato in the Jaffna Peninsula.

The overall pattern of potential land suitability reveals that only a few administrative divisions were assessed as 'most suitable' for most of the crops: Valikamam East, Valikamam North, Valikamam South and Valikamam South West. However, paddy presents a different suitability pattern. In fact, large areas of Thanmaradchi and Pachchilaipalli divisions were evaluated under 'most suitable' category for paddy but unsuitable for other crops. Most parts of the Islands of the Jaffna Peninsula and Vadamaradchi East division were ranked as lower suitability classes for most of the crops. More than 65 percent of the total land was ranked as unsuitable for paddy in the study area.

Conclusion

This study has dealt with mainly physical land suitability evaluation; however, selection of a particular crop will be undertaken is a social and economic decision. Land suitability evaluation depends on the initial choice of evaluation criteria. These are subjective judgments, which can be improved by comparison of the predicted performance of the land with its actual performance. Land is ranked from most suitable to not suitable, but estimates of performance are not reliable, because performance is determined by management. An optimal land use planning should consider the objectives of efficiency, equity and acceptability, and sustainability of the land use activities. A land suitability evaluation study alone does not meet all of the above objectives. Land evaluation studies provides range of promising land use type for particular land area in terms of mainly physical criteria; however, there is no assurance for efficiency and acceptability because decision of particular crop depend on many other factors. To determine exact amount of land to be allocated each crop and to satisfy different types of objectives as mentioned earlier, land use optimization studies have been recommended in recent years. Particularly, the studies on land suitability evaluation switch from multi-criteria decision making to multi-objective decision making. Nevertheless, potential land suitability evaluation is an important component for land use optimization process and it suggests initial recommendation for selection of promising land use types.

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