GIS-BASED MULTI-CRITERIA MODEL FOR COTTON CROP LAND SUITABILITY: A PERSPECTIVE FROM SINDH PROVINCE OF PAKISTAN

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Abstract

Land use potentialities and local agro-ecologies limits are key principles of sustainable land management. Geographical Information System (GIS) is an efficient tool for collecting, storing, retrieving transforming and displaying spatial data and also non-spatial data from the real world for a particular set of objectives. In this study agroinformatics and geo-spatial technologies are combined to design a model for evaluating the cotton crop land suitability. Soil, ground water availability, irrigation methods, climate, land use, cropping patterns and agro-ecological zoning are used in a model with GIS framework as a Spatial Decision Support System. Multi-criteria decision-making methodology is employed in a systematic manner. It starts with the selection of significant factors and goes on with normalization, ranking, weight extraction and implementation of weighted overlays function for graded suitable areas identification for cotton crop cultivation in the Sindh province of Pakistan. The criteria are normalized on a same scale viz. suitable, less suitable and not suitable land for cotton crop cultivation. The output of model is validated through practicing cropping pattern in the region and associated agriculture statistics. We found a highly significant correlation (r = 0.92) between multi-criteria cotton crop suitability and practicing crop patterns in the study area. This model can be extended for local scale with variety of crop types and in other regions of the world.

Introduction

One of the most primitive occupation of the civilized man is agriculture. It dedicates a lot on its development, from shifting cultivation to advanced precision agriculture. With this agriculture development man came to know about new crops and their proper cultivation. Now days, it has become a profession and named as commercial agriculture, sustainable agriculture and precision agriculture (Bongiovanni and Lowenberg-DeBoer, 2004).

Plant scientists and policymakers are looking for new methods of accelerating the rate of adoption of sustainable agriculture, though sustainable agriculture is a complex innovation and is still in progress. Compared to other types of innovations, the change to sustainable agriculture imposes various risks on farmers. These risks are not only economical and technical nature, also have social and political aspects (Somers, 1997). Since the Rio Earth Summit, sustainable agriculture has been documented as encompassing three interdependent dimensions: economic impact, social needs and the environment friendly. (Urech, 2000; Pietro, 2001).

Cotton fiber is economically important and is the world's leading natural fiber used in the manufacturing of textiles (Xu *et al.* 2008). Pakistan is a semi-industrialized country with heavy dependence on the agricultural sector hence there is a strong relationship between its industrial and agriculture sectors. This relationship is very important due to the prominence of this crop in the Pakistani agriculture. As a result, the policymakers are facing a great challenge to carry out agricultural reforms in their pursuit for sustainability and optimization of resources (Henneberry *et al.* 2000).

The population growth of the country is considerably high, so food cropping (wheat, rice and sugarcane) requires a major share of arable land. This situation has forced scientists and researchers to find new methods and technologies in competitive environment. To meet the increasing demand of agri-products for the growing population there is a strong need to produce more and more. But it is not feasible to bring more area under cultivation in the current circumstances due to the limited water and land resources. To tackle this limitation of land, the focus has shifted from extensive farming to intensive farming (more production from the available land). Intensive farming has the potential to increase the crop production using modern technologies through eco-friendly practices. This practice gives the way for precision farming concepts as well as sustainability in agriculture.

Resultantly, the attention of agri-scientists and decision makers has moved to the selection of crops according to its suitability to an area (Kalogirou, 2002). Besides the general land characteristics, climate, rainfall, ground water, irrigation and agro-ecological zones are the other driving forces that can influence the suitability of a crop with respect to an area (Prakash, 2003). The procedure to determine crop-suitable land is also complex due to its multi-disciplinary nature, as it involves several decisions that employ bio-physical, socio-economic and politico-governance aspects.

However, the technological advancements in geo-spatial domain have brought ease for decision makers to utilize land resource at maximum (Carver 1991; Taylor 1997; Mapedza *et al.* 2003). In order to arrive at a decision for suitability, many data layers have to be handled in multi-criteria evaluation. A host of studies show that geo-spatial technologies are capable of delineating potential crop-suitable land, in addition to time saving and good data yielding (Prakash, 2003; Ceballos-Silva and Lopez-Blanco, 2003). Agricultural land suitability also involves efficient decisions at different levels. It starts from choosing a land use types, criteria selection and organization, deciding limits of suitability limits for every class of the criteria and preferences decision making (quantitative and qualitative). Relative significance of these parameters can be well evaluated by multi-criteria evaluation techniques to decide the suitability. This study is designed to prepare a multi-criteria model for cotton crop-suitable land evaluation in the Sindh province of Pakistan by utilizing GIS, remote sensing and statistical tools. This model is also a validation analysis of the existing cotton growing areas and the potential of land in other parts of the province.

Materials and Methods

a. Study area: Sindh province selected as study area for this study. The name of the province, Sindh, has been derived from the Indus River. The Indus Plain is the most prosperous agricultural region of Pakistan, with an area about 21 million hectares. It is made up of fertile alluvial - - thousands of feet thick, transported and deposited by the pre-historic river system (Maik *et al.* 2003). The average gradient of Indus Plain is about 19 cm per km towards the sea and divided into the upper and lower plains. The upper Indus Plain is divided into a number of doabs, meaning the land lying between the two rivers. The lower Indus Plain has been formed by the meandering and shifting courses of the Indus River (Anonymous, 2005). The Fig. 1(a) shows the study area.

As a subtropical region, Sindh is hot in summers and cold in winters. Temperatures frequently rise above 46 °C between May and August, and the minimum average temperature of 2 °C occurs during December and January. The annual rainfall average is about seven inches, falling mainly during July and August. The Southwest Monsoon wind begins to blow in mid-February and continues until the end of September, whereas the cool northerly wind blows during the winter months from October to January. Sindh lies between the two monsoons -- the southwest monsoon from the Indian Ocean and the northeast or retreating monsoon -- deflected towards it by Himalayan mountains and escapes the influence of both. The average rainfall in Sindh is only 15 to 18 cm per year, but the loss during the two seasons is compensated by the Indus, in the form of inundation, caused twice a year by the spring and summer melting of Himalayan snow and by rainfall in the monsoon season. These natural patterns have changed somewhat with the construction of dams and barrages on the Indus (Khan, 1993).

b. Data: Selection of dataset for preparing criteria variables (factors) is a critical aspect that has to be performed carefully to arrive at the objectives and final goals (Densham, 1991)**.** The factors affecting land suitability analysis for the cotton crop are one of the most significant parts of this study. The methods and calculations for multi-criteria decision rules completely rely on the selected factors. Fig.1 shows the selected criterion maps of the study area which are prepared in ArcGIS for the study. The land use, soil, climate, ground water condition, irrigation and agro-ecological zones have been finalized for land suitability. There is no set technique or defined rule to select the evaluation criteria variables. The selection process of the criteria variables is iterative in nature. Literature survey, analytical study and the opinion survey are tools that aid in the selection of the criteria variables. Once the criteria variable is prepared in GIS spatial data, they are transformed into raster and normalization process is done in ArcGIS for further processing.

The Landsat Enhanced Thematic Mapper Plus (ETM+) satellite image of 15 meter resolution for the year 2000 is selected for land use data extraction. Other secondary data like climate, soil, agro-ecological zones, irrigation map, and ground water were collected from different secondary sources. Table1 shows the data used in this study.

c. Methodology: In this study the spatial multi-criteria decision making (SMCDM) methodology has been adopted. SMCDM is a systematic process where geographical data is combined and transformed into a decision. SMCDM involves input data, the decision makers' preferences and manipulation of both information using specified decision rules **(**Jankowski, 1995**)**. In SMCDM weighted overlay (equation 1) is one of the commonly used procedures for applying a normalized measurement scale of values to varied and dissimilar inputs.

$$S = \sum Wi \times Xi \qquad (1)$$

Where

S = Multi-criteria suitability
wi = weight of factor i
xi = normalized criterion score of factor i

Within each criterion variable, we used prioritization technique for normalization. The favorable (suitable) factors with favorable conditions for cotton crop are ranked as 1 (suitable). The less suitable factors ranked as 2, which are the potential suitable areas for cotton crop with some development and changes in conditions. The not suitable areas which are not feasible by any means for cotton crop cultivation are ranked as 3. The normalized criteria variables on a common scale are shown in Fig. 2.

Geographic problems often require the analysis of many different factors. Additionally, the factors in these analyses may not be equally significant. It may be that the soil type is more important in choosing a land for cotton than the irrigation water availability or any other factor. However, same weights have been assigned to all criteria variables for equal participation in the evaluation process.

Results and Discussion

Sources of data is provided in Table 1. Fig. 3 and Table 2 are showing the suitable, less suitable and not suitable areas for cotton crop cultivation in Sindh. The decision-making process involved spatial multi-criteria approach for evaluation of these suitable areas. It is important to note that a major part of the suitable areas is already under cultivation of cotton, but some more areas can still be cultivated, as they show suitability. The not suitable areas comprise of the eastern Thar Desert and the western mountain ridges of Kohistan. Additionally, the Indus Delta area is also not suitable for cotton cultivation.

Based on spatial analysis, the district wise statistics for existing and suitable areas under cultivation has been evaluated to see the difference in cotton production (Table 3). The average annual yield of cotton crop is 937 kg per hectare in Sindh. Based on this average yield the cotton production has been calculated and the results show that there is a great potential to cultivate cotton without making any major development in the areas suitable for cultivation, while reviewing the results, Karachi and Tharparker districts came as not suitable but have some areas (existing) under cotton cultivation. Other regions including Jacobabad, Kashmore and Qambar Shahdadkot are suitable areas for cotton cultivation.

Fig. 3 shows that the well irrigated areas, sweet ground water, loamy lithosole soils and arid climate regions comprise the major part of the cotton suitable land in this analysis. There are many other crops cultivated under these evaluated, potentially suitable areas so there is a need of crop suitability analysis for other crops in order to get better yields by utilizing the present resources at their optimum. The areas which are less suitable for cotton may be more suitable for another crop and better management can lead to excellent results as millions of kilogram of cotton may be produced in this region. This will eventually give boost to economy of Pakistan because cotton is the major cash crop and has the potential to boost economy. This will also support the industrial sector which is suffering due to many reasons including high price of produced cotton.

Table 1. Data Sources.

S. No	Data	Source
1	Land use	Landsat TM Image (NASA Landsat program, 2000)
2	Soil	Pakistan Agriculture Research Council (PARC)
3	Ground Water	Ground Water in Hyderabad & Khairpur Division (Panwar, 1964)
4	Climate	Pakistan Meteorological Department
5	Canal Irrigation command area	Sindh Irrigation and Drainage Authority (SIDA)
6	Agro-ecological Zones	Pakistan Agriculture Research Council (PARC)
7	Cropping Pattern	Pakistan Agriculture Research Council (PARC)

Table 2. Cotton Crop Cultivation Areas in Acres.

S. No	Land for Cotton Crop Cultivation	Area in Hectors
1	Suitable	3364404
2	Less Suitable	6904700
3	Not Suitable	3703146

Table 3. The district wise statistics for existing and suitable areas for cotton cultivation (*Source: Agricultural Statistics of Pakistan).

S.No	Regions	Existing Cotton Cropping Area* (Hectares)	Suitable Cotton Cropping Area (Hectares)	Difference	Existing Average Yield* (Kg)	Potential Average Yield (Kg)	Difference (Kg)
1	Khairpur	80,197	214,188	133,991	75,144,589	125,549,516	50,404,927
2	Ghotki	90,687	183,081	92,394	84,973,719	86,573,043	1,599,324
3	Sukkur	35,749	127,437	91,688	33,496,813	85,911,346	52,414,533
4	N.Feroze	40,966	248,388	207,422	38,385,142	194,354,720	155,969,578
5	ShaheedBenazirabad	55,973	280,842	224,869	52,446,701	210,702,033	158,255,332
6	Jacobabad		14,251	14,251	0	13,353,521	13,353,521
7	Kashmore		114,727	114,727	0	107,498,884	107,498,884
8	Shikarpur	187	224,851	224,664	175,219	210,509,923	210,334,704
9	Larkana	3,365	227,093	223,728	3,153,005	209,632,900	206,479,895
10	QambarShahdadkot		31,763	31,763	0	29,762,350	29,762,350
11	Sanghar	135,615	422,292	286,677	127,071,255	268,616,641	141,545,386
12	Tharparkar	1,098	0	-1,098	1,028,826	-1,028,826	-2,057,652
13	Mirpurkhas	40,317	285,096	244,779	37,777,029	229,357,872	191,580,843
14	Umerkot	24,786	183,838	159,052	23,224,482	149,032,064	125,807,582
15	Dadu	12,113	164,449	152,336	11,349,881	142,738,429	131,388,548
16	Jamshoro	18,203	86,442	68,239	17,056,211	63,940,358	46,884,147
17	Hyderabad	7,896	121,740	113,844	7,398,552	106,671,400	99,272,848
18	Matiari	38,214	138,198	99,984	35,806,518	93,685,268	57,878,750
19	TandoAllahyar	23,307	150,279	126,972	21,838,659	118,972,801	97,134,142
29	Tando Mod. Khan	4,979	92,971	87,992	4,665,323	82,448,655	77,783,332
21	Badin	18,890	47,268	28,378	17,699,930	26,590,030	8,890,100
22	Thatta	2,056	5,210	3,154	1,926,472	2,955,075	1,028,603
23	Karachi	116	0	-116	108,692	-108,692	-217,384
	Total	634,714	3,364,404	2,729,690	594,727,018	2,557,719,312	1,962,992,294

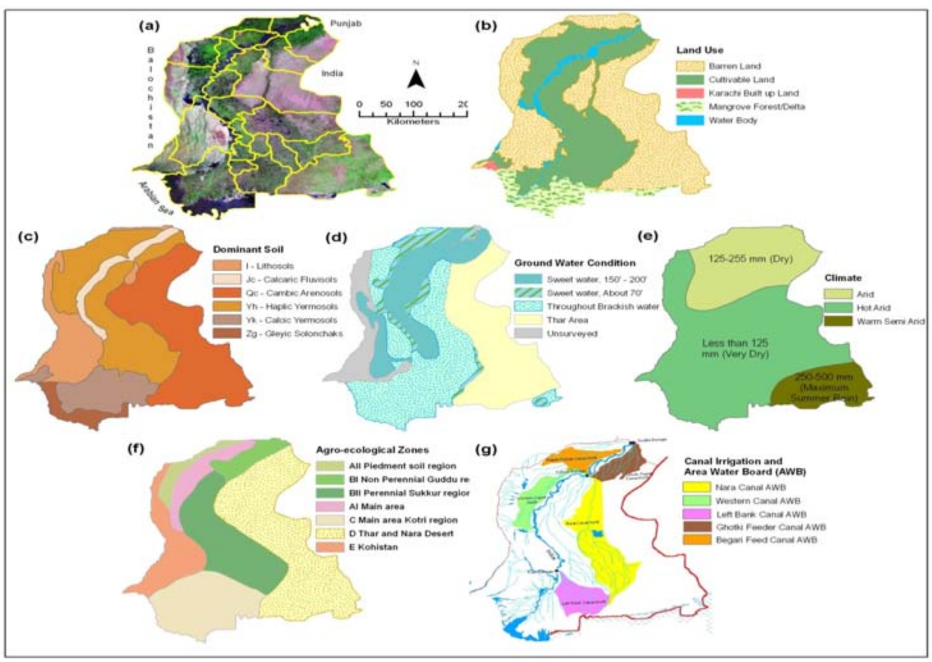

Fig. 1. Selection criterion map of study area. Prepared in ArcGIS.

(a) Landsat ETM Satellite Image of Study Area (b) Land use Map (c)Dominant Soil Map (d) Ground Water Condition (e) Climate zones (f) Agro-Ecological Zones (g) Canal Irrigation Area Water Board

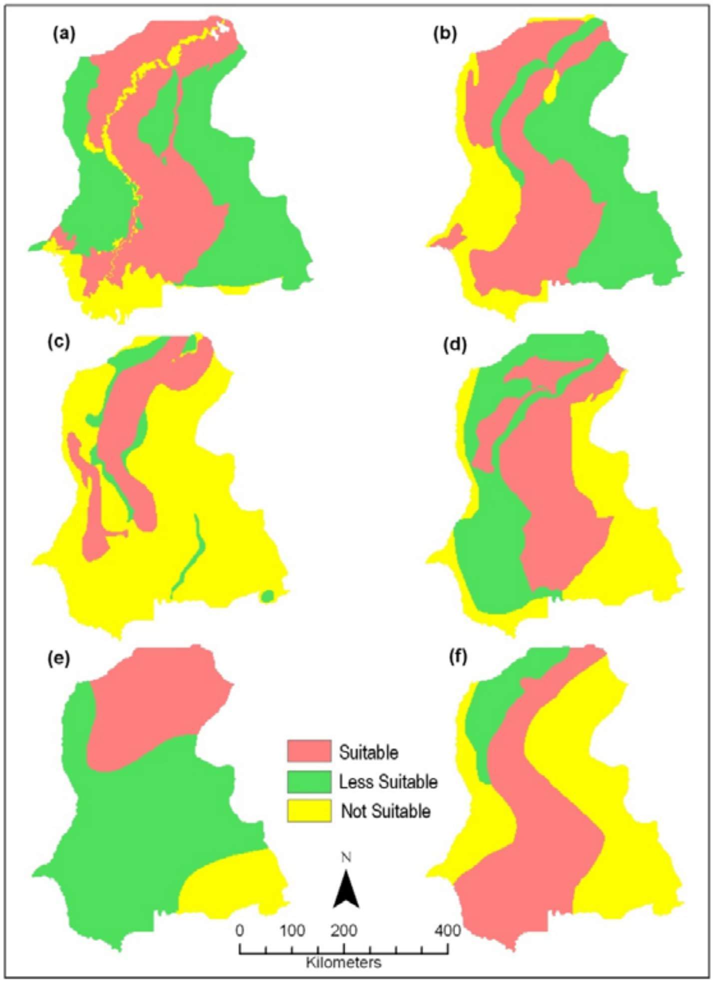

Fig. 2. Re-Classified Criterion to a common scale (a) Land use (b) Dominant Soil (c) Ground Water Condition (d) Canal Irrigation (e) Climate zones (f) Agro-Ecological Zones.

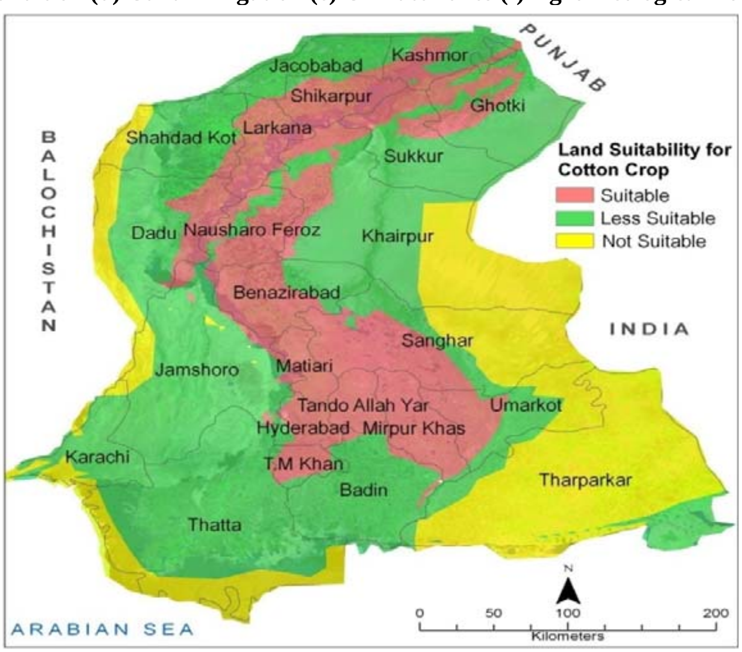

Fig. 3. Suitable Land for Cotton Crop Cultivation in Sindh-Pakistan.

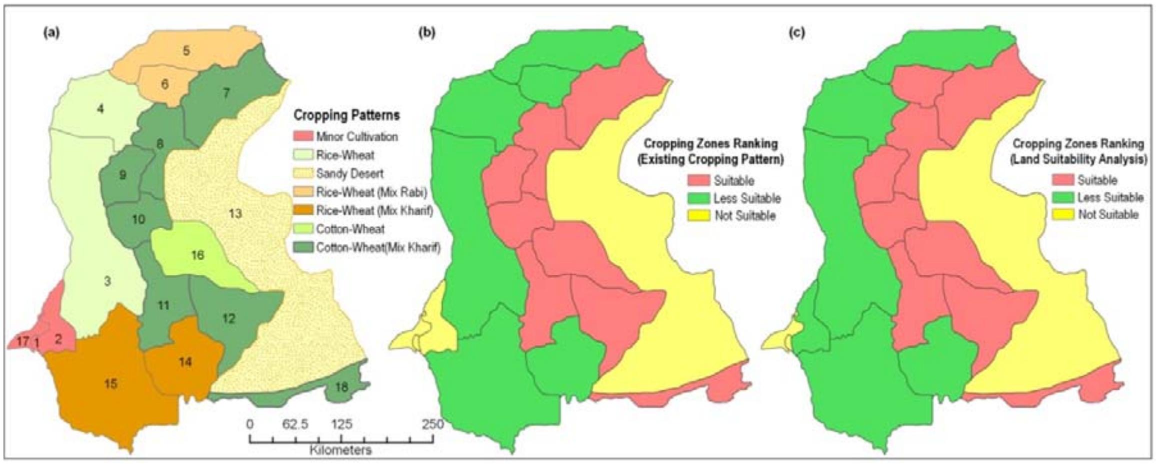

Fig. 4. Comparison between the SMCDM output and existing cropping patterns (a) *Cropping Zones and Patterns of Sindh (b) Cropping zones suitability ranking based on existing pattern (b) Cropping zones suitability ranking based on SMCDM Results,
*(Source: * Pakistan Agriculture Research Council (PARC).*

Validation: The cropping zone map developed by Pakistan Agriculture Research Council (PARC) for existing cropping pattern is used for the validation of the results. The study area comprises of 16 cropping zones categorized into 6 classes based on predominant cropping cultivation. These predominant cultivation patterns are Cotton-Wheat, Cotton-Wheat (Cropping Mix for Kharif), Rice-Wheat, Rice-Wheat (Cropping mix for Rabi), Sandy Desert, Minor Cultivation. We have re-classified these six cropping patterns into a scale same as for SMCDM results i.e., suitable, less suitable and not-suitable, according to cotton cultivation pattern. Cotton, Cotton-Wheat and Cotton-Wheat (Cropping Mix for Kharif) are ranked as 1 (primary cotton cultivation areas - suitable). The Rice-Wheat and Rice-Wheat (Cropping mix for Rabi) ranked as 2 (secondary cotton cultivation areas - less suitable), whereas the Sandy Desert and Minor Cultivation ranked as 3 (not suitable). The result of SMCDM has been converted into similar cropping pattern zone with its predominant level of suitability. Ultimately, Spearman's coefficient was calculated between SMCDM and existing cropping pattern.

Fig.4 shows the similarity between the SMCDM output and existing cropping patterns in study area. That similarity generated the highly significant correlation (r=0.92). The all-cotton growing zones (8 out of 8) lie in the suitable areas category according to SMCDM results. The rice and mixed cultivation regions (5 out of 6) lie in the less suitable areas for cotton whereas sandy desert and minor cultivation regions (3 out of 4) are consisted of not-suitable areas. According to SMCDM results the Rice-Wheat (Cropping mix for Rabi) region in Shikarpur District is suitable for cotton cultivation. But due to availability of water and demand for rice crop, farmers prefer to grow food crop instead of cotton.

Conclusions

The land suitability evaluation involves multi factors, which are in different scales ranging from nominal to ratio. Geospatial technologies have been utilized for handling such a complex phenomenon for long. Remote sensing and GIS techniques are producing firsthand information and providing an integrated platform respectively where diversified and multi-dimensional data can be analyzed. Spatial multi-criteria decision methodology has proven its significance for evaluating the cotton crop suitability analysis. The outcome of SMCDM is highly comparable with the existing cropping patterns. However, the model delineated some more regions where cotton can be grown sustainably and can satisfy the demand of cotton in the textile industry of Pakistan. This methodology can be extended for local scale to analyze land suitability in detail and can be applied on variety of crop types in other regions of the world.

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