GeoJournal (2018) 83:595–611
https://doi.org/10.1007/s10708-017-9788-5

Land suitability assessment for sugarcane cultivation in Bijnor district, India using geographic information system and fuzzy analytical hierarchy process

Mubashir Jamil · Raihan Ahmed · Haroon Sajjad

Published online: 19 June 2017

Abstract Land suitability evaluation is prerequisite for assessing the limitations for sustainable land use planning. We used ten site specific criteria (rainfall, texture, drainage, soil depth, slope, distance to major road, distance to nearest sugar mill, erosion hazard, risk of flooding and pH) and applied weighted multi-criteria evaluation (MCE) technique in a geographic information system (GIS) environment to evaluate land suitability for sugarcane cultivation in Bijnor district, India. The weightage of all the parameters was calculated through fuzzy analytical hierarchy process. Sugarcane suitability map was prepared integrating various parameters through weighted overlay analysis. The map was categorized as highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and unsuitable (N). The analysis revealed that of the total cultivable land of the district, largest area (61%) was highly suitable followed by moderately suitable (24%), marginally suitable (7%) and unsuitable (8%) for sugarcane cultivation. Nagina, Najibabad and Bijnor sub-districts need attention of land managers and policy makers to remove the limitations and increase the suitability of sugarcane in such areas. Only 7% area was unsuitable for sugarcane cultivation. Slope, soil depth and erosion hazard were the major limiting factors making the land unsuitable for sugarcane cultivation. Therefore, these areas should be given priority for land and soil restoration efforts. The study showed effectiveness of integrated GIS and MCE approach for land suitability analysis of sugarcane.

Keywords Land suitability · Land evaluation · FAHP · GIS · Sugarcane · Bijnor

Introduction

Agriculture not only provides food but also provides raw material to the manufacturing industries (Sajjad et al. 2016). It is the major source of livelihood and helps in accelerating economic growth of most of the developing countries (Sajjad et al. 2014). Though share of agriculture and allied sectors in India has declined to 13.9% of the Gross Domestic Product in 2014–15 (The Economic Survey 2014–15), it is still the largest economic sector accounting for about 54.6% of total employment and playing a significant role in the overall socio-economic development of the country (Census of India 2011).

Sugarcane occupies an important place among cash crops of India. About 4.99 million hectares of land is devoted to its cultivation with an annual cane production of around 352 million tonnes (Directorate of Economics and Statistics 2015). After the textiles, the sugar industry ranks second among all the agro-based industries in the country. It also generates employment

M. Jamil · R. Ahmed · H. Sajjad (✉)
Faculty of Natural Sciences, Jamia Millia Islamia, New Delhi, India
e-mail: haroon.geog@gmail.com

revenues owing to its location being generally in the rural areas. Sugarcane is an important source of livelihood in Bijnor district. Of the net sown area, 51% area is devoted to sugarcane cultivation. Among all the crops grown in the district sugarcane has the highest productivity of 641 quintals/hectare. The early 1960s witnessed a revolution in agricultural production and productivity with the introduction of new agricultural technology. Since then the country has made rapid strides in agricultural sector but at the same time this process has brought with its land degradation and environmental challenges (Sajjad and Nasreen 2016). Hence, land utilization within its carrying capacity to meet human needs while ensuring agricultural sustainability is the need of the hour.

Land evaluation process is concerned with the assessment of land performance and potential for specific land utilization type. Planning for land use must be done in such a way that the resources are utilized in long perspective of sustainability. Understanding of both natural environment and kinds of land utilization is essential for optimum land use planning (FAO 1976). Food and Agriculture Organization defined land suitability as "the fitness of a given type of land for specified kind of use" (FAO 1983). Suitability is determined through the quality of land and the inputs required for a specified land use. Land suitability analysis is thus prerequisite to utilize available land resource for specific land use in sustainable manner (Feizizadeh and Blaschke 2012).

Several researches on land suitability have been carried out globally using specific methodological procedure. Burrough (1989) suggested that selection of crops can be efficiently done by incorporating the fuzzy method in land suitability evaluation. Ahamed et al. (2000) applied GIS-based fuzzy membership model to analyse crop-land suitability in which maximum area was found to be potentially suitable for growing ground nut. Malczewski (2002) incorporated the concept of fuzzy screening over the conventional screening method for land suitability analysis. Joss et al. (2008) conducted land suitability for hybrid poplar in which they found 28% of the land base suitable for afforestation. Rasheed and Venugopal (2009) examined crop-land suitability based on agro-ecological characterization. Their result indicated that the cultivated area was less than the area suitable for cultivation. Shearer and Xiang (2009) assessed land suitability in North Carolina. They identified suitable lands for park land-banking program. Qiu et al. (2014) used fuzzy evaluation method for analyzing land suitability/capability and showed its effectiveness in producing suitability maps. Zhang et al. (2015) assessed land suitability for tobacco production using AHP and fuzzy set and stressed on the efficiency of fuzzy and AHP to calculate the weights of multiple factors.

Land use planning and management can be effectively carried out by integrating Geographic Information System (GIS) and multi-criteria decision analysis (Kalogirou 2002; Malczewski 2006; Feizizadeh and Kienberger 2017; Jamil and Sajjad 2016; Feizizadeh et al. 2017; Gheshlagi and Feizizadeh 2017). MCDA technique has the ability to solve problems related to spatial decision involving conflicting criteria. In GIS-based MCDA, information from several criteria is combined to form a single index of evaluation in order to support land use planning and management (Chen et al. 2011). The multi-criteria evaluation approach based on GIS decision rules can reduce the number of factors used in land suitability analysis thereby making analysis easier for decision makers (Karimzadeh et al. 2017). Land suitability assessment in a GIS environment involves three steps, firstly selecting important factors which influence land suitability. These factors are commonly accessible in vector or raster layers which may include precipitation, soil texture, soil pH, slope, erosion hazard, risk of flooding, proximity to major roads, etc. The factors under consideration may vary depending upon the nature and characteristics of the study area. Secondly, the attributes of respective sites are compared based on desirable criteria and thus corresponding suitability ratings for each of the factors are generated. Simple threshold or standardization function is applied so that all factors may be compared, allowing their subsequent aggregation and finally, combined suitability map based on aggregate ratings of individual factors is generated either by traditional map overlay or fuzzy logic based approaches (Jafari and Zaredar 2010; Hall et al. 1992).

Currently map overlay based approaches are very commonly used for land suitability mapping and analysis (Chen 2013; Lingjun et al. 2008; Shahram 2010; Li et al. 2012; Qiu et al. 2014; Elaalem 2012; Collins et al. 2001; Joerin et al. 2001; Scat et al. 2005). McHarg (1969) firstly used modern GIS overlay method. Map overlay- based approaches are generally classified into three categories namely (1) Boolean overlay (2) gradual screening and (3) weighted linear combination (WLC) (Eastman 1999; Kuta et al. 2016).

Boolean Overlay also known as pass/fail screening is a simple method where all variables are converted to Boolean values of suitability using thresholds. In land suitability evaluation, map overlay is based on traditional Boolean logic. The membership (i.e. True or False or {0, 1}) of variables are obtained through crisp set in Boolean overlay, which can only be suitable or unsuitable and cannot be both at the same time thus partial membership between suitability classes is not possible. Binary membership in this approach can be best utilized for sharp edged non-continuous phenomena.

Another approach, which is applied in agricultural land evaluation, is Graduated screening (Qiu et al. 2014). In this approach, numerical ratings are obtained by converting raw values of the chosen factors on a predefined range representing relative suitability rankings. All the rankings of the factors are then integrated based on standard function. Graduated screening tries to overcome the binary nature of Boolean overlay by introducing multi-valued suitability ratings. However, this approach doesn't actually overcome the limitations of the Boolean method as it replaces one clear-cut boundary with many clear-cut boundaries.

In weighted linear combination approach, like Graduated screening approach, suitability ratings are obtained by converting raw values of selected factors. However, during evaluation some factors are given more value as compared to others (Malczewski 2000). Weightage to the factors are given in such a way that the sum of all the weights equals 1. All the weighted ratings are added to determine the final suitability rating. Delineation of suitability areas and land suitability can also be attempted by combining Boolean approach with weighted linear approach (Riad et al. 2011). The main advantage of this approach is to treat factors differently in accordance to their importance. Conceptually Boolean overlay and gradual screening are based on Boolean logic framework. However, in case of weighted linear combination approach there is no definite logic operator to determine the weights of factors under consideration. The weightage thus can be calculated by AHP, ideal vector approach, parametric approach, fuzzy logic etc.

Amongst all the logic operators used in WLC, AHP given by Saaty (1980) has been widely used for land suitability assessment (Akinci et al. 2013; Kazemi et al. 2015; Bozdag et al. 2016; Yalew et al. 2016; Cengiz and Akbulak 2009; Feizizadeh et al. 2013). AHP relies on expert opinion for pairwise matrix thus introducing a degree of subjectivity which can be passed on to weight assignment. It has limitations of handling uncertainty and imprecision present in multi criteria evaluation (Deng 1999; Elsheikh et al. 2013; Malczewski 1999; Munda 1999; Chen et al. 2011). These limitations could be overcome by FAHP as integrating AHP with fuzzy logic methods provides flexibility in the assessment of results. FAHP uses a range of values instead of a crisp value to assess criteria and thus provides a framework having advantages of fuzzy membership functions (FMFs) thereby improving the accuracy of the results (Feizizadeh et al. 2014).

FAHP possesses advantages of conventional AHPs particularly handling multiple criteria and combination of data (both quantitative and qualitative). Like AHP, it helps in pairwise comparison, reduces ambiguity and uses uncertainty to generate decisions. Thus, FAHP can be utilized as an efficient tool for making complex decisions in agricultural management. Many researchers have utilized GIS-MCDA integrated Fuzzy logic for agricultural land suitability analysis. We used integrated approach of GIS and FAHP to evaluate land suitability for sugarcane cultivation. The study examines sugarcane suitability with expert knowledge thereby serving as an important guideline to suggest an optimum sugarcane production and also support the farmers in complex agricultural decision-making process. The methodology adopted in this study is an attempt to overcome the non-spatial assessment and problem of determining criteria weights using pair-wise comparison matrix.

Study area

Bijnor is one of the agriculturally prosperous districts of Uttar Pradesh state in India. The district has five administrative sub-districts and community development blocks (Fig. 1). River *Ganga* separates Bijnor from neighbouring districts and is the main river of the district. The total population of the district is 3.6 million with a population density of 808 inhabitants/km^2.

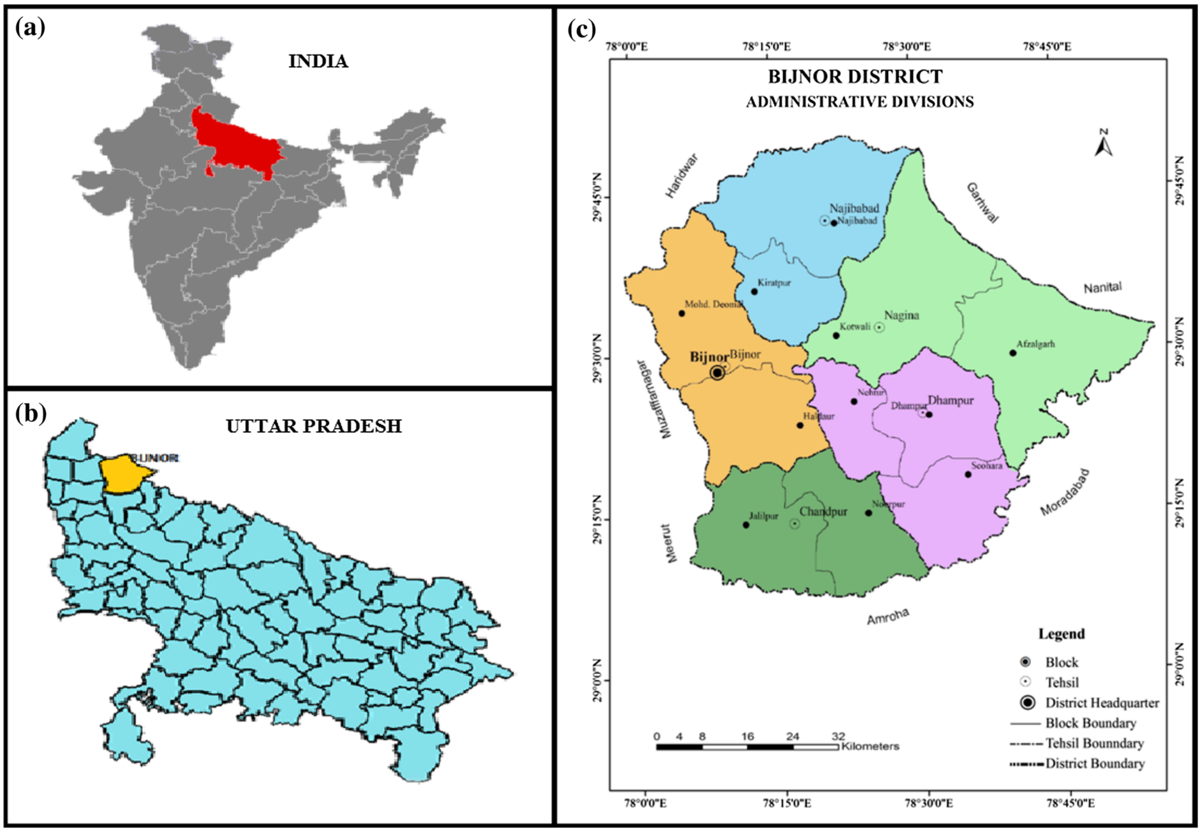

Fig. 1 Map of study area **a** Uttar Pradesh in India, **b** Bijnor in Uttar Pradesh, **c** Administrative divisions of Bijnor

Nearly 76% population of the district lives in villages. There has been 17.6% growth in population during 2001–2011 (Census of India 2011). Agriculture accounts for the highest share in the economy of the study area. Sugarcane, wheat and rice are the major crops grown in the district. The total geographical area accounts for 4,51,058 hectares. Out of this, net sown area is 3,95,952 hectares. Area sown more than once occupies 1,30,252 hectares (Land record office and Economics and Statistical Department 2015).

The average annual temperature ranges between 24 and 27 °C. This part of the state receives moderate rainfall ranging between 90 and 140 cm (Indian Meteorological Department 2013). Typic haplustepts, udic haplustepots and typic ustipsamments are the major soils found in the district. These soils are naturally fertile as grass and foliage deposition enriches the humus content of the soil. Sugarcane guarantees higher net return as compared to other crops as it can withstand erratic weather conditions and sustain no or less damage by the wild animals. There are ten sugar mills in Bijnor among these are two of India's leading sugar mills namely Dhampur and Bundki sugar mills. Thus, there is a constant demand for raw material which facilitates the farmers to grow sugarcane extensively. More than 80% of the total agricultural area of the district is under irrigation. Tube wells and canals are most common sources of irrigation used for agricultural purposes. Most of the land holdings in the district (65.5%) are marginal, followed by small (19.4%), semi-medium (11.2%), medium (3.7%) and large (0.2%). Classification of main workers shows that 21% are cultivators, 29% are agricultural laborers, 5% are household industry workers, and 45% are other workers (Census of India 2011).

Methods

Climate, soil and satellite data was collected and respective criteria maps were generated using Arc GIS and ERDAS. These criteria maps were then reclassified on the basis modified FAO land suitability classification. FAHP was used to compute weights of each criteria. The final suitability map was obtained by weighted overlay analysis. The flow diagram of methodology is given in Fig. 2.

Selection of criteria

Scholars have used different criteria for evaluating agricultural suitability at various scales. Olaniyi et al. (2015) identified soil physical units, bio-physical, social and economic variables for assessing agricultural suitability. Zhang et al. (2015) used climatic condition, soil nutrients and topography as criteria to access tobacco suitability. Mendas and Delali (2012) utilized agronomic and socio-economic factors for assessing wheat suitability. Kumar et al. (2010) included soil characteristics, topography and erosion hazard as criteria to analyse crop suitability. Abdel Kawy and Abou El-Magd (2013) accessed agricultural suitability on the basis of soil's physical and chemical characteristics and wind erosion. Bojorquez-Tapia et al. (2001) used soil type, distance to major road, flooding as key criteria for land suitability. Yalew et al. (2016) used properties of soil, slope and elevation, proximity of water, roads and towns to the farm land as important criteria for assessing agricultural land use suitability. On the basis of literature review, ten site specific parameters, such as rainfall, texture, drainage, soil depth, slope, distance to major road, distance to nearest sugar mill, erosion hazard, risk of flooding and pH values were identified to determine sugarcane suitability in the district.

Generation of criteria maps

Thematic maps were prepared for all the respective criteria and rasterised in GIS environment. Slope layer was prepared using Cartosat-1 digital elevation model (DEM) data of 2.5 m spatial resolution available on Bhuvan (India Geo-Platform of Indian Space Research Organization, ISRO). Agricultural land suitability largely depends upon the soil characteristics (Rasheed and Venugopal 2009; Bhandari et al. 2014; Juhos et al. 2016; Dominati et al. 2016). Soil characteristics such as soil depth, soil texture and pH were taken as evaluation criteria for sugarcane suitability. The maps of these soil characteristics were generated using soil testing lab data (Ministry of Agriculture and Farmers Welfare 2015). Spatial proximities to nearest sugar mills and roads are important factors controlling cost efficiency thereby effecting the decision making of a farmer. Spatial proximity to major roads, nearest sugar mill and the drainage density maps were generated in ArcMap environment using Survey of India (SOI) toposheet of the scale 1:50,000. Rainfall criteria map was obtained by digitizing IMD rainfall map (IMD 2013). Erosion hazard and risk of flooding criteria maps were generated by digitizing maps of National Bureau of Soil Survey and Land Use Planning (NBSS and Department of Agriculture 2004).

Standardization of criteria layers

Standardization of criteria layers is prerequisite for executing weighted overlay analysis for land suitability analysis therefore, we converted the criteria vector layers to raster format in GIS environment. The standardization criteria used for sugarcane suitability is presented in Table 1. We followed the FAO land suitability guidelines in which land has been classified into five categories such as highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently unsuitable (N1) and permanently unsuitable (N2). Highly suitable land has no significant limitation for a specific kind of land use, or only minor limitations that will not have a significant impact on productivity and will not require inputs above an acceptable level. Moderately suitable land has moderately severe limitations for a given land use. The limitations if not corrected will reduce the productivity. These lands require inputs to the extent that the overall benefits will still be attractive but less than highly suitable class. Marginally suitable land has severe limitations for a given land use and will reduce productivity and benefits. The expenditure on the inputs required will be marginally justified. Currently unsuitable land has severe limitations which may be corrected in time but not with the present knowledge at current acceptable costs. Permanently unsuitable land has unmanageable limitations where the expenditure on inputs will be higher than the benefits, so there is no possibility of sustained use of land. We made a slight modification in currently unsuitable and permanently unsuitable classes. These two classes were customized to form one class as 'unsuitable'. We excluded built up area, water bodies and those areas which cannot be

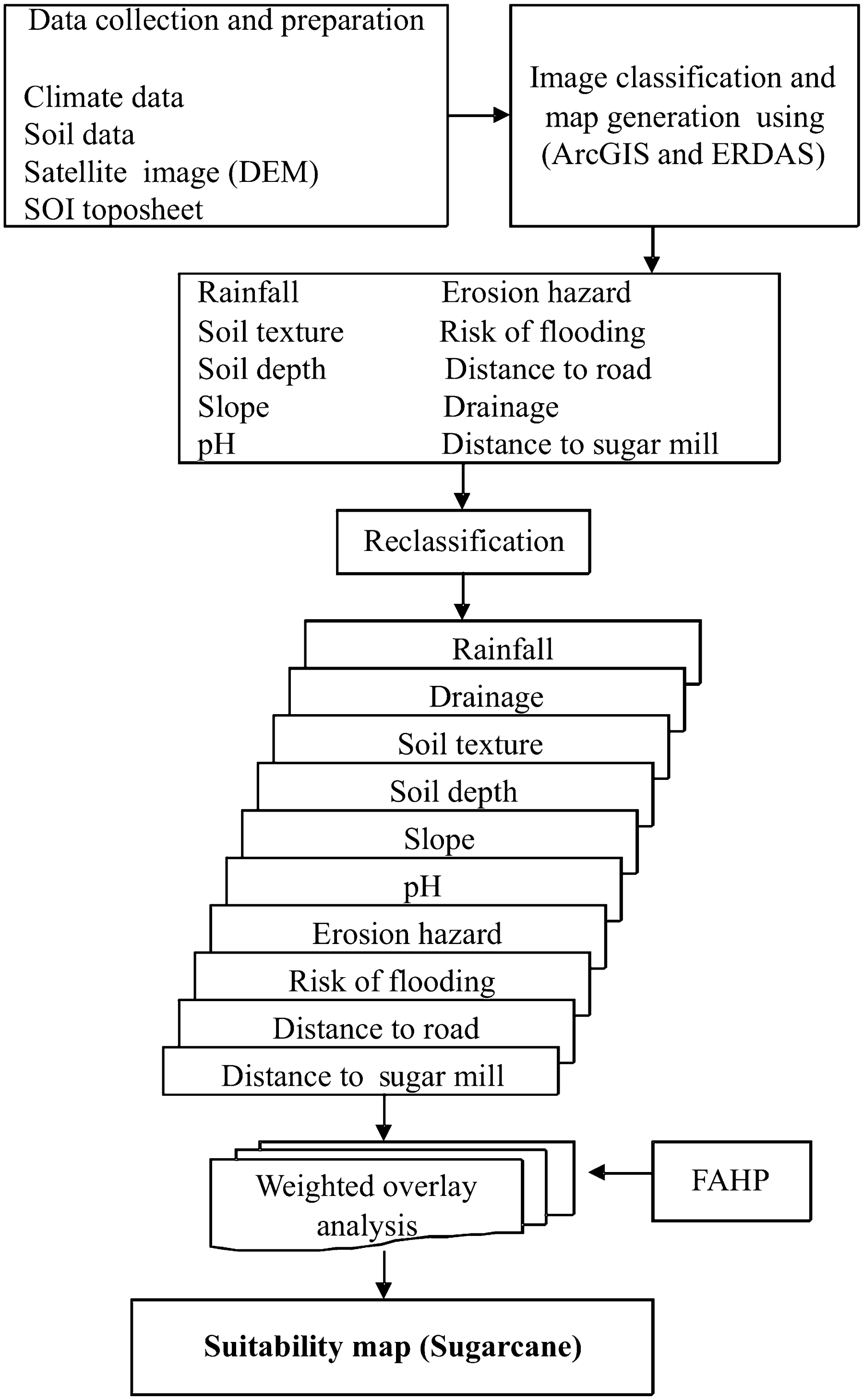

Fig. 2 Flowchart of the methodology of integrated GIS–MCE for suitability analysis of sugarcane

Table 1 Standardization criteria used for sugarcane suitability

Factors	S1	S2	S3	N
Rainfall	120–140	100–120	90–100	<90/> 140
Soil drainage	Well drained	Moderately drained	Imperfect	Poor/excessive
Soil texture	Clay, clay loam	Sandy/loam	Sandy clay loam	Too sandy
Soil depth	Deep	Moderately deep	Shallow	Very shallow
pH	Slightly acidic	Neutral/alkaline	Moderately alkaline	Too alkaline/acidic
Slope	Level to gentle	Undulating	Moderate	Steep
Erosion hazard	None	Slight	Moderate	Severe
Risk of flooding	None	Low	Moderate	High
Distance to road (km)	0–4	4–8	8–16	>16
Distance to sugar mill (km)	0–5	5–10	10–20	>25

Table 2 Modified land suitability classification *Source* FAO

Symbol	Suitability	Description
S1	High	Land with no significant limitation for any specific use
S2	Moderate	Land with moderate limitation which reduce productivity or increase required input
S3	Marginal	Land with severe limitations to specified use
N*	Unsuitable	Severe limitations which cannot be corrected with existing knowledge within acceptable cost limits

* Includes the currently unsuitable and permanently unsuitable land of FAO land suitability classification

reclaimed by removing constraints from suitability as these areas may not available for sugarcane cultivation. In this manner we used four categories of highly suitable, moderately suitable, marginally suitable and unsuitable land (Table 2). These categories were then assigned suitability score ranging from 4 to 1 respectively (4 = highly suitable (S_1); 3 = moderately suitable (S_2); 2 = marginally suitable (S_3); and 1 = unsuitable (N).

Weight derivation for criteria layers

Fuzzy AHP (FAHP) method transforms crisp judgments into fuzzy judgments which enable the decision maker to remove any kind of ambiguity present in the criteria parameters (Mikhailov and Tsvetinov 2004). The criteria selected for accessing land suitability were assigned triangular fuzzy numbers (TFN) based on their influence on each other (Fuller 1991; Yen et al. 1999). The TFN were categorized as very strongly importance (VSI-2,5/2,3), second highest value was rated as strongly importance (SI-3/2,2,5/2), and the least value was rated as weakly importance (WI-1,3/2,2), and both parameters meet an same influence was rated as just equal (JE-1,1,1). The TFN's were then used for pair-wise comparison matrix in FAHP to generate the criterion weight (Table 3). Values of each criteria through extent analysis, gi; can be represented as:

$$M_{gi}^{1}, M_{gi}^{2}, M_{gi}^{3}, M_{gi}^{4}, \ldots, M_{gi}^{n}$$

where gi represents goal set for each criteria (i = 1, 2, 3, 4,…n) and all value of M_{gi}^{j} are triangular fuzzy number (j = 1, 2, 3, 4,…,m). The step wise description of FAHP as given by Chang (1996) is given below:Fuzzy synthetic extent value (S_1) is derived and expressed as:

$$S_1 = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \quad (1)$$

It involves calculation of

Table 3 Pair-wise matrix of sugarcane suitability parameters

	Rainfall	Drainage	Soil texture	Soil depth	pH	Slope	Erosion Hazard	Risk of Flooding	Distance to road	Distance to mill	Wc
Rainfall	(1,1,1)	(2,2.5,3)	(1,1.5,2)	(1,1.5,2)	(1,1.5,2)	(1,1.5,2)	(2,2.5,3)	(2,2.5,3)	(1,1.5,2)	(1,1.5,2)	0.17
Drainage	(0.33,0.4,0.5)	(1,1,1)	(1,1.5,2)	(1,1.5,2)	(1,1.5,2)	(0.5,0.66,1)	(2,2.5,3)	(1.5,2,2.5)	(1,1.5,2)	(1,1.5,2)	0.14
Soil texture	(0.5,0.66,1)	(0.5,0.66,1)	(1,1,1)	(0.4,0.5,0.66)	(1,1.5,2)	(0.4,0.5,0.66)	(1,1.5,2)	(1.5,2,2.5)	(1,1.5,2)	(1,1.5,2)	0.11
Soil depth	(0.5,0.66,1)	(0.5,0.66,1)	(1.5,2,2.5)	(1,1,1)	(1,1.5,2)	(0.33, 0.4,0.5)	(0.33, 0.4,0.5)	(1,1.5,2)	(1,1.5,2)	(1,1.5,2)	0.10
pH	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(1,1,1)	(0.5,0.66,1)	(1,1.5,2)	(1,1.5,2)	(1,1.5,2)	(1,1.5,2)	0.9
Slope	(0.4,0.5,0.66)	(1,1.5,2)	(1.5,2,2.5)	(2,2.5,3)	(1,1.5,2)	(1,1,1)	(0.33,0 .4,0.5)	(2,2.5,3)	(1,1.5,2)	(1,1.5,2)	0.15
Erosion hazard	(0.33,0.4,0.5)	(0.33,0.4,0.5)	(0.5,0.66,1)	(2,2.5,3)	(0.5,0.66,1)	(2,2.5,3)	(1,1,1)	(1,1.5,2)	(1,1.5,2)	(1,1.5,2)	0.12
Risk of flooding	(0.33,0.4,0.5)	(0.4,0.5,0.66)	(0.4,0.5,0.66)	(0.5,0.66,1)	(0.5,0.66,1)	(0.33, 0.4,0.5)	(0.5,0.66,1)	(1,1,1)	(1.5,2,2.5)	(1,1.5,2)	0.05
Distance to road	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.4,0.5,0.66)	(1,1,1)	(1,1.5,2)	0.04
Distance to mill	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(0.5,0.66,1)	(1,1,1)	0.03

$$\sum_{j=1}^{m} M_{gi}^{j} \tag{2}$$

M extent value of a particular matrix can be obtained using fuzzy addition operation as expressed in Eq. (3). These obtained values can form a new set for further use i.e. (l, m, u).

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{3}$$

where l lower limit value, m middle limit value and u upper limit value

With the help of these values we obtain (4); this involves calculation of:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{4}$$

Further, fuzzy addition operation for M_{gi}^{j} (j = 1, 2, 3, 4,…,m) is performed.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{5}$$

The inverse vector of Eq. (5) is calculated to obtain Eq. (6) as given below:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} = \left[1 \Big/ \sum_{i=1}^{n} u_i, 1 \Big/ \sum_{i=1}^{n} m_i, 1 \Big/ \sum_{i=1}^{n} l_i \right] \tag{6}$$

Degree of possibility for $M_1 \geq M_2$ can be calculated as given below:

$$V(M_1 \geq M_2) = \sup_{x \geq y} [\min(\mu_{M1}(x), \mu_{M2}(y))] \tag{7}$$

where x and y are the membership function value of each criterion. Since M_1 and M_2 are convex fuzzy numbers we have:

$$V(M_1 \geq M_2) = 1$$

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu m_1(d) \tag{8}$$

where d is the highest intersection point between (μ_{M1}) and (μ_{M2}).

When, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$

The ordination of d is express as below:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \tag{9}$$

The convex fuzzy number and its degree of possibility to be greater than k convex fuzzy umber M_1 (i = 1, 2, 3, 4,…,k) can be expressed by:

$$\begin{aligned} V(M \geq M_1, M_2, \ldots M_k) &= V[(M \geq M_1) and (M \geq M_2) and \ldots and (M \geq M_k)] \\ &= \min V(M \geq M_i), i = 1, 2, 3, \ldots, k \end{aligned} \tag{10}$$

Equation (10) is supported by the following

$$d(A_1) = \min V(S_i \geq S_k)$$

where k = 1, 2, 3,…,n; k ≠ i.

The weight vectors are expressed as:

$$W_1 = [d(A_1), d(A_2), d(A_3), \ldots, d(A_n)]^{\mathrm{T}} \tag{11}$$

where $A_i (i = 1, 2, 3, \ldots, n)$

Process of normalization for weight vectors is express by following equation

$$W = [d(A_1), d(A_2), d(A_3), \ldots, d(A_n)]^{\mathrm{T}} \tag{12}$$

Weighted overlay analysis (WOA)

Land suitability analysis in a GIS environment is a function of several criteria layers. Weighted overlay analysis was performed after standardization and calculation of weightage for each criteria using FAHP. This method integrates reclassified input layers and dissimilar weighted layers where each individual sub-criteria layer is multiplied by a weight assigned for each criteria and finally are added together to generate the final suitability map. (Eq. 13)

$$S = \sum_{i=1}^{n} W_i X_i \tag{13}$$

where S is the suitability index for each pixel in the map, Wi is the weight of i-th criteria layer, Xi is sub criteria score of criteria layer i, n is the total number of suitability criteria layer (Prakash 2003; Elaalem et al. 2010; Pramanik 2016).

In the present study, sugarcane suitability was assessed by integrating all the thematic layers in ArcGIS 10.2 platform. The aggregate weights of each pixel of the final integrated layer were derived from the following equation:

$$S = R_f R_c + ST_f ST_c + SD_f SD_c + SH_f SH_c + SL_f SL_c + DR_f DR_c + DM_f DM_c + EH_f EH_c + RF_f RF_c + SR_f SR_c \quad (14)$$

where R is rainfall, ST is soil texture, SD is soil drainage, SH is soil depth, SL is slope, DR is distance to major road, DM is distance to sugar mill, EH is erosion hazard, RF is risk of flooding and SR is soil reaction (pH). The subscript letter ‘f’ refers to the weight of each criteria (calculated by FAHP), while ‘c’ refers to the weight of each class of the individual criteria. Thus sugarcane suitability index ‘S’ was estimated using Eq. (14).

Results

Soil quality suitability

Three selected soil quality parameters include texture, pH and depth, respective land suitability maps were generated and their area was calculated. Clay loam and loam soils are considered best for sugarcane production. The result revealed that 27.6% of the total area was highly suitable where as only 15.2% was unsuitable for sugarcane cultivation. Moderately and marginally suitable areas constitute 32.4 and 24.8% respectively (Fig. 3a). Sugarcane can tolerate considerable degree of soil acidity and alkalinity. It is cultivated in soils with slight acidic and alkaline reaction. However, soil pH ranging from 6.5 to 8.5 is considered best for sugarcane cultivation. Most of the area under sugarcane cultivation (79%) showed pH within range and was found highly suitable, 16.4% was moderately suitable and 4.6% area was marginally suitable (Fig. 3b). It should be noted that in terms of soil pH, no area was found to be unsuitable for sugarcane cultivation. The northern and eastern part of the study area is characterised with gentle to steep slope (Fig. 3c), hence these areas have shallow soil depth. Well drained deep soils are required for sugarcane cultivation. The results revealed that 34.2% of area was highly suitable as the soils in these areas were very deep. Deep soils accounted for 29.4% of the total area hence were moderately suitable. About 29% of the total area had shallow soil depth and indicated marginally suitable for sugarcane production (Fig. 3d).

Erosion and floods are limiting factors which greatly affect crop cultivation. River margins and the upper reaches of the district are vulnerable to erosion. The results show that 59.2% of the total area was devoid of erosion hence it was highly suitable. Areas along river *Ganga* and *Ram Ganga* were most affected by erosion and therefore were classified as unsuitable for sugarcane cultivation. These areas accounted for 3.2% of the total area. Moderately suitable and marginally suitable areas constitute 19.4 and 18.2% respectively (Fig. 4a). Floods during monsoon season are common in areas close to river *Ganga*. About 6.7% of the total area was susceptible to floods and classified as unsuitable for sugarcane cultivation. Highly suitable and moderately suitable areas accounted for 47.6 and 34.4% respectively (Fig. 4c).

Proximity to major roads and sugar mill

Road network play an important role in transporting sugarcane as raw material for sugar industry. Nearly 30% area had fairly good road network whereas only 7.6% was not connected to major roads. Moderate and marginal suitable areas were found to have 36.5 and 26.2% respectively (Fig. 4d). Number and location of sugar mills encourage the farmers to grow sugarcane extensively. The results revealed that 38.8% of total area was highly suitable, 56.5% area was moderately suitable whereas only 4.7% area was marginally suitable. No area was found to be unsuitable in terms of proximity to sugar mills (Fig. 4e).

Rainfall and drainage suitability

Indian agriculture has often been called as rainfed agriculture. Here rainfall is one of the important factors for sugarcane cultivation. The district was divided into four categories (<100, 90–120, 120–140 and >140 cm) based on rainfall. Out of total area 23.6% area was highly suitable for sugarcane cultivation. Marginally suitable and moderately suitable area constituted 38.1 and 26.8% respectively (Fig. 4b). No area was found to be unsuitable. Drainage ensures proper soil aeration and reduces soil and nutrient loss through runoff in form of erosion. In terms of drainage, 56% of the total area was highly suitable and 24% of total area was moderately suitable for sugarcane production. Marginally suitable area constituted 12% of the total area, where as only 8% area was found

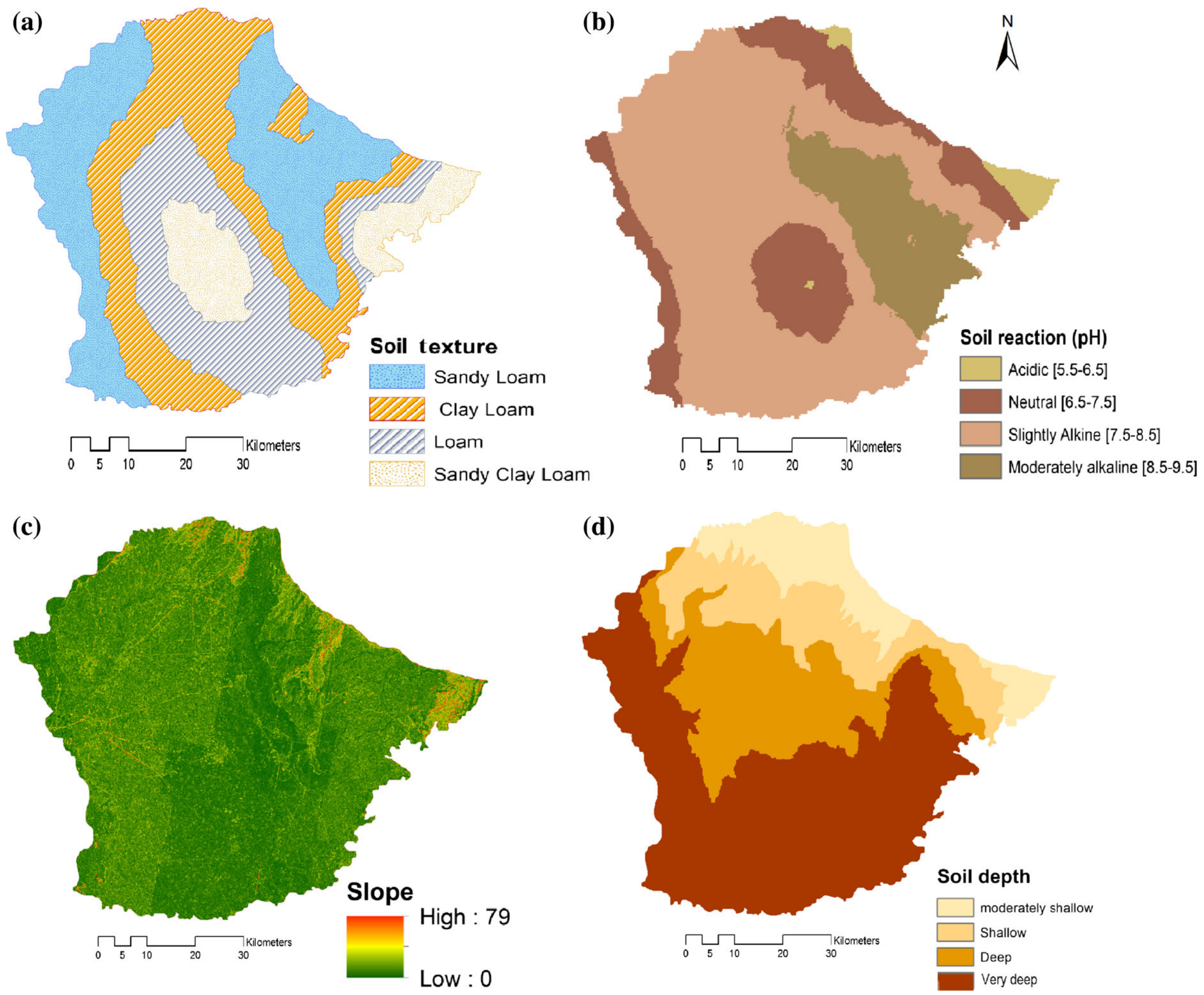

Fig. 3 Criterion layers **a** soil texture, **b** soil reaction, **c** slope, **d** soil depth

to be excessively drained thus considered unsuitable for sugarcane production (Fig. 4f).

Overall suitability

A combined suitability map was generated by integrating the criteria layers with their respective weights through weighted overlay method (Table 4; Fig. 5). Analysis of the map revealed that 60.8% (2,40,571 hectares) of the study area was highly suitable, 23.7% (93,981 hectares) was moderately suitable, and 7.2% (28,468 hectares) was marginally suitable. About 8% (32,930 hectares) is determined to be unsuitable for sugarcane cultivation.

Sub-district wise area of sugarcane suitability in Bijnor district is presented in Table 5. A close perusal of the table shows variation in land suitability categories among the sub-districts. Chandpur has the largest area (75%) under high suitable category followed by Dhampur (74%, Bijnor (66%), Najibabad (56%) and Nagina (42%). High suitable area in all these sub-districts can be attributed to favorable soil qualities (texture, pH and depth). The limiting factors such as floods and erosion have no effect in these areas. These areas have good road connectivity and are located in vicinity of sugar mills. Largest area under moderate suitability of sugarcane was found in Najibabad (30%) followed by Nagina (26%), Dhampur (22%), Bijnor (21%) and Chandpur (17%). Najibabad accounts for the largest area (12%) under marginally suitable category followed by Bijnor (10%), Nagina (9%), Chandpur (2%) and Dhampur (1%).

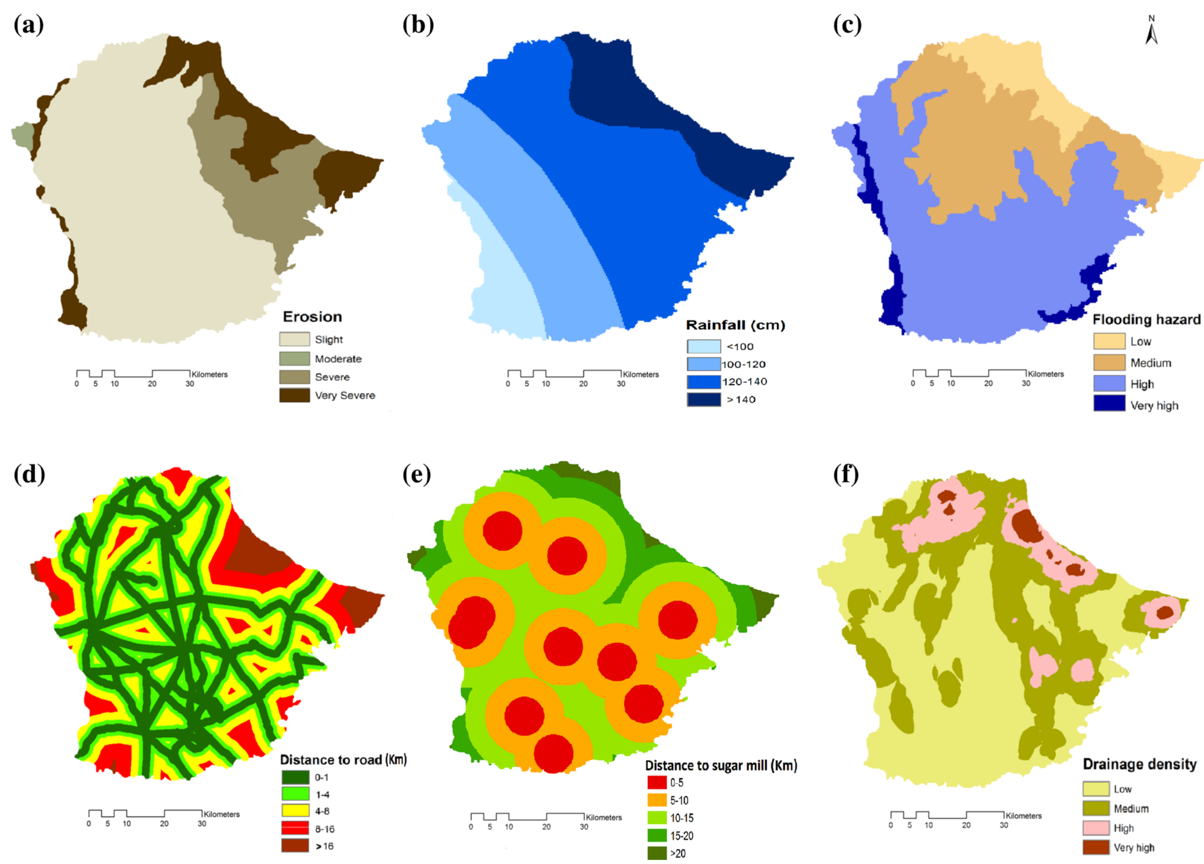

Fig. 4 Criterion layers **a** erosion, **b** rainfall, **c** flooding hazard, **d** distance to road, **e** distance to sugar mill, **f** drainage density

Nagina has the largest area (22%) while Najibabad (1%) and Dhampur (1%) sub-districts have smallest area under unsuitable category. Nagina sub-district is characterised by steep slope, soil erosion, shallow soil depth and acidic soil reaction. The combined effect of steep slopes and higher susceptibility of erosion resulted in land degradation thus making land unsuitable for sugarcane cultivation. Chandpur (6%) and Bijnor (3%) have unsuitable area along the river *Ganga*. These areas were found to be prone to flooding.

Discussion

Sugarcane suitability analysis is incumbent as sugarcane has a direct impact on the livelihood of the people of the study area. Sugarcane suitability was assessed by weighted overlay techniques based on MCDM using GIS methods. Out of the total area of the district (4,51,058 hectares), 88% (3,95,951 hectares) is available for agricultural land use and remaining 12% (55,107 hectare) is comprised of built-up, water bodies and unreclaimed area. The area which cannot be reclaimed by removing constraints was considered as unavailable. Thus, such area was excluded from the suitability analysis. A comparison between land under sugarcane for the year 2016 (Land record office and Economics and Statistical Department 2016) and land suitable for sugarcane cultivation is shown in Table 6. It is evident from the results that the land is not fully utilized to its potential. About 61% area is highly suitable for sugarcane cultivation where as only 51% area is being utilized for growing sugarcane in the district.

Sub district wise, there is great potential to increase the land under sugarcane cultivation. In Bijnor sub district 55% area was under sugarcane cultivation as compared to 66% suitable area for sugarcane cultivation, thus sugarcane cultivation here could be

Table 4 Sugarcane suitability in Bijnor district

Suitability	Area (hectares)	Percentage to total area
Highly suitable	240,571.1	53.33
Moderately suitable	93,981	20.84
Marginally suitable	28,468.6	6.31
Unsuitable	32,930.6	7.30
Unavailable*	55,106.7	12.22
Total	451,058	100

* This includes built-up area and water bodies

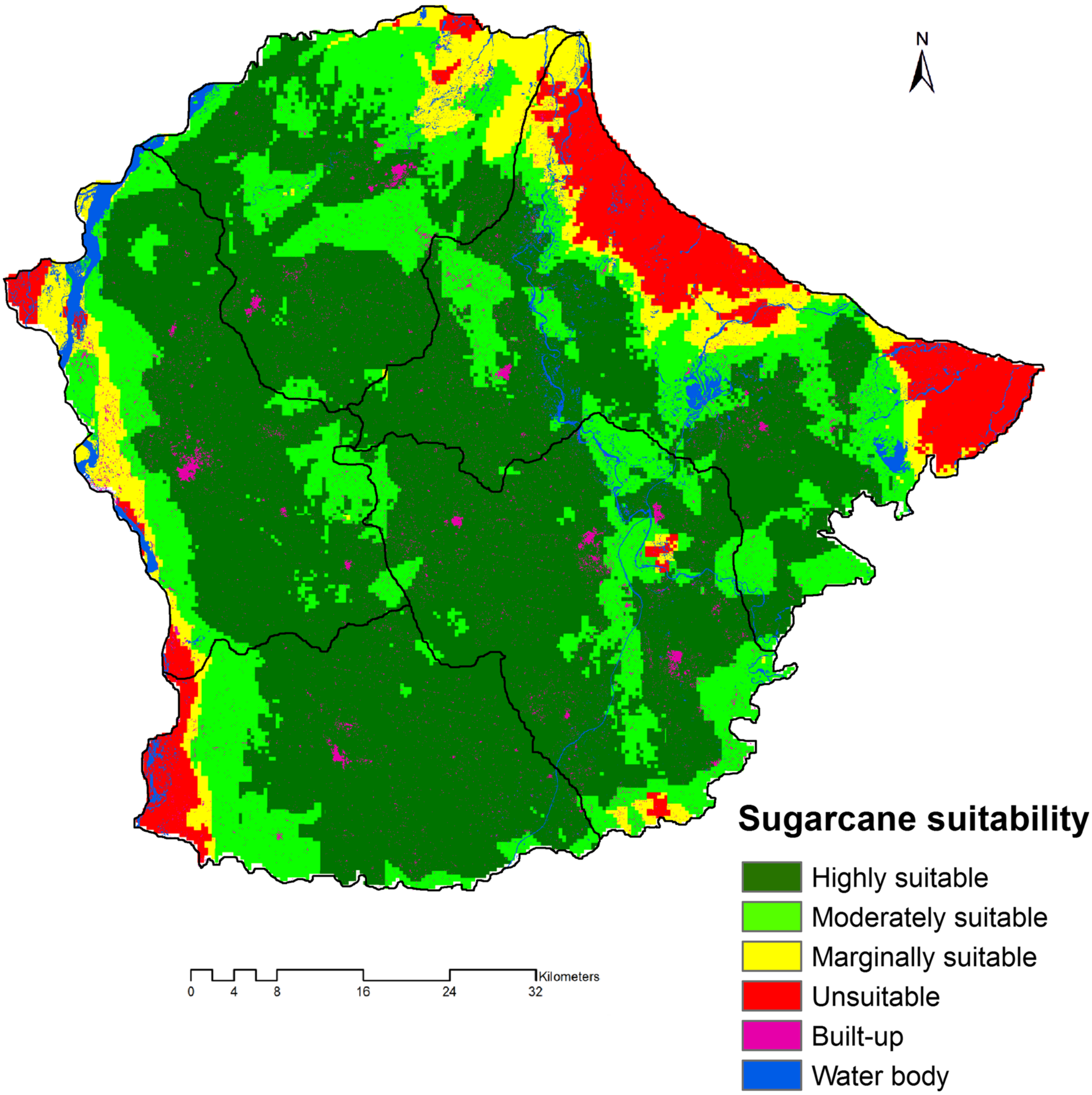

Fig. 5 Map showing sugarcane suitability in the Bijnor district

Table 5 Sub-district wise area of sugarcane suitability in Bijnor district

Sub district	Highly suitable	%	Moderately suitable	%	Marginally suitable	%	Unsuitable	%	Total Area
Bijnor	48,123.9 (66)	20.0	15,392.2 (21.1)	16.4	7406.3 (10.1)	26.0	20.22.2 (2.8)	6.1	72,944.58
Chandpur	45,852.6 (74.8)	19.1	10,286.4 (16.8)	10.9	1143.8 (1.9)	4.0	3974.2 (6.5)	12.1	61,257
Dhampur	58,886.5 (74.7)	24.5	17,860.4 (22.7)	19.0	1048.5 (1.3)	3.7	1022.1 (1.3)	3.1	78,817.49
Nagina	48,453.8 (42.7)	20.1	29,514.9 (26)	31.4	10,615.6 (9.3)	37.3	24,965.6 (22)	75.8	113,549.9
Najibabad	39,254.3 (56.5)	16.3	20,927.1 (30.2)	22.3	8254.4 (11.9)	29.0	946.6 (1.4)	2.9	69,382.4
Bijnor district	240,571.1 (60.8)	100	96,981 (23.7)	100	32,376.8 (7.2)	100	32,930.7 (8.3)	100	395,951.37

Figures in brackets show the percentages to the total area

Table 6 Comparison between area under sugarcane cultivation in 2016 and area highly suitable for sugarcane cultivation *Source* Land Record office and Economics and Statistics Department (2016)*

Sub district	Area under sugarcane (2016)*	Area highly suitable for sugarcane cultivation	Potential
Bijnor	40,071 (54.9)	48,123.9 (66)	8052.9 (11)
Chandpur	43,185 (70.49)	45,852.6 (74.8)	2667.6 (4.4)
Dhampur	42,567 (54)	58,886.5 (74.7)	16,319.5 (21)
Nagina	44,684 (39.3)	48,453.8 (42.7)	3769.8 (3.3)
Najibabad	31,563 (45.49)	39,254.3 (56.5)	7691.0 (11)
Bijnor district	202,070 (51.03)	240,571.1 (60.8)	38,501.1 (9.7)

Figures in brackets show the percentages to the total area

expanded to another 8052 hectares. Similarly Najibabad had an area of about 45% under sugarcane cultivation as compared to 56% of suitable area indicating a possible increase of 7691 hectares for sugarcane cultivation. Chandpur and Nagina have utilized most of the suitable area as they have only 4 and 3% respective area which possibly could be utilized for sugarcane cultivation. Dhampur has a greater potential to develop about 16,319 hectares of land for sugarcane cultivation. Only 54% area is devoted to sugarcane cultivation as compared to 74% suitable area.

The soil qualities ascertained that the soils of the district are highly conductive for sugarcane cultivation. However, some areas were found to have alkaline soil reaction Organic matter and acidifying fertilizers such as ammonium sulfate should be applied and Millet crops having short growing period and higher productivity should be favoured to grow in such areas. The peripheral areas in these sub-districts are located at a greater distance from major roads and sugar mills. The transportation cost thus incurred will eventually minimize the farmers' profit therefore land in these sub-districts should be utilized to grow pulses having higher net returns. Preventive steps such as applying mulch to the top soil and geotextiling should be adopted in areas experiencing soil erosion. The area along side river *Ganga* and *Ram Ganga* were affected by flooding thus were found unsuitable for sugarcane cultivation. These areas should be utilized to grow flood tolerant rice.

Conclusion

We evaluated land suitability for sugarcane cultivation in Bijnor district, India using FAO framework, GIS and multi-criteria evaluation approach. This study demonstrated that integrated approach of FAHP and GIS can be effectively used for deriving the weights of multiple factors and land suitability analysis. The sugarcane suitability map showed the inherent capability of the land to support sugarcane cultivation. Most of the cultivable land of the study area (61%) was highly suitable followed by moderately suitable (24%), marginally suitable (7%) and unsuitable (8%) for sugarcane suitability. There was a marked variation in moderate and marginal suitable categories among sub-districts. Nagina and Najibabad sub-districts had more area under these two categories while Bijnor sub-district also require attention as it has 27.2% of the total marginally suitable area under sugarcane. The main limiting factors for sugarcane cultivation in these sub-districts are slope, shallow soil depth, alkaline soil reaction and erosion hazard. Hence action plan for increasing land efficiency in these sub-districts be adopted. Application of organic matter, pH specific fertilizers, and provision of improved road network and better irrigation facilities may remove the limitations and increase the suitability. Trees should be planted on slopes and along the river to reduce erosion. The findings of the study can help in improving land use efficiency and better management of sugarcane cultivation in the district. The integrated approach of GIS and MCDA could also be applied to assess the potential of land for other crops.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights No human and/or animal participation was involved in the study.

References

Abdel Kawy, W. A. M., & Abou El-Magd, I. H. (2013). Use of satellite data and GIS for assessing the agricultural potentiality of the soils South Farafra Oasis, Western Desert, Egypt. *Arabian Journal of Geosciences, 6*(7), 2299–2311.

Ahamed, N., Rao, G. T. R., & Murthy, J. S. R. (2000). GIS-based fuzzy membership model for crop-land suitability analysis. *Agricultural Systems, 63*(2), 75–95.

Akinci, H., Özalp, A. Y., & Turgut, B. (2013). Agricultural land use suitability analysis using GIS and AHP technique. *Computers and Electronics in Agriculture, 97,* 71–82.

Bhandari, S., Jhadav, S. T., & Kumar, S. (2014). Land capability classification and crop suitability assessment in a watershed using RS and GIS—a case study of watershed in Dehradun, Uttarakhand. *SSARSC International Journal of Geoscience and Geoinformatics, 1*(1), 1–15.

Bhuvan, Indian Geo-platform of Indian Space Research Organization (ISRO). http://bhuvan.nrsc.gov.in/. Assessed 21 Aug 2016.

Bojorquez-Tapia, L. A., Diaz-Mondragon, S., & Ezcurra, E. (2001). GIS-based approach for participatory decision making and land suitability assessment. *International Journal of Geographical Information Science, 15*(2), 129–151.

Bozdağ, A., Yavuz, F., & Günay, A. S. (2016). AHP and GIS based land suitability analysis for Cihanbeyli (Turkey) Country. *Environmental Earth Sciences, 75,* 813. doi:10.1007/s12665-016-5558-9.

Burrough, P. A. (1989). Fuzzy mathematical methods for soil survey and land evaluation. *Journal of Soil Science, 40*(3), 477–492.

Cengiz, T., & Akbulak, C. (2009). Application of analytical hierarchy process and geographic information systems in land-use suitability evaluation: A case study of Dümrek village, Çanakkale, Turkey. *International Journal of Sustainable Development and World Ecology, 16*(4), 286–294.

Census of India. (2011). District census handbook, Bijnor: Village and town directory. *Directorate of Census Operations, Uttar Pradesh,* 10(12b). http://www.censusindia.gov.in/2011census/dchb/0903_PART_B_DCHB_BIJNOR.pdf. Accessed 15 November 2016.

Chang, D. Y. (1996). Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research, 95*(3), 649–655.

Chen, H. (2013). Evaluation of soil fertility suitability of tobacco planting fields on slant plain in the east side of Funiushan mountainin at central China supported by GIS. *Journal of Food, Agriculture and Environment, 2*(2), 1459–1463.

Chen, V. Y. C., Pang Lien, H., Liu, C. H., Liou, J. J. H., Hshiung Tzeng, G., & Yang, L. S. (2011). Fuzzy MCDM approach for selecting the best environment-watershed plan. *Applied Soft Computing, 11,* 265–275.

Collins, M. G., Steiner, F. R., & Rushman, M. J. (2001). Land-use suitability analysis in the United States: Historical development and promising technological achievements. *Environmental Management, 28*(5), 611–621.

Deng, H. (1999). Multicriteria analysis with fuzzy pairwise comparisons. *International Journal of Approximate Reasoning, 21*(3), 215–231.

Directorate of Economics & Statistics. (2015). Agricultural statistics at a glance. Ministry of Agriculture and Farmers Welfare, Department of Agriculture, Government of India. http://eands.dacnet.nic.in/Agricultural_Statistics_At_Glance-2015%20E-book/book.swf.

Dominati, E., Mackay, A., Bouma, J., & Green, S. (2016). An ecosystems approach to quantify soil performance for multiple outcomes: The future of land evaluation? *Soil Science Society of America Journal, 80*(2), 438–449.

Eastman, J. R. (1999). Multi-criteria evaluation and GIS. In P. A. Longley, M. F. Goodchild, D. J. Maguire, & D. W. Rhind (Eds.), *Geographical information systems* (pp. 493–502). New York: Wiley.

Elaalem, M. (2012). Land suitability evaluation for sorghum based on boolean and fuzzy-multi-criteria decision analysis methods. *International Journal of Environmental Science and Development, 3*(4), 357–361.

Elaalem, M., Comber, A., & Fisher, P. (2010). Land evaluation techniques comparing fuzzy AHP with TOPSIS methods. In *13th AGILE International Conference on Geographic Information Science, Guimares, Portugal* (pp. 1–8).

Elsheikh, R., Rashid, A., Shariff, M., Amiri, F., Ahmad, N. B., Balasundram, K. S., et al. (2013). Agriculture land suitability evaluator (ALSE): A decision and planning support tool for tropical and subtropical crops. *Computers and Electronics in Agriculture, 93,* 98–110.

FAO. (1976). *A Framework for Land Evaluation, Soils Bulletin 32*. Rome: FAO and Agriculture Organization of the United Nations.

FAO. (1983). *Guidelines: Land Evaluation for Rain fed Agriculture. FAO Soils Bulletin 52*. Rome: FAO.

Feizizadeh, B., & Blaschke, T. (2012). Land suitability analysis for Tabriz County, Iran: A multi-criteria evaluation approach using GIS. *Journal of Environmental Planning and Management, 56,* 1–23.

Feizizadeh, B., Blaschke, T., & Shadman Roodposhti, M. (2013). Integration of GIS based fuzzy set theory and multicriteria evaluation methods for landslide susceptibility mapping. *International Journal of Geoinformatics, 9*(3), 49–57.

Feizizadeh, B., & Kienberger, S. (2017). Spatial explicit sensitivity and uncertainty analysis for multicriteria based vulnerability assessment. *Journal of Environmental Planning and Management*. doi:10.1080/09640568.2016.1269643.

Feizizadeh, B., Shadman Roodposhti, M., & Blaschke, T. (2017). Comparing GIS-based support vector machine kernel functions for landslide susceptibility mapping. *Journal of Arabian Geoscience, 10*(5), 122.

Feizizadeh, B., Shadman Roodposhti, M., Jankowski, P., & Blaschke, T. (2014). A GIS-based extended fuzzy multi-criteria evaluation for landslide susceptibility mapping. *Computers & Geosciences, 73,* 208–221.

Fuller, R. (1991). On product-sum of triangular fuzzy numbers. *Fuzzy Sets and Systems, 41*(1), 83–87.

Gheshlagi, A. H., & Feizizadeh, B. (2017). An integrated approach of analytical network process and fuzzy based spatial decision making systems applied to landslide risk mapping. *Journal of African Earth Sciences, 133,* 15–24.

Hall, G. B., Wang, F., & Subaryono, J. (1992). Comparison of Boolean and fuzzy classification methods in land suitability analysis by using geographical information systems. *Environment and Planning A, 24*(4), 497–516.

Indian Meteorological Department. (2013). *Climate profile of India, MET monograph, environment meteorology*. New Delhi: Ministry of Earth Sciences, Government of India.

Jafari, S., & Zaredar, N. (2010). Land suitability analysis using multi attribute decision making approach. *International Journal of Environmental Science and Development, 1*(5), 441–445.

Jamil, M., & Sajjad, H. (2016). Deriving cropping system efficiency pattern using remote sensing and GIS: A case study of Bijnor District, India. *International Journal of Advancement in Remote Sensing, GIS and Geograph, 4*(2), 27–40.

Joerin, F., Theriault, M., & Musy, A. (2001). Using GIS and outranking multicriteria analysis for land-use suitability assessment. *International Journal of Geographical Information Science, 15*(2), 153–174.

Joss, B. N., Hall, R. J., Sidders, D. M., & Keddy, T. J. (2008). Fuzzy-logic modeling of land suitability for hybrid poplar across the Prairie Provinces of Canada. *Environmental Monitoring and Assessment, 141*(1), 79–96.

Juhos, K., Szabo, S., & Ladanyi, M. (2016). Explore the influence of soil quality on crop yield using statistically-derived pedological indicators. *Ecological Indicators, 63,* 366–373.

Kalogirou, S. (2002). Expert systems and GIS: An application of land suitability evaluation. *Computers, Environment and Urban Systems, 26*(2), 89–112.

Karimzadeh, S., Feizizadeh, B., & Matsuoka, M. (2017). From a GIS-based hybrid site condition map to an earthquake damage assessment in Iran: Methods and trends. *International Journal of Disaster Risk Reduction, 22,* 23–36.

Kazemi, H., Sarvestani, Z. T., Kamkar, B., Shataei, S., & Sadeghi, S. (2015). Ecological zoning for wheat production at province scale using geographical information system. *Advances in Plants & Agriculture Research, 2*(1), 1–7.

Kumar, R., Mehra, P. K., Singh, B., Jassal, H. S., & Sharma, B. D. (2010). Geostatistical and visualization analyses of crop suitability for diversification in sub-mountain area of Punjab, North-West India. *Journal of the Indian Society of Remote Sensing, 38*(2), 211–226.

Kuta, A. A., Opaluwa, Y. D., Zitta, N., Ojatah, E., & Ugolo, E. M. (2016). Application of GIS sieve mapping and overlay techniques for building site suitability analysis in part of FUT, Gidan Kwano, Minna, Nigeria. *Indian Journal of Science and Technology, 46*(9), 1–6.

Land Record Office and Economics and Statistical Department. (2015). Block wise land usage in the district. *Spider District Sankhyikiya Patrika*, Government of Uttar Pradesh.

Land Record Office and Economics and Statistical Department. (2016). Blockwise area covered by main crops in the district. *Spider District Sankhyikiya Patrika*, Government of Uttar Pradesh.

Li, B., Zhang, F., Zhang, L. W., Huang, J. F., Jin, Z. F., & Gupta, D. K. (2012). Comprehensive suitability evaluation of tea crops using GIS and a modified land ecological suitability evaluation model. *Pedosphere, 22*(1), 122–130.

Lingjun, L., Zong, H., & Hu, Y. (2008). Study on land use suitability assessment of urban–rural planning based on remote sensing: A case study of Liangping in Chongqing. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 37*(8), 123–130.

Malczewski, J. (1999). *GIS and multicriteria decision analysis*. New York: Wiley.

Malczewski, J. (2000). On the use of weighted linear combination method in GIS: Common and best practice approaches. *Transactions in GIS, 4*(1), 5–22.

Malczewski, J. (2002). Fuzzy screening for land suitability analysis. *Geographical and Environmental Modelling, 6*(1), 27–39.

Malczewski, J. (2006). Ordered weighted averaging with fuzzy quantifiers: GIS-based multicriteria evaluation for land-use suitability analysis. *International Journal of Applied Earth Observation and Geoinformation, 8*(4), 270–277.

McHarg, I. (1969). *Design with nature*. New York: Doubleday.

Mendas, A., & Delali, A. (2012). Integration of multi-criteria decision analysis in GIS to develop land suitability for agriculture: Application to durum wheat cultivation in the region of Mleta in Algeria. *Computers and Electronics in Agriculture, 83,* 117–126.

Mikhailov, L., & Tsvetinov, P. (2004). Evaluation of services using a fuzzy analytic hierarchy process. *Applied Soft Computing, 5,* 23–33.

Ministry of Agriculture and Farmers Welfare. (2015). Soil testing lab data, Bijnor. Department of Agriculture & Cooperation and Farmers Welfare, Government of India.

Munda, G. (1999). *Multi-criteria evaluation in a fuzzy environment: Theory and applications in ecological economics*. Berlin: Physica-Verlag.

NBSS & Department of Agriculture. (2004). Soils of India series: Soils of Uttar Pradesh for optimizing land use, NBSS publication no 68. Government of Uttar Pradesh.

Olaniyi, A., Ajiboye, A., Abdullah, A., Ramli, M., & Sood, A. (2015). Agricultural land use suitability assessment in Malaysia. *Bulgarian Journal of Agricultural science, 21*(3), 560–572.

Prakash, T. N. (2003). Land suitability analysis for agricultural crops: A fuzzy multicriteria decision making approach. MS Thesis, International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands.

Pramanik, M. K. (2016). Site suitability analysis for agricultural land use of Darjeeling district using AHP and GIS techniques. *Model Earth Systems and Environment, 2,* 1–22.

Qiu, F., Chastain, B., Zhou, Y., Zhang, V., & Sridharan, H. (2014). Modeling land suitability/capability using fuzzy evaluation. *GeoJournal, 79*(2), 167–182.

Rasheed, S., & Venugopal, K. (2009). Land suitability assessment for selected crops in Vellore district based on agro-ecological characterisation. *Journal of Indian Society of Remote Sensing, 37*(4), 615–629.

Riad, H. S., Billib, M., Hassan, A. A., Salam, M. A., & El Din, M. N. (2011). Application of the overlay weighted model and Boolean logic to determine the best locations for artificial recharge of groundwater. *Journal of Urban and Environmental Engineering, 5*(2), 57–66.

Saaty, T. L. (1980). *The analytic hierarchy process*. New York: McGraw-Hill.

Sajjad, H., Chauhan, C., & Jamil, M. (2016). Indebtedness and its causal factors among farmers in Sangroor district, Punjab: A Household level analysis. *Transactions of the Institute of Indian Geographers, 38*(1), 101–115.

Sajjad, H., & Nasreen, I. (2016). Assessing farm-level agricultural sustainability using site-specific indicators and sustainable livelihood security index: Evidence from Vaishali district, India. *Community Development, 47*(5), 602–619.

Sajjad, H., Nasreen, I., & Ansari, S. A. (2014). Assessing spatiotemporal variation in agricultural sustainability using sustainable livelihood security index: Empirical illustration from Vaishali district of Bihar, India. *Agroecology and Sustainable Food System, 38*(1), 46–68.

Scat, R. S., Carranza, E. J. M., & Nidumolu, U. B. (2005). Fuzzy modeling of farmers' knowledge for land suitability classification. *Agricultural Systems, 83*(1), 49–75.

Shahram, A. (2010). Land suitability analysis for wheat using multicriteria evaluation and GIS method. *Research Journal of Biological Sciences, 5*(9), 601–605.

Shearer, K. S., & Xiang, W. N. (2009). Representing multiple voices in landscape planning: A land suitability assessment study for a park land-banking program in Concord, North Carolina, USA. *Landscape and Urban Planning, 93*(2), 111–122.

The Economic Survey. Agricultural and Processed Food Products Export Development Authority (APEDA). The Union Budget 2014–15. Press releases. https://www.ibef.org/archives/detail/b3ZlcnZpZXcmMzY0OTYmODY=. Accessed 22 November 2016.

Yalew, S. G., Van Griensven, A., Mul, M. L., & Zaag, P. V. D. (2016). Land suitability analysis for agriculture in the Abbay basin using remote sensing, GIS and AHP techniques. *Modeling Earth Systems and Environment, 2*(101), 1–14.

Yen, K. K., Ghoshray, S., & Roig, G. (1999). A linear regression model using triangular fuzzy number coefficients. *Fuzzy Sets and Systems, 106*(2), 167–177.

Zhang, J., Su, Y., Wu, J., & Liang, H. (2015). GIS based land suitability assessment for tobacco production using AHP and fuzzy set in Shandong province of China. *Computer Electronics in Agriculture, 114,* 202–211.