

# A comparative assessment of land suitability evaluation methods for agricultural land use planning at village level

Duraisamy Vasu\*, Rajeev Srivastava, Nitin G. Patil, Pramod Tiwary, Padikkal Chandran, Surendra Kumar Singh

ICAR – National Bureau of Soil Survey and Land Use Planning, Nagpur, Maharashtra 440033, India

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## ABSTRACT

Defining the relationship between soil characteristics and crop requirements must be the first step in planning future agriculture land use. The aim of the present study is to identify the constraints and potentials of major soils in a block of Telangana, India and evaluate them for crop suitability and propose agricultural land use plans (ALUP) at village level. Using IRS P6 LISS IV, Cartosat-I and DEM data, we identified and mapped six soil series through detailed soil survey. Soils varied in depth (< 25 to > 150 cm), texture, water holding capacity, hydraulic conductivity, pH, organic carbon and other inherent properties. We compared parametric, Storie index and multi-criteria land suitability evaluation (MC-LSE) methods for evaluating land suitability for pigeon pea, maize, cotton, groundnut and rice. The land suitability index (LSI) by the three methods varied for three soil series, but for one series, the methods produced similar results for cotton, maize and pigeon pea. The correlation of LSI with crop yield showed that MC-LSE performed better than other two methods. After analysing the LSE results, existing cropping pattern, potential and adaptability of alternate options through participatory interaction with farmers, ALUP for 19 villages of the study area were developed. Moreover, we also discuss the challenges and opportunities in proposing and implementing ALUP in India. The results of the present study will be helpful for farm managers for making the best use of soils based on their suitability. However, to demonstrate the applicability, practicability, and most importantly, the sustainability of proposed ALUP, coordinated implementation strategies are necessary.

## 1. Introduction

Being integral to all functions of terrestrial ecosystems, soils are intended to produce food for feeding the ever-increasing population of the world (Bouma, 1989; Paustian et al., 2016). “Food and biomass production” is listed first among the seven functions of soils by European Commission in 2006 (Jónsson et al., 2016). However, soils are under prodigious pressure due to competing demands from various sectors of the society in general and diversion of prime arable lands to non – arable uses like urbanisation and industrialisation, in particular (Foley et al., 2011; Erickson et al., 2013). Owing to the exerting pressure, 24% of the total land area is degraded, increasing at an alarming rate of 5–10 million ha per annum (Lal, 2012) and threatens the livelihood of more than 1.5 billion people (Bai et al., 2013; Stavi and Lal, 2015). India supports 17.5% of world’s population with only 2.4% of geographical area and 9% arable lands (Srinivasarao et al., 2015). The largest share of arable land in India has already been put under use and

crop-land expansion is not probable as the untitled lands are mostly not suitable for agriculture. Therefore, agricultural land use planning (ALUP) based on the suitability of soils to support different crops in a particular agro-environment is imperative for making the best use of cultivated soils.

ALUP is defined as “systematic assessment of land and water potential, alternatives for land use and economic and social conditions for the purpose of selecting agricultural land use which is sustainable for farmers, without degrading the environment” (FAO, 1996). With climate change taking centre stage in planning future agricultural land use, defining the relationship between soil characteristics and crop requirements must be the first step towards answering sustainability issues (Bonfante and Bouma, 2015). This has been the motivation for systematic soil surveys, soil survey interpretations and mapping of soils (Bouma, 1989, 1994). The use of soil survey information for ALUP received attention in the recent years (Fontes et al., 2009). For example, De la Rosa et al. (2009) used soil survey data for developing ALUP for

\* Corresponding author at: Division of Soil Resource Studies, ICAR – National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur, Maharashtra 440 033, India.

E-mail address: [d.plantdoctor@gmail.com](mailto:d.plantdoctor@gmail.com) (D. Vasu).

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nine benchmark sites in different agro-ecological regions in Sevilla province, Spain. Rhebergen et al. (2016) used soil texture, depth, drainage and water holding capacity along with climate and land use data for evaluating land suitability for oil palm production in Ghana. Thus, recent studies established the value of soil information in evaluating constraints, potential and suitability of land for cultivation of various crops (Yalew et al., 2016; Bonfante and Bouma, 2015; Akinchi et al., 2013). For quantitative land suitability evaluation (LSE), Bonfante and Bouma (2015) suggested using the soil series data as soils of a given series respond similarly to land use and management practices. Moreover, using soil series can be effective for communicating to the farmers as it carries the location specific name for each soil.

The first step in agricultural land use planning is land-suitability evaluation which is defined as “the process of assessment of land performance when used for alternative kinds of agriculture” (He et al., 2011). Many concepts and methods were developed to evaluate the soils from the early 20<sup>th</sup> century. Among them, land capability classification (LCC) (Klingebiel and Montgomery, 1966), Storie index (SI) (Storie, 1978), FAO land suitability evaluation (FAO, 1976) and Parametric method (Sys et al., 1991) were the most commonly used methods. More recently, LSE methodologies have shifted from broad-based to specific assessment. Elsheikh et al. (2013) developed an automated system (as per FAO framework) that allows land evaluators to build expert systems for land evaluation. GIS based multi-criteria analysis (MCA) method was developed by Nguyen et al. (2015). However, a quantitative procedure, inclusive of all the factors influencing crop production, for evaluating soil series needs to be developed and evaluated. Using a multi-criteria land evaluation method (MC-LSE) proposed by El Baroudy (2016), the present study aims to fill this gap by including most of the inherent properties of soil series in land suitability evaluation for tropical soils of India.

## 2. Materials and methods

### 2.1. Description of the study area

The study area Thimmajipet is located between 16° 35′ 13″ to 16° 44′ 31″ N latitude and 78° 07′ 37″ to 78° 18′ 36″ E longitude in Mahabubnagar district, Telangana, India and covers an area of 215.6 km<sup>2</sup> (Fig. 1). The topography comprises of an undulating terrain and the ground surface slope is towards north-eastern direction with micro-topographical variations and intermittent hillocks. The study

area forms a part of the stable Dharwar Craton of south Indian shield. It consists of exposed rocks of Peninsular Gneissic Complex (PGC) of Archaean to Paleoproterozoic age, Dharwar super group, Cuddapah supergroup, Kurnool and Bhima groups and also alluvium of basaltic Deccan traps (CGWB, 2013). The PGC, which covers most of the area, is composed of granites, gneisses and migmatites with undigested patches of older metamorphic rocks. Rocks of PGC and Dharwar supergroup are intruded by younger granitoids of tonalite – trondhjemite – granodiorite composition. These rocks are generally medium to coarse grained and are foliated due to alternate arrangements of minerals and the dimensional orientation of light minerals such as quartz and feldspar (Balakrishnan et al., 1990).

The area falls under agro-ecological subregion 7.2 and characterized by *ustic* soil moisture and *hyperthermic* soil temperature regimes (Mandal et al., 2014). The length of growing period is 120–150 days in a year with medium to high available soil water content. Typically, summer period is from April to June when the temperature ranges from a maximum of 46 °C to a minimum of 27 °C. During winter (December to February), the maximum temperature is around 33 °C and the minimum temperature is 18 °C. The study area is in the rain shadow of the Indian monsoon and the average annual rainfall is around 500–600 mm most of which occurs during southwest monsoon (July–September). The data for potential evapotranspiration (PET), mean annual rainfall (MAR) and maximum recorded summer temperature over a period (2003–2015) of 13 years were collected from Department of Agriculture, Government of Telangana, Hyderabad (Fig. 2). Thimmajipet comprises of 19 villages. Agriculture is the main occupation and livelihood with 15,020 ha of the cultivated area out of which only 1960 ha (13%) are irrigated with bore-well water. The total number of farm holdings is 13,123. The natural vegetation comprises of Acacia (*Acacia nilotica*), ber (*Ziziphus jujuba*), palas (*Butea monosperma*), buffel grass (*Cenchrus ciliaris*), datura (*Datura stramonium*), teak (*Tectona grandis*), bamboo (*Dendrocalamus calostachyus*), prosopis (*Prosopis juliflora*) and tamarind (*Tamarindus indica*). The major crops grown during monsoon season (June–September) are cotton (*Gossypium hirsutum*), maize (*Zea mays*) followed by rice (*Oryza sativa*), pigeon pea (*Cajanus cajan*), sorghum (*Sorghum bicolor*) and castor (*Ricinus communis*). In rabi (October–January) rice is the major crop followed by groundnut (*Arachis hypogaea*), and chillies (*Capsicum annum*). Sunflower (*Helianthus annuus*), tomato (*Solanum lycopersicum*) and watermelon (*Citrullus lanatus*) are grown in patches.

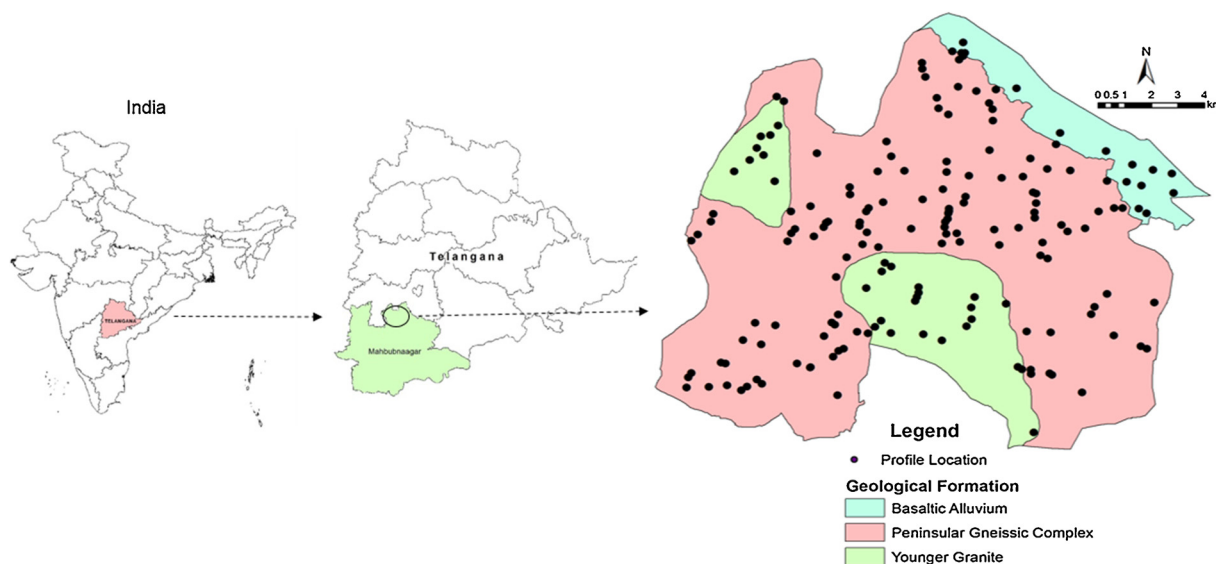


Fig. 1. Location of the study area, its geological formations and location of studied soil profiles covering all the geological regions.

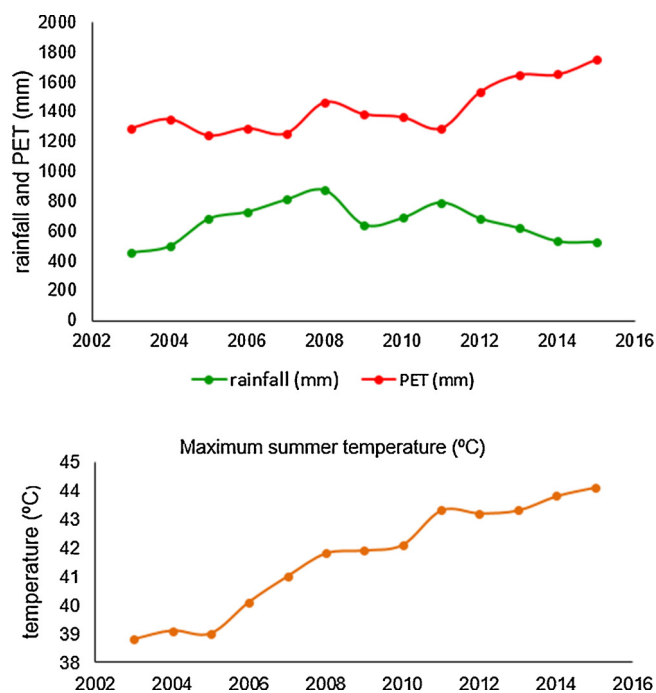


Fig. 2. Mean annual rainfall (MAR), potential evapotranspiration (PET) and recorded maximum summer temperature (MAST) in the study area during 2003–2015.

## 2.2. Soil resource inventory

### 2.2.1. Digital image processing and landform delineation

The procedure adopted for soil resource inventory is presented in Fig. 3. In the first step, the base map of the study area was prepared and landform units were delineated. Digital elevation model (DEM) was generated from Cartosat-1 stereo data pairs, using Leica Photogrammetric Suite (LPS). The stereo pair images, band ‘a’ and ‘f’ were added to the frame. The interior and exterior orientations corresponding to the Rational Polynomial Coefficients (RPC) files were carried out. Tie points were generated by LPS and additional tie points were added manually for even distribution throughout the image. Triangulation was performed to check the accuracies of all the tie points. DEM was generated with 10 m resolution and ortho-rectified by using ERDAS IMAGINE software. Terrain attributes like slope, aspect, contour, drainage and hillshade were derived from DEM. IRS (Indian Remote Sensing) P6 LISS-IV data with high-resolution (5.8 m) in cloud-free condition (November 2014) was procured from National Remote Sensing Centre (NRSC), Hyderabad, India. It was merged with the ortho-rectified Cartosat-1 (2.5 m resolution) data and spatial resolution of LISS-IV data was sharpened to 2.5 m. Geomorphic features were interpreted based on key image elements such as shape, tone or colour, pattern, shadow, association and texture for delineation of landforms using onscreen visual image interpretation techniques. Landform analysis was carried out in ArcGIS 10.1 using elevation data from DEM and hillshade. Ortho-rectified Cartosat-1 data along with hillshade and 10 m contour were superimposed on DEM and a stereo view was generated. Using the stereo tool, the area was visually interpreted for various landforms. Different landform units, slope and land use/land cover classes were confirmed through field traversing and checking at random points in the field before the survey and correlated with image interpretation units using GPS. The boundaries were verified and corrected wherever found necessary.

### 2.2.2. Soil survey, correlation and laboratory analyses

Detailed soil survey was carried out to study the morphological characteristics of soils based on the method outlined by Soil survey staff

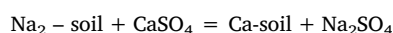
(2014). Transect approach, from higher elevation to lower elevation, covering all the identified landform units, was followed to study the soils. A total of 182 soil profiles from 39 transects were studied and the location of soil profiles was recorded using handheld GPS. Horizon-wise morphological properties including depth, colour, structure, texture, gravels, consistence, the occurrence of nodules, and special features were described using USDA soil description guidelines (Soil Survey Staff, 2014). Soil series were identified by following soil correlation procedure (Reddy, 2006) and samples were collected from all the horizons of typifying pedons.

Soil samples were air-dried and sieved through 2 mm sieve and stored in plastic containers for analysis of physical and chemical properties. Soil samples were sieved through 80 mesh sieve for estimating organic carbon. Particle size analysis was carried out using hydrometer method (Gee and Bauder, 1986); bulk density (BD) by core method (Blake and Hartge, 1986); gravimetric water content at  $-33$  kPa and  $-1500$  kPa by pressure plate apparatus (Klute, 1986). Available water content (AWC) was calculated as the difference between water content at  $-33$  kPa and  $-1500$  kPa. Volumetric water content was determined by multiplying the gravimetric water content with bulk density. Total porosity was calculated from bulk density and assumed particle density of  $2.65 \text{ Mg m}^{-3}$ . Saturated hydraulic conductivity (sHC) was estimated by constant head method (Klute and Dirksen, 1986). The Coefficient of Linear Extensibility (COLE) was determined by the method proposed by Schafer and Singer (1976).

Soil pH and electrical conductivity (EC) were measured with 1:2 soil:water ratio (Whitney, 1998). Organic carbon (OC) was determined by the method of Walkley and Black, (1934) whose correction factor was modified by Bhattacharyya et al. (2015).  $\text{CaCO}_3$  equivalent (%) was determined by the method described by Piper (1966). Cation exchange capacity (CEC) and exchangeable cations were estimated by standard procedures (Schollenberger and Simon, 1945; Sumner and Miller, 1996). Base saturation (BS) was calculated as the ratio of total bases to CEC. Exchangeable sodium percentage (ESP), exchangeable magnesium percentage (EMP) and exchangeable calcium percentage (ECP) were calculated as the ratio of sodium, magnesium and calcium to CEC, respectively. Sodium adsorption ratio (SAR) was calculated as the square root of the ratio of sodium (Na) to half of calcium (Ca) and Magnesium (Mg). Soil available nitrogen was estimated by the method of Subbiah and Asija (1956); available P by Olsen et al. (1954) for neutral and alkaline soils; by Bray and Kurtz (1945) for acid soils; Soil available K was estimated in flame photometer by the method of Schollenberger and Simon (1945). Available sulphur was extracted by 0.15%  $\text{CaCl}_2$  (Williams and Steinbergs, 1959) and measured by turbidimetry method (Chesnin and Yien, 1950) using spectrophotometer. Available Zn, Fe, Mn and Cu were estimated by DTPA extractant (Lindsay and Norvell, 1978) and boron by hot water method (Berger and Truog, 1939) and measured in Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP – AES).

### 2.2.3. Estimation of gypsum requirement

Sodicity has been a common problem in soils of arid and semi-arid regions of India and the sodic soils are characterised by excess sodium in their exchange complex. To remove the excess sodium, gypsum is the commonly used amendment as a source of calcium. Gypsum requirement (GR) is defined as “the amount of gypsum required to replace exchangeable sodium for the reclamation of sodic soil”. However, the sodic soils contain carbonate and bicarbonate ions associated with high pH and they precipitate when coming in contact with calcium. Hence, the Schoonover’s method overestimates the GR. The surface applied gypsum followed by leaching does not necessarily react with all the soluble carbonate and bicarbonate (Abrol et al., 1975). Gupta and Singh (2005) attributed the overestimation of GR to the following reaction.



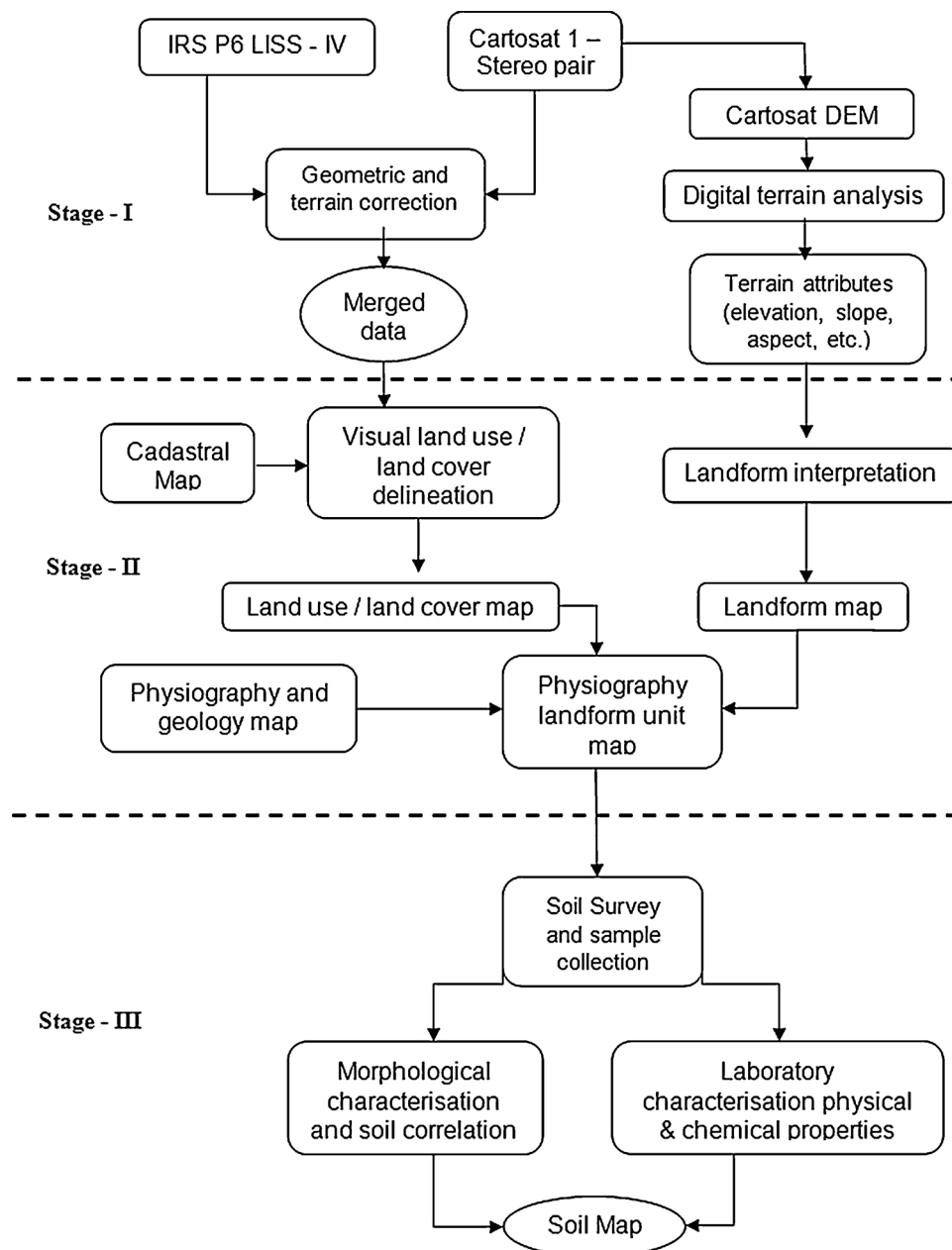
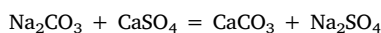


Fig. 3. Methodology of soil mapping.



To eliminate the influence of carbonate and bicarbonate on GR of the soil, Chauhan and Chauhan (1979) proposed a modified Schoonover method for estimation of GR. Further improvements were suggested by Gupta et al. (2001) and it is used in this study as modified Schoonover's method (Gupta and Singh, 2005). In this method, gain in sodium ions instead of the loss of calcium ions in the equilibrated gypsum solution is determined to estimate total sodium ions in the soil. The soluble sodium ions determined separately are then subtracted to give exchangeable sodium which gives the measure of gypsum requirement. A total of 21 surface soil samples with pH greater than 8.5 from the villages Pothireddipally, Koduparthi, Appajipally, Vedirepally, Budhasamudram, Avancha and Nerelapally were selected (3 samples from each village). Five gram sample of each soil was equilibrated with 100 ml saturated standard gypsum solution and the gypsum requirement was determined by estimating the loss of calcium ions in the filtrate as per Schoonover's method without any modification. Simultaneously,  $\text{Na}^+$  was

determined in the filtrate. In another set, 5.0 g sample from each selected soil was equilibrated with 100 ml 1.0 N ammonium acetate solution at pH 7.0 (Richards, 1954) and  $\text{Na}^+$  determined in the filtrate. In the third set, water-soluble  $\text{Na}^+$  was determined in the saturation extract (SE) of each sample. Flame photometer was used for  $\text{Na}^+$  determination. Gypsum requirement was calculated by subtracting soluble  $\text{Na}^+$  from gypsum solution extracted  $\text{Na}^+$ . Similarly, exchangeable  $\text{Na}^+$  was determined by subtracting soluble  $\text{Na}^+$  from  $\text{NH}_4\text{OAc}$  extracted  $\text{Na}^+$ . The results have been expressed in  $\text{cmol}(\text{p}^+)\text{kg}^{-1}$ .

### 2.3. Land suitability evaluation (LSE)

In the present study, parametric method, Storie index (SI) and MC-LSE (El Baroudy, 2016) methods were used for LSE of identified soil series and the performance of the methods were evaluated by correlating the LSI with crop yield. The soil-site characteristics used for the crop suitability evaluation were selected with respect to the AESR 7.2.

### 2.3.1. Parametric method

Land suitability evaluation for five commonly grown major crops viz., cotton, pigeon pea, maize, groundnut and rice was carried out. The selection of influencing factors was based on the growth requirement of the crops according to Sys et al. (1991). In the present study, after considering the agro-climatic condition (semi-arid dry), slope, drainage, soil texture, coarse fragments (%), CEC, soil depth,  $\text{CaCO}_3$ , soil pH, organic carbon (%), EC (salinity) and ESP (alkalinity) were selected for evaluating land suitability index. The selected parameters were scored based on Sys et al. (1993).

### 2.3.2. Storie index

Storie index is a method based on soil and landscape characteristics that govern the land's potential utilization and productive capacity. The ratings are highly subjective and inherently biased towards classification system which was originally developed for some irrigated soils of California. O'Geen et al. (2008) developed a revised version which generates ratings digitally from the USDA Natural Resources Conservation Services (NRCS).

The Storie index (SI) rating was calculated by the following formula:

$$\text{SI} = [(\text{factor A}/100) \times (\text{factor B}/100) \times (\text{factor C}/100) \times (\text{factor X}/100)] \times 100$$

where,

A – Degree of profile development

B – Surface texture

C – Slope factor

X – Other soil and landscape conditions

<sup>s</sup> X – Sub factors of X;

X value is derived by the formula,  $X = {}^aX \times {}^bX \times {}^cX \times {}^dX$

### 2.3.3. Multi-criteria method

The MC-LSE proposed by El Baroudy (2016) was used and modifications were made wherever found necessary. Three thematic indicators i.e. physical, chemical and fertility quality indices were used in the evaluation of land suitability. The following equations were used to compute the land suitability.

$$\text{LS} = (\text{FQI} \times \text{CQI} \times \text{PQI})^{1/3}$$

where LS is the land suitability factor, FQI is the fertility quality index, CQI is the chemical quality index and PQI is the physical quality index.

The fertility quality index was calculated using the following formula

$$\text{FQI} = (\text{S}_{\text{OC}} \times \text{S}_{\text{N}} \times \text{S}_{\text{P}} \times \text{S}_{\text{K}} \times \text{S}_{\text{S}} \times \text{S}_{\text{Zn}} \times \text{S}_{\text{Fe}} \times \text{S}_{\text{Mn}} \times \text{S}_{\text{Cu}} \times \text{S}_{\text{B}})^{1/10}$$

where the  $\text{S}_{\text{OC}}$ ,  $\text{S}_{\text{N}}$ ,  $\text{S}_{\text{P}}$ ,  $\text{S}_{\text{K}}$ ,  $\text{S}_{\text{S}}$ ,  $\text{S}_{\text{Zn}}$ ,  $\text{S}_{\text{Fe}}$ ,  $\text{S}_{\text{Mn}}$ ,  $\text{S}_{\text{Cu}}$ , and  $\text{S}_{\text{B}}$  are soil organic carbon, the available fractions of soil nutrients nitrogen, phosphorus, potassium, sulphur, zinc, iron, manganese, copper and boron, respectively.

The chemical quality index was calculated using the following formula:

$$\text{CQI} = (\text{S}_{\text{H}} \times \text{S}_{\text{CC}} \times \text{S}_{\text{CEC}} \times \text{S}_{\text{E}} \times \text{S}_{\text{M}})^{1/5}$$

where,  $\text{S}_{\text{H}}$ ,  $\text{S}_{\text{CC}}$ ,  $\text{S}_{\text{CEC}}$ ,  $\text{S}_{\text{E}}$  and  $\text{S}_{\text{M}}$  are parameters that express respective factors for soil pH,  $\text{CaCO}_3$  content, cation exchange capacity, exchangeable sodium percentage, and exchangeable magnesium percentage.

The physical quality index was computed using the following formula:

$$\text{PQI} = (\text{S}_{\text{D}} \times \text{S}_{\text{Y}} \times \text{S}_{\text{T}} \times \text{S}_{\text{R}} \times \text{S}_{\text{F}} \times \text{S}_{\text{G}} \times \text{S}_{\text{W}})^{1/7}$$

where  $\text{S}_{\text{D}}$ ,  $\text{S}_{\text{Y}}$ ,  $\text{S}_{\text{T}}$ ,  $\text{S}_{\text{R}}$ ,  $\text{S}_{\text{F}}$ ,  $\text{S}_{\text{G}}$  and  $\text{S}_{\text{W}}$  are factors for soil depth, surface stoniness, texture, drainage, topology, hydraulic conductivity and available water content, respectively.

The parameters and factors were rated based on experts' suggestions

and review of the literature (FAO, 1976; Sys et al., 1991 and 1993). The rates were assigned to the elements of a particular parameter with valid scores ranging from 0.2 indicating the worst conditions and to 1.0, the best conditions. The crop wise scores assigned to each property are given in supplementary information Appendix A (Table A1, A2, A3, A4 and A5). Each class was given a weighted index according to the importance of its role in land suitability for crop production.

### 2.3.4. Comparison of methods

To assess the agreement between the methods, the Kappa statistic developed by Cohen (1960) was used. Kappa coefficient was used to assess the agreement between alternative methods of categorical assessment. The calculation is based on the difference between how much agreement is actually present compared to how much agreement would be expected to be present by chance alone. The Kappa coefficient was calculated using the following formula:

$$K = \frac{P(A) - P(E)}{1 - P(E)}$$

where K is the Kappa coefficient, P(A) is the proportion of times that the coders agree and P(E) is the proportion of times that we would expect them to agree by chance. A Kappa value of 0 indicates that there is a poor agreement between the methods and a value of 1 indicates an almost perfect agreement.

The rating of Storie index is different from the other two methods. Hence, for comparison we use the suitability terms N (not suitable), S3 (marginally suitable) and S2 (moderately suitable) for SI rating VI (non-arable), IV (poor) and II (good), respectively. The indexes derived by the three methods were correlated with crop yield to compare their effectiveness in land evaluation. Crop yield data (village average) for the period 2008–2015 was obtained from Department of Agriculture, Government of Telangana, Hyderabad.

## 2.4. Developing ALUP

To create awareness about the need to evaluate soil suitability for crops, initially, we addressed the local farmers, policy makers, agricultural officers and extension workers about the importance of knowing potential and constraints of soils through the display of developed soil maps (Appendix B). The suitability evaluation results were shared with the farmers who provided their perspective on LSI and matched them based on average crop yield obtained on their farm land, field observation, and prevailing socio-economic conditions. Feasibility of the plan including possible allocations to suggested crops, landscape level changes and effects, potential gains to be made and sustainability were discussed. This led to identification of scientific interventions. Following broad steps were followed to prepare ALUP.

- 1 Baseline survey of the villages including information on current agricultural practices, crop yields, livestock, implements, equipment, credit availability, agriculture inputs used, animals, fodder needs, literacy, and infrastructure was carried out using a questionnaire (Appendix C).
- 2 Test of farmers' awareness about potential and constraints of soils, their crop suitability through the same questionnaire. Village / Panchayat (local administrative unit) level discussions were held to prioritise and rank soil related problems and solutions by adopting matrix ranking approach.
- 3 Participatory transect walks with many groups of farmers were carried out to test their agreement with the LSI. Then group discussions with other farmers were conducted to verify the observations and decisions of the group. Based on the consensus arrived after discussion among experts, farmers, and policy makers, ALUPs were prepared for each village.

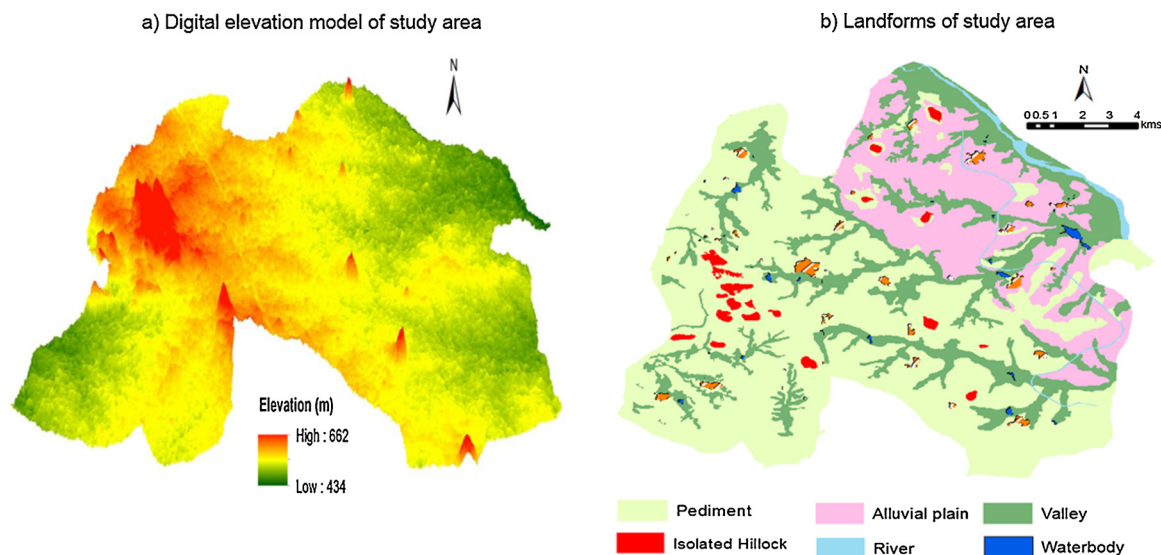


Fig. 4. Digital elevation model (a) and characterised landforms (b) of the study area.

### 3. Results and discussion

#### 3.1. Landform characterisation and soil series identification

The terrain attributes of the study area derived from DEM were used for characterisation of landforms. DEM data showed that elevation of the study area varied with a maximum of 662 m on the south-western side and a minimum of 434 m on the north-eastern side (Fig. 4a). Thimmajipet was characterised into three major landforms (Fig. 4b) viz., piedmont (474–550 m), alluvial plain (451–474 m) and valley (434–451 m) occupying an area of 9899 (46%), 5021 (23%) and 4262 ha (20%), respectively. The intermittently occurring hillocks (551–662 m) occupied an area of 1840 ha (8.5%) out of the total geographical area of 21,560 ha. Six soil series were identified namely Gummagonda, Pullagiri, Chegunta, Nerelapally, Avancha and Koduparthi and they were mapped based on the soil-landform relationship (Fig. 5). The variability observed in the soils are presented in Fig. 6 and for the description of the soil series viz., the morphology of typifying

pedon, range in characteristics, and area coverage the reader is referred to supplementary information (Appendix D). Soils were classified based on climate parameters, soil morphology, physical and chemical properties according to USDA soil taxonomy (Soil survey staff, 2014).

The depth of the soils varied from very shallow to very deep and it could be ascertained to the topographical position on which the soils occur. Soil erosion in Thimmajipet varied from slight on nearly level alluvial plains, to moderate and severe on gently sloping and moderately sloping piedmont areas, respectively. In general, the soils in upper piedmont were shallow due to erosion and have *Lithic* contact was observed within shallow depths. The removal of fine material causes high per cent of stoniness (> 15%) in the surface horizons. Micro-topographical variation caused by the modification in landforms due to several cycles of erosion and sedimentation in south Deccan plateau in an earlier period could be the possible reason for the occurrence of skeletal soils (Dutta et al., 2001). The soils occurring in lower topographic position showed development in structure, texture (finer) or consistency as compared to surface horizons, which might be due to in

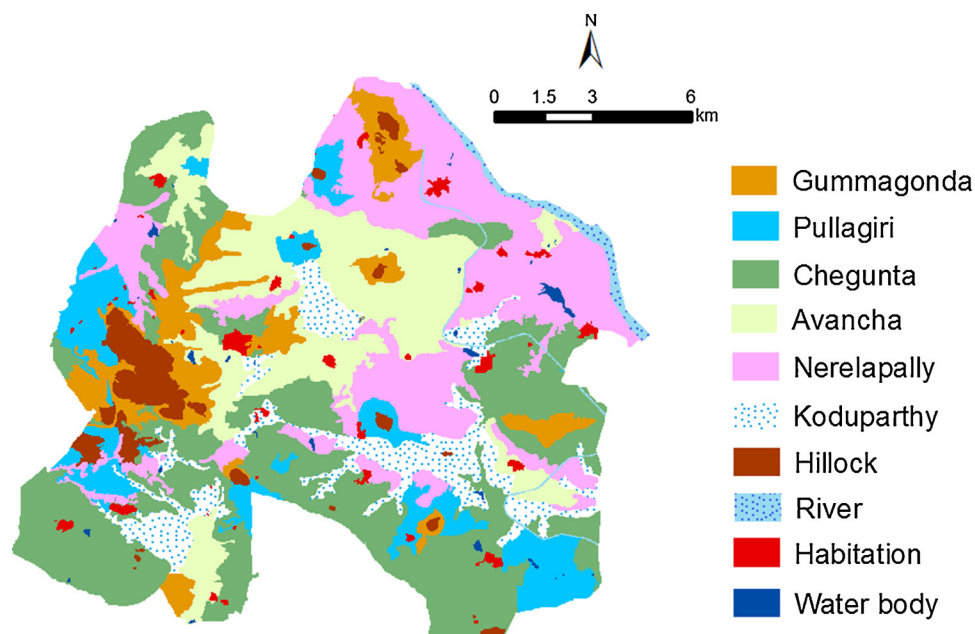


Fig. 5. Soil map of the study area indicating the spatial distribution of identified six soil series and other features.

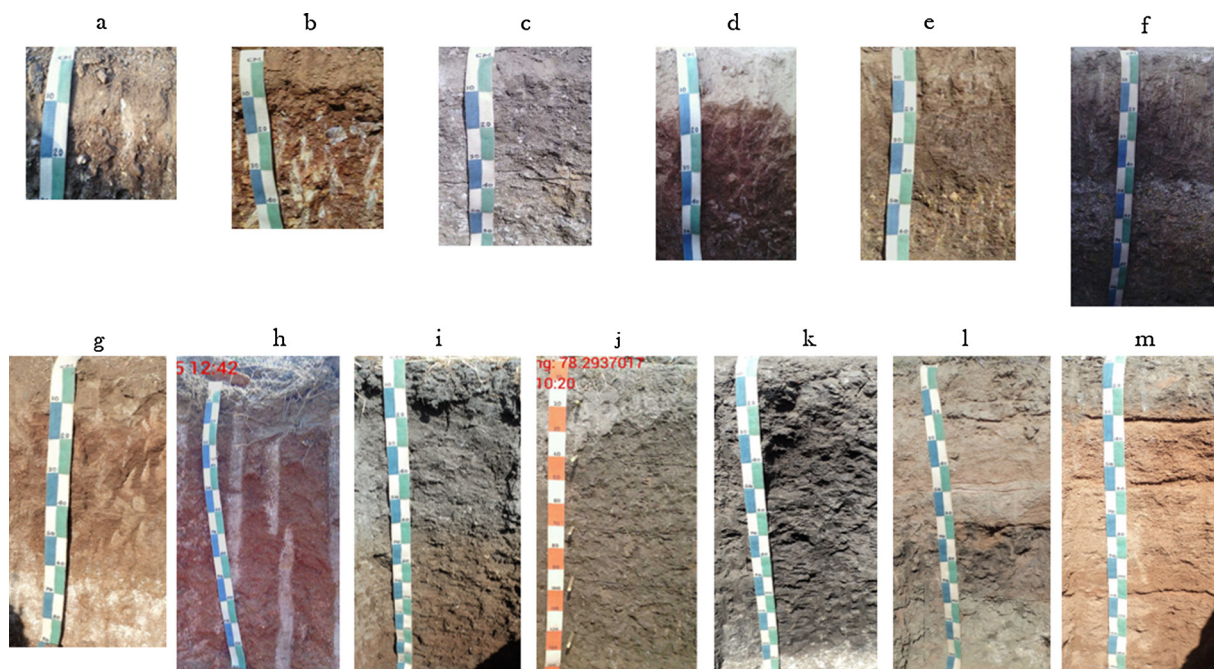


Fig. 6. Soil variability recorded in the study area. i.e., *Lithic Ustorthents* (a, b); *Typic Haplustepts* (c, e and f); *Typic Haplustalfs* (g); *Rhodic Haplustalfs* (d, h); *Vertic Haplustepts* (i, j); *Sodic Haplusterts* (k); *Typic Ustifluvents* (l, m). The soil profiles are presented in the order of increasing depth.

*situ* weathering. The large variation in the soil texture might be due to the difference in nature and composition of parent material (Nayak et al., 2002), topographic position, *in situ* weathering and translocation of clay (Vara Prasad Rao et al., 2008). However, Gummagonda and Pullagiri soils, which occur predominantly in upper piedmont areas, did not show variations in structure, texture or consistency among surface and subsurface horizons and their depth ( $\leq 50$  cm) indicated that they were poorly developed soils.

### 3.2. Soil properties and their depth distribution

The matrix colour did not differ much between horizons in Gummagonda and Pullagiri soils but the hue decreased from 5YR to 2.5YR and redness increased with depth in Chegunta soils. The variation in the colour of surface horizons was due to the admixture of iron oxides and organic matter. Dutta et al. (2001) also observed that the colour of *Rhodustalfs* occurring in southern Telangana was redder than 5YR in hue. The dark red colour (2.5YR hue) of Chegunta soils could be attributed to well-drained conditions and presence of oxidized form ( $\text{Fe}^{3+}$ ) of iron and variation in the colour appears to be the function of chemical and mineralogical composition of soils (Geetha Sireesha and Naidu, 2013). Moreover, it is well established that the red colour of the soils occurring in tropical environments is due to desilication, leaching and illuviation (Bhattacharyya et al., 1993). The colour of the Nerelapally (*Vertic Haplustepts*) and Avancha soils (*Sodic Haplusterts*) varied from dark gray to very dark grayish brown (10YR hues). The moist condition prevailing for relatively longer period, due to *vertic* properties, facilitates the reduction of iron and leads to the gray colour (Maji et al., 2005). The intensity of the gray colour is influenced by the drainage conditions. The dark coloured soils were the weathering products of basaltic alluvium deposits and gneissic complex parent material. The colour of Koduparthi soils (*Typic Ustifluvents*) varied from brown to dark yellowish brown to dark red. The hue varied from 10 YR to 7.5 YR to 5 YR; the value from 2 to 6 and chroma 1 to 5. The large variation in colour was due to wide variation in texture. Also, the colour of these soils was influenced by moisture regime and topographic position. Thus, the matrix colour is an important indicator of many inherent soil properties.

Distribution of soil properties with depth assumes significance in the context of movement of soil water and its re-distribution. The depth wise distribution of few selected properties of the six soil series is presented in Fig. 7. Clay is considered as the seat of chemical reaction in soils and its concentration and distribution with depth influences other soil properties. It did not vary with depth in Pullagiri soils but increased with depth in other soils, except in soils of Koduparthi where its distribution was irregular. The physical and chemical properties were irregularly distributed in soils of Koduparthi. The sHC of the soils varied from 0.0 to  $15.85 \text{ cm h}^{-1}$ . It decreased with depth in all the soils except in Koduparthi soils. Hydraulic conductivity is a function of porosity, soil structure and clay content. The sHC of the soils of Nerelapally and Avancha were nil in their subsurface horizons indicating that the drainage of these soils was severely impaired. The highest sHC value ( $15.85 \text{ cm h}^{-1}$ ) observed in the subsurface layers of Koduparthi soils was the result of the occurrence of sandy layers due to the lithological discontinuity or vertical contrast in texture. The large variation in sHC among the soils could be attributed to the chemical properties of the soils influencing water movement through soil profile (Chaudhari, 2001).

The pH of the soils varied from 5.7 to 7.7 (piedmont), 8.1 to 9.8 (alluvial plain) and from 8.3 to 9.6 (valley). It decreased with depth in Chegunta soils but increased in soils of other five series. The variation in the pH of the soils is due to the nature and chemical composition of parent material, topographic position and base saturation. The soil pH of piedmont landform was slightly acidic to neutral because of leaching of bases due to highly weathered conditions. The high pH in alluvial plain and valley soils was due to the high concentration of  $\text{Na}^+$  in the exchange complex and accumulation of bases removed from higher topographical areas by runoff water.  $\text{CaCO}_3$  generally increased with depth except in soils of Avancha and Koduparthi. Moreover,  $\text{CaCO}_3$  increases the subsoil sodicity by forming  $\text{NaHCO}_3$  upon reacting with exchangeable  $\text{Na}^+$ . Organic carbon (OC) decreased with depth except Koduparthi soils in which it was irregularly distributed. The low OC content could be attributed to the semi-arid climate which induces oxidation of organic carbon due to high temperature (Bhattacharyya et al., 2007). Moreover, the study area is predominantly single cropped area with cotton and maize occupying the large area of cultivation.

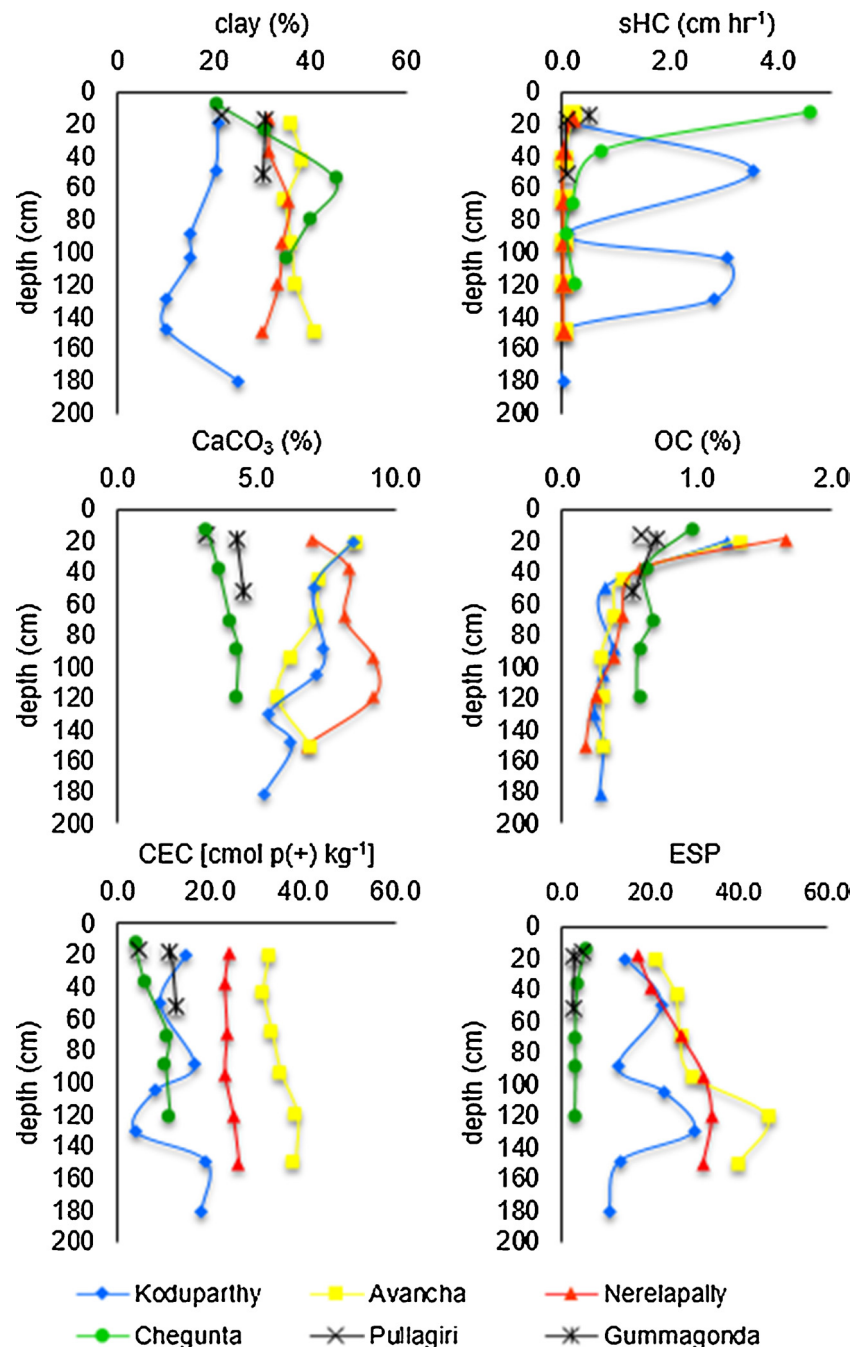


Fig. 7. Depth distribution of some properties of six soil series.

Hence, the limited addition of crop residues to the soil also contributed to the poor accumulation of OC. Exchangeable sodium percentage (ESP) decreased with depth in soils of Pullagiri and Chegunta, but increased in soils of Nerelapally and Avancha. The subsoil sodicity (high pH and ESP) in the soils of Nerelapally, Avancha and Koduparthi could be attributed to the accelerated formation of *pedogenic carbonate* induced by semi-arid climate (Vasu et al., 2017; Pal et al., 2016). This impaired the hydraulic properties of these soils. The clay dispersion caused by high ESP (18.9–46.7) and EMP (16.4–24.3) reduced the sHC in these soils (Fig. 7).

Soil available nutrients indicate the inherent fertility status of the soils. The analytical results of soil available nutrients are presented in suppl. (Appendix E). Available nitrogen varied from 78.4 to 209.9 kg ha<sup>-1</sup> in the surface and from 6.2 to 185.0 kg ha<sup>-1</sup> in the subsurface. Available phosphorus varied from 21.9 to 91.8 kg ha<sup>-1</sup> in the surface

and from 9.9 to 48.6 kg ha<sup>-1</sup> in the subsurface. Available potassium varied from 157.2 to 528.5 kg ha<sup>-1</sup> in the surface and from 52.4 to 510.4 kg ha<sup>-1</sup> in the subsurface. Available sulphur varied from 21.1 to 87.4 mg kg<sup>-1</sup> in the surface and from 17.0 to 71.2 mg kg<sup>-1</sup> in the subsurface. Available iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and boron (B) varied from 5.9 to 19.4, 6.2 to 61.0, 0.3 to 1.1, 0.3 to 6.2, 0.4 to 1.1 mg kg<sup>-1</sup>, respectively in the surface horizons. At the subsurface horizons, they varied from 3.4 to 11.8, 1.6 to 25.9, 0.1 to 0.6, 0.5 to 2.0 and 0.2 to 0.8 mg kg<sup>-1</sup> in the same order.

### 3.3. LSE by parametric method

Suitability class for five major crops evaluated by the parametric method is presented in Table 1. According to the parametric method, Gummagonda soils were only marginally suitable (S3) for groundnut

**Table 1**

Land suitability class for major crops by parametric method.

Series	Cotton	maize	Pigeon pea	groundnut	Rice
Gummagonda	14 (N)	31 (N)	24 (N)	42(S3)	17(N)
Pullagiri	43(S3)	49(S3)	51(S3)	63(S2)	42(S3)
Chegunta	87(S1)	69(S2)	84(S1)	81(S1)	72(S2)
Nerelapally	85(S1)	70(S2)	83(S1)	81(S1)	77(S2)
Avancha	79(S2)	81(S1)	81(S1)	82(S1)	70(S2)
Koduparthi	45(S3)	47(S3)	47(S3)	81(S1)	21(N)

If index > 80 = S1; 60–80 = S2; 40–60 = S3; < 40 = N; S1 – highly suitable; S2 – moderately suitable; S3 – marginally suitable; N – unsuitable.

but unsuitable for the cultivation of the other four crops. Pullagiri soils were marginally suitable (S3) for cotton, maize, pigeon pea and rice and moderately suitable (S2) for groundnut. The soils of Chegunta and Nerelapally were highly suitable (S1) for cotton, pigeon pea and groundnut but moderately suitable (S3) for maize and rice. Avancha soils were highly suitable (S1) for maize, pigeon pea and groundnut and moderately suitable (S2) for cotton and rice. Koduparthi soils were unsuitable (N) for rice; marginally suitable (S3) for cotton, maize and pigeon pea. However, they were highly suitable (S1) for groundnut.

### 3.4. LSE by Storie index method

The results of the Storie index method are presented in Table 2. Accordingly, Gummagonda soils were unsuitable (class VI) for agricultural use as indicated by Storie index. It is worth to note that though Gummagonda soils have high scores for surface texture, slope and landscape conditions, poor degree of profile development (depth < 20 cm) and multiplication of factor scores resulted in unsuitable class. Koduparthi soils were classified as good and the soils of Pullagiri, Chegunta, Nerelapally and Avancha were classified as poor in their agricultural productivity. It is evident from Table 2, low scores for factor A (Pullagiri); factor B (Chegunta and Avancha); factor <sup>b</sup>X (Nerelapally); and <sup>b</sup>X and <sup>d</sup>X (Avancha) resulted in poor (class IV) crop suitability.

### 3.5. LSE by multi-criteria method

In multi-criteria approach, the criteria used for land suitability evaluation is presented in Table 3. Results indicate that fertility quality index (FQI) of Gummagonda soils was low for all the selected crops except groundnut (Table 4). FQI was high for Pullagiri soils for all crops except pigeon pea. Similarly, the FQI was high for all the crops for soils of Chegunta, Nerelapally and Avancha but it was low for all the crops except groundnut for Koduparthi soils. The chemical quality index (CQI) of Gummagonda soils was low for cotton and rice but high for Chegunta soils. CQI of Nerelapally and Koduparthi soils were very low

**Table 2**

Storie index rating for Thimmajipet soils.

Factor	Gummagonda	Pullagiri	Chegunta	Nerelapally	Avancha	Koduparthi
A	0.20	0.50	1.00	1.00	1.00	1.00
B	0.95	0.95	0.50	0.95	0.50	0.95
C	0.85	0.95	1.00	1.00	1.00	1.00
<sup>a</sup> X	<sup>a</sup> 0.85	<sup>a</sup> 0.95	<sup>a</sup> 0.95	<sup>a</sup> 1.00	<sup>a</sup> 1.00	<sup>a</sup> 1.00
	<sup>b</sup> 1.00	<sup>b</sup> 1.00	<sup>b</sup> 1.00	<sup>b</sup> 0.50	<sup>b</sup> 0.50	<sup>b</sup> 0.85
	<sup>c</sup> 0.80	<sup>c</sup> 0.80	<sup>c</sup> 0.80	<sup>c</sup> 1.00	<sup>c</sup> 1.00	<sup>c</sup> 0.80
	<sup>d</sup> 0.85	<sup>d</sup> 0.95	<sup>d</sup> 1.00	<sup>d</sup> 1.00	<sup>d</sup> 0.40	<sup>d</sup> 1.00
X	0.60	0.70	0.75	0.40	0.40	0.68
I	0.10	0.31	0.37	0.38	0.38	0.68
Class	VI	IV	IV	IV	IV	II
Suitability	Non-arable	Poor	Poor	Poor	Poor	Good

A – Degree of profile development; B – Surface texture; C – Slope factor; X – Other soil and landscape conditions; <sup>a</sup>X – sub factors of X; I – Storie index; a – drainage; b – alkali; c – nutrient level; d – erosion.

**Table 3**

Criteria used for evaluating suitability of major crops by MC-LSE method (after El Baroudy, 2016).

Index quality	Class	Suitability	FQI	CQI	PQI	LSI
High	S1	Highly suitable	> 0.75	> 0.9	> 0.9	1.00-0.81
Moderate	S2	Moderately suitable	0.75-0.50	0.9-0.7	0.9-0.7	0.80-0.61
Low	S3	Marginally suitable	0.50-0.25	0.7-0.5	0.7-0.5	0.60-0.40
Very low	N	Unsuitable	< 0.25	< 0.5	< 0.5	< 0.40

FQI – Fertility Quality Index; CQI – Chemical Quality Index; PQI – Physical Quality Index; LSI – Land suitability index.

for maize and pigeon pea; low for cotton and groundnut; moderate for rice. It was low for all crops except rice for Avancha soils. The soil physical quality index (PQI) was low for groundnut and very low for other four crops for Gummagonda soils. PQI of Pullagiri soils was very low for rice. It was moderate for all crops for soils of Chegunta and Nerelapally except for maize (Nerelapally). It was moderate for all crops of soils of Avancha.

The land suitability for selected crops by multi-criteria method was assessed from the land suitability index (LSI) (Table 5) derived from thematic indices and interpreted from criteria presented in Table 3. The soils of Gummakonda were marginally suitable (S3) for maize and pigeon pea; moderately suitable (S2) for groundnut and unsuitable (N) for cotton and rice. The soils of Pullagiri were moderately suitable (S2) for all the five crops. The Chegunta soils were highly suitable (S1) for cotton, groundnut and rice (under irrigated conditions); moderately suitable (S2) for maize and pigeon pea. The soils of Nerelapally and Avancha were moderately suitable (S2) for all the crops except rice (S1). The soils of Koduparthi were marginally suitable (S3) for all the crops except groundnut for which they were moderately suitable (S2). In view of the criteria in Table 3, the suitability of cotton under Gummagonda series with LSI value 40 is considered as N because of high stoniness in surface with underlain hard rock. Similarly, for groundnut under Chegunta series (LSI value 80), the suitability class is S1 due to high soil depth, light texture and optimum nutrient holding capacity.

### 3.6. Comparison of land suitability evaluation methods

Land evaluation, in general, assesses the suitability of land for agricultural land use and specific crops, in particular. Many methods are in vogue such as Storie index (Storie, 1978), Riquier's index (Riquier et al., 1970), and Sys index (Sys et al., 1991). These methods have been applied to Indian conditions for different crops (Tamgadage et al., 2002; Kadu et al., 2003). But, the applicability of these qualitative methods, under varied agro-climatic conditions remains a

**Table 4**  
Thematic land quality index of soil series for major crops.

Soil series	Cotton			Maize			Pigeon pea			Groundnut			Rice		
	FQI	CQI	PQI	FQI	CQI	PQI	FQI	CQI	PQI	FQI	CQI	PQI	FQI	CQI	PQI
Gummagonda	0.32	0.68	0.20	0.51	0.76	0.40	0.41	0.76	0.20	0.66	0.84	0.66	0.32	0.62	0.24
Pullagiri	0.75	0.90	0.50	0.70	0.86	0.54	0.67	0.86	0.50	0.82	0.96	0.63	0.76	0.84	0.41
Chegunta	0.75	0.90	0.83	0.70	0.80	0.80	0.67	0.80	0.77	0.74	0.84	0.83	0.77	0.90	0.89
Nerelapally	0.72	0.64	0.76	0.69	0.44	0.69	0.69	0.44	0.76	0.74	0.58	0.80	0.74	0.88	0.89
Avancha	0.85	0.68	0.80	0.85	0.60	0.77	0.87	0.60	0.83	0.87	0.60	0.83	0.82	0.88	0.89
Koduparthi	0.58	0.66	0.47	0.58	0.44	0.56	0.53	0.44	0.56	0.68	0.60	0.87	0.54	0.54	0.59

FQI – Fertility Quality Index; CQI – Chemical Quality Index; PQI – Physical Quality Index.

challenge. Apart from them, methods like multi-criteria method, fuzzy logic (Chatterji et al., 2014) were also used recently for evaluating land suitability for cotton (Walke et al., 2012). Hence, two commonly used methods viz., Sys parametric method and Storie index and one recent method i.e. MC-LSE were compared for their effectiveness in the assessment of soil and site characteristics for the cultivation of major crops.

For cotton and rice, all the three methods produced similar results for Gummagonda soils and classified them as unsuitable (N). Contradictorily, the suitability of Nerelapally soils for cotton is different for each method (Table 6). The suitability class for cotton varied with methods for other four soil series. For maize and pigeon pea, the Gummagonda soils were marginally suitable (S3) as per MC-LSE but unsuitable by SI and parametric methods.

The land suitability classes by the three methods varied for the soils of Chegunta, Nerelapally and Avancha with respect to the crops. However, for soils of Koduparthi, the methods produced similar results for cotton, maize and pigeon pea. These soils were classified as unsuitable, moderately suitable and marginally suitable for rice by parametric, Storie index and multi-criteria method, respectively.

The results of Kappa statistic and the data in Table 6 indicate that the methods vary in the evaluation of land suitability for different crops. The Kappa coefficient (K) between MC-LSE and parametric method is 0.64 indicating moderate level of agreement between them. However, K is 0.37 between MC-LSI and SI suggesting the poor agreement between these methods. Moreover, results of correlation between LSI and crop yield showed that multi-criteria LSI (MC-LSI) was highly correlated (0.78) with pigeon pea yield and moderately correlated with the yield of maize (0.63) and rice (0.56). Parametric LSI was moderately correlated with the yield of rice and pigeon pea but poorly correlated for the other crops (Table 7). The Storie index was moderately correlated with the yield of maize and pigeon pea and poorly correlated with cotton, groundnut and rice. The results of the correlation study indicate that the MC-LSI had comparatively better correlation with the yield of major crops than other two methods. These results were also supported by the findings of Mandal et al. (2001). They found that Sys index was modified by rainfall, i.e. the index was low in dry years whereas it was reasonable in wet and normal years and it had good correlation ( $r^2 = 0.75$ ) with cotton yield. They also observed that, most notably, though the index value was reduced in dry years, soil suitability class remained unchanged. Thus, our results coupled with the

findings of Mandal et al. (2001) indicate the non-universality of the method. In general, the index limits are fixed based on a class value in the parametric methods.

In the present study, all the evaluated soils were found to be poor in suitability for crop production except Koduparthi series by the SI method. The factors surface texture, sodicity, and erosion reduced the index value of Chegunta, Nerelapally and Avancha soils, respectively. Thus, it is evident that one or few factors may determine the index value and lead to misinterpretation or wrong conclusion. Moreover, it could also be observed that the Storie index rated the Koduparthi soils as good for crop production whereas these soils were only marginally suitable or unsuitable for most of the crops except groundnut according to other two methods. The poor agreement between SI and other methods could be attributed to the following: The Storie index was originally developed for irrigated soils of California (1920s and 1930s) but it is commonly used at all the agro-ecological conditions irrespective of irrigation. Since the index is based on multiplication of the factors, limitation of any single soil parameter reduces the index value as discussed in Section 3.4. Moreover, it is highly subjective due to the arbitrary ranges of factors (O'Geen et al., 2008). Hence, the masking effect of the wide range of values is a major disadvantage in Storie index method. Moreover, if any value is zero, then the SI value will be zero and unsuitable for use.

The anomalies in these parametric methods could be reduced by adopting the multi-criteria method. It is based on all land quality indices (for example, physical, chemical and fertility indices which were used in the present study) and designed to give equal weight to all the indices. Many researchers (Yu et al., 2011; Akinchi et al., 2013) advocated multi-criteria method for agricultural land evaluation. Similar to our study, Zolekar and Bhagat, (2014) characterised and evaluated the soils of hilly terrains by the MC-LSE method using IRS P6 LISS IV data and found that slope, soil depth, erosion, texture, water holding capacity, and nutrient availability as dominant factors influencing crop production. In support of the results of the present study, Sarkar et al. (2014) successfully used multi-criteria approach for LSE for wheat in the eastern plateau region of India. In a similar exercise, Rhebergen et al. (2016) identified slope, drainage and available water content of the soils determine their suitability for successful oil palm production in Ghana. Therefore, it is advantageous to use multi-criteria approach for land suitability evaluation for agricultural land use planning.

**Table 5**  
Land suitability for major crops in Thimmajipet by multi-criteria method.

Crop	Gummagonda		Pullagiri		Chegunta		Nerelapally		Avancha		Koduparthi	
	LSI	Suitability	LSI	Suitability	LSI	Suitability	LSI	Suitability	LSI	Suitability	LSI	Suitability
Cotton	0.40	N	0.72	S2	0.83	S1	0.71	S2	0.78	S2	0.57	S3
Maize	0.56	S3	0.70	S2	0.77	S2	0.61	S2	0.74	S2	0.53	S3
Pigeon pea	0.46	S3	0.68	S2	0.75	S2	0.63	S2	0.77	S2	0.51	S3
Groundnut	0.72	S2	0.80	S2	0.80	S1	0.71	S2	0.77	S2	0.72	S2
Rice	0.39	N	0.67	S2	0.85	S1	0.84	S1	0.86	S1	0.56	S3

**Table 6**  
Comparison of land suitability class by three methods.

Series	Cotton			Maize			Pigeon pea			Groundnut			Rice		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Gummagonda	N	N	N	S3	N	N	S3	N	N	S2	S3	N	N	N	N
Pullagiri	S2	S3	S3	S2	S3	S3	S2	S3	S3	S2	S2	S3	S2	S3	S3
Chegunta	S1	S1	S3	S2	S2	S3	S2	S1	S3	S1	S1	S3	S1	S2	S3
Nerelapally	S2	S1	S3	S2	S2	S3	S2	S1	S3	S2	S1	S3	S1	S2	S3
Avancha	S2	S2	S3	S2	S1	S3	S2	S1	S3	S2	S1	S3	S1	S2	S3
Koduparthi	S3	S3	S2	S3	S3	S2	S3	S3	S2	S2	S1	S2	S3	N	S2

A – Multi criteria method S1 – Highly suitable; B – Parametric method S2 – Moderately suitable; C – Storie index method S3 – Marginally suitable; N – Unsuitable.

**Table 7**  
Relationship ( $r^2$ ) between land evaluation methods and crop yield.

Crop	MC-LSI vs yield	Parametric LSI vs yield	Storie index vs yield
Cotton	0.30	0.20	0.12
Maize	0.63	0.03	0.51
Pigeon pea	0.78	0.47	0.61
Groundnut	0.35	0.18	0.29
Rice	0.56	0.59	0.18

### 3.7. Developing agricultural land use plans

Characterisation and evaluation of the identified soil series helped to assess their constraints and potentials for crop production. Gummagonda soils were shallow with root limiting hard rock. Hence, poor nutrient supply and low available water content due to limited depth were major limiting factors for crop production in these soils. Chegunta soils have similar limitations, however, these soils have sufficient clay (> 20%) and soil test based nutrient management with assured supplemental irrigation can make these soils productive. Calcareousness and alkalinity due to high pH and ESP were the major limitation in soils of Nerelapally and Avancha. High level of Ca and Na causes micronutrient deficiency. The high clay content of these soils reduces their workability when they are wet and dry (Prasad, 2000). Though leaching is a difficult process due to high clay content, a suitable amendment like gypsum or organic manures need to be used to reduce the alkalinity.

#### 3.7.1. Management of sodic soils

The data in Table 8 shows that pH of the sodic soils ranged from 8.7 to 10.3 with a mean of 9.2 and EC ranged between 0.254 to 1.665 dS m<sup>-1</sup> indicating that all the samples were non-saline but sodic in character. GR values in Schoonover method ranged from 8.4 to 16.2 with a mean of 11.2 cmol (p<sup>+</sup>) kg<sup>-1</sup> which were higher than the GR values by modified Schoonover method (Table 8). The data also showed that there was poor relationship between soil pH and Schoonover GR in soils with considerable amount of carbonates (CaCO<sub>3</sub>). This indicates that soil pH was increased by the presence of CaCO<sub>3</sub>. Gypsum solution extracted Na<sup>+</sup> ranged from 9.4 to 22.8 with a mean of 14.3 cmol (p<sup>+</sup>) kg<sup>-1</sup>. It was similar to the ammonium acetate extracted Na<sup>+</sup> (Table 8) and indicates that both the solutions extract exchangeable and soluble forms of sodium from the soil. Water soluble sodium is the Na<sup>+</sup> ions extracted by distilled water and it ranged from 1.6 to 13.4 with a mean of 6.2 cmol (p<sup>+</sup>) kg<sup>-1</sup> soil. Subtraction of water soluble sodium from gypsum solution extracted sodium and ammonium acetate extracted sodium separately gives the modified Schoonover GR values and exchangeable sodium, respectively. The modified Schoonover GR values ranged from 6.6 to 12.3 with a mean of 8.12 cmol (p<sup>+</sup>) kg<sup>-1</sup> and close to ammonium acetate extracted exchangeable sodium. The gypsum requirement of the soils varied from 3 to 5.5 t ha<sup>-1</sup> with a mean value of 3.6 t ha<sup>-1</sup>. The correlation coefficient is 0.794 between exchangeable sodium and GR estimated by modified Schoonover method. It

indicates that this method can be employed for more precisely determining the GR of sodic soils.

Gypsum was primarily used as an amendment for the amelioration of sodic soils in India during the last three decades but the reduction in subsidy on gypsum made it cost-intensive and subsequently slowed down its usage. Qadir et al. (2001) argued that using fine particles of gypsum in soils containing Na<sub>2</sub>CO<sub>3</sub> leads to the formation of CaCO<sub>3</sub> precipitation and its further coating on gypsum particles decreases the dissolution rate of gypsum (Keren and Kauschansky, 1981). Hence, coarse grade gypsum should be preferred for the management of these calcareous sodic soils. Our study area is predominantly rainfed dependent for agriculture and growing less water required crops like cowpea (*Vigna unguiculata* L.) and bean (*Dolichos lablab* L.) in calcareous sodic soils (Avancha soils) can solubilise calcium carbonate and also fix atmospheric nitrogen (Mubarak and Nortcliff, 2010).

Biological methods can supplement the chemical amendments for effective and inexpensive reclamation of sodic soils (Qadir et al., 2001). Studies showed cultivation of fruit crops like pomegranate (*Punica granatum*) and other tree species such as salvadora (*Salvadora persica*); *Dalbergia sissoo* and *Leucaena leucocephala* under water stagnated conditions by adopting raised and sunken bed land configuration method can reduce the subsoil sodicity (Mishra et al., 2002; Goel and Behl, 2002; Dagar et al., 2001). In order to improve the poor hydraulic conductivity of Avancha and Nerelapally soils, management of macro porosity is important. Deep ploughing disturbs the soil profile, thus reduces bulk density and increases total porosity. We recommend suitable management practices for sodic soils of the study area which is presented in Table 9.

#### 3.7.2. Scenario analysis of study area

Rainfed agriculture is predominant in the study area and the yield of crops was low due to mid-season droughts, low management, poor soil quality and other socio-economic factors. Analysis of cropping pattern during the period of 2003–15 showed that farmers prefer to cultivate cash crops like cotton and maize in *kharif* season when southwest monsoon provides rainfall. Fig. 8 shows that the area under cultivation was more than 90% less in *rabi* season compared to *kharif*. Moreover, only farmers assured of irrigation water from bore-well cultivate rice and farmers less assured of bore-well water cultivate short duration crops like chilli, groundnut and watermelon. MAR, PET, temperature, and vegetation are the major factors influencing the water balance in soils. Increase in air temperature leads to increase in PET and affect the soil-water balance negatively. In the study area, about 80–85% of the rainfall occurs during the south-west monsoon (June–September) season during when crops are cultivated under rainfed conditions. The coefficient of variation of the rainfall was 19.2% which indicates that rainfall pattern is temporally erratic and results in drought during the crop-growth. The rainfall was very low for consecutive years from 2003 to 2004 (458 and 502 mm) and 2014 to 2015 (533 and 529 mm) indicating the occurrence of severe drought. The frequency of drought determines the natural vegetation and cultivation of crops. The highest rainfall recorded was 873 mm and the amount of rainfall varied over

**Table 8**

Gypsum requirement (GR) of selected sodic soils by modified Schoonover method.

S.No	Village	pH	EC dS m <sup>-1</sup>	CaCO <sub>3</sub> (%)	Schoonover GR cmol (p <sup>+</sup> ) kg <sup>-1</sup>	Gypsum extracted Na <sup>+</sup> kg <sup>-1</sup>	NH <sub>4</sub> OAc extracted Na <sup>+</sup>	Water extracted Na <sup>+</sup>	Modified Schoonover GR	NH <sub>4</sub> OAc exchangeable Na <sup>+</sup>	GR t ha <sup>-1</sup>
1	Pothireddipally	10.3	1.645	9.2	15.4	20.8	20.4	12.8	8.0	7.6	3.6
2	Pothireddipally	8.9	1.122	5.6	16.2	22.8	21.5	13.4	9.4	8.1	4.2
3	Pothireddipally	10.0	0.520	8.8	14.0	19.8	19.4	11.7	8.1	7.7	3.6
4	Koduparthi	9.7	1.665	7.9	8.5	10.1	10.2	2.9	7.2	7.3	3.2
5	Koduparthi	9.6	0.396	7.8	10.5	12.1	12.0	4.8	7.3	7.2	3.3
6	Koduparthi	9.5	1.010	8.1	12.5	16.8	16.8	8.4	8.4	8.4	3.8
7	Appajipally	8.9	0.590	6.4	11.6	14.6	14.1	7.1	7.5	7.0	3.4
8	Appajipally	9.3	0.466	9.4	9.0	10.5	9.4	1.8	8.7	7.6	3.9
9	Appajipally	9.3	0.280	9.3	9.2	11.6	11.8	4.3	7.3	7.5	3.3
10	Vedirepally	8.9	0.578	9.1	8.4	9.4	9.8	2.1	7.3	7.7	3.3
11	Vedirepally	8.9	0.395	8.7	8.6	10.1	10.0	3.5	6.6	6.5	3.0
12	Vedirepally	8.9	0.458	7.1	11.7	15.2	14.6	2.9	12.3	11.7	5.5
13	Budhasamudram	9.7	0.856	7.9	10.5	12.5	10.4	3.4	9.1	7.0	4.1
14	Budhasamudram	9.4	1.050	8.0	14.8	21.2	18.5	12.1	9.1	6.4	4.1
15	Budhasamudram	9.2	1.222	9.2	13.5	19.3	17.9	10.9	8.4	7.0	3.8
16	Avancha	8.7	0.556	8.0	11.6	14.9	14.1	8.1	6.8	6.0	3.0
17	Avancha	8.8	0.254	6.3	8.4	9.6	8.9	1.6	8.0	7.3	3.6
18	Avancha	9.1	1.540	7.8	10.4	12.0	11.1	4.0	8.0	7.1	3.6
19	Nerelapally	9.2	1.615	8.0	12.4	15.4	15.6	7.0	8.4	8.6	3.8
20	Nerelapally	8.6	1.056	5.9	8.9	10.8	10.0	4.1	6.7	5.9	3.0
21	Nerelapally	8.9	1.121	6.0	8.8	11.2	9.9	3.1	8.1	6.8	3.6
	Mean	9.2	0.875	7.8	11.2	14.3	13.6	6.2	8.1	7.4	3.6

Correlation coefficient  $r = 0.794$ ; GR = Gypsum requirement; EC = Electrical conductivity; NH<sub>4</sub>OAc = Ammonium acetate.

the analysed period (Fig. 2). The recorded maximum summer temperature increased alarmingly from 38.8 °C in 2003 to 44.1 °C in 2015 indicating the intensity of dryness which increases the soil temperature by facilitating the evaporation of soil-water coupled with reduced vegetative cover. The PET increased from 1290 to 1755 mm, suggesting the negative soil-water balance for all the years. This trend of climatic factors indicated that extreme weather events like drought, high temperature, and heavy precipitation affect crop production through their interaction with soils and crops causing soil erosion, physical and chemical degradation (Wen-bin et al., 2014).

Considering the above factors, the generated information with respect to soil series characteristics, identified soil limitations, and crop wise land suitability index was integrated with cadastral data as described in Fig. 9 to prepare ALUP for the 19 villages of the study area (Table 9). For example, Lithic Ustorthents (Gummagonda) and Typic Haplustepts (Pullagiri) are the major soils of Pullagiri village. Cotton, maize and groundnut are the major cultivated crops. LSI indicates that soils of Gummagonda series are only marginally suitable (S3) for maize due to the limited depth. Soils are prone to erosion and poor in nutrient supplying capacity. However, groundnut, which is one of the major crops grown in this village during *rabi* season, could be extended to a larger cultivated area in place of cotton and maize to prevent soil erosion since it can act as a cover crop. Also, being a legume crop, it can also enrich the nitrogen content in soils. Watermelon (*Citrullus lanatus*), which occupies the sparse area, could be a viable option for the post-*rabi* season with optimum application of potassium fertilizer. Maize can be grown in *kharif* in soils with more than 50 cm depth (Typic Haplustepts). In a similar exercise, Lu et al. (2012) proposed water availability based agricultural land use plan for a south-central rural region of China.

### 3.8. Challenges and opportunities in exercising ALUP in India

Though the increase in food production might be achieved by horizontal expansion of agricultural land in Asia, Africa and South America (Foley et al., 2005; OECD-FAO, 2009; Macedo et al., 2012), countries like India and China lost considerable amount of agricultural land to urbanisation. In India, the amount of agricultural land converted to

industrial purpose is steadily increasing (0.7 million ha) in the last decade and more alarmingly, loss of agricultural land is largely accounted in states and districts which have highly productive lands (Pandey and Seto, 2014). Similarly, Verhoeve et al. (2015) identified that 15% of the statutory agricultural area is not factually used for agriculture in Flanders region of Belgium and they introduced the concept ‘virtual farmland’ as statutory agricultural land with non-agricultural land uses.

Although spatial policy allocates land for agricultural use within a restricting framework towards other activities, local farmers do introduce other non-agricultural activities and land-uses in agricultural land (Primdahl and Swaffield, 2010). In India, land use rights for specific land use is not clearly defined. Brick kilns within agricultural land is a typical example of diverting productive soils for construction purpose. Moreover, intensification, abandonment, and the widespread degradation adds to the pressure (Mishra, 2002; Varughese et al., 2009). As a result, the land suitability for crop cultivation reduced (Prokop and Poreba, 2012). This highlights the need to develop ALUP based on land suitability for crop production and also to generate improved information on potentially productive lands (Mosleh et al., 2017).

ALUP is often challenged by complex ownership structure controlled by the cadastral system. The implementation of proposed ALUP with uniform management encounters difficulties because of the preferences of the individual farmer. Hence, all the farmers in a village need to be brought under single consensus in order to effectively implement particular land use plan in each village covered by one or few soil series. For example, the collection of non-timber forest produce was the major livelihood activity of rural people in Gondia district of Central India. Participatory land use planning with the timely establishment of community nursery, water conservation measures and transplanting with the on-set of southwest monsoon increased rice yield by 56–112% in Gondia district (Chaturvedi et al., 2015). Moreover, adequate income generated from agriculture led to conservation of forest resources and sustaining the forest cover. In another exercise, Rhebergen et al. (2016) identified that slope, drainage and available water content of the soils determine their suitability for successful oil palm production in Ghana.

**Table 9**  
Data integration for village level agricultural land use planning.

Village	Major Soils	Soil limitations	Interpretation after interaction between scientists and stakeholders	Crops (LSI)	Agriculture land use plan
Pullagiri	Lithic Ustorthents	Depth is the major limitation for crop cultivation	Soil moisture is most limiting factor. Germination problems are experienced if first rains are sporadic	Maize(S3) Groundnut(S2)	a) Groundnut could be extended to larger area in place of cotton and maize to prevent soil erosion since it can act as a cover crop and, being a legume crop, enrich the soil with nitrogen.
	Typic Haplustepts	Depth, poor nutrient supplying capacity and water holding capacity	Erosion prone soils need conservation measures.	Cotton (S2) Maize (S2)	b) Watermelon is a viable crop if water is available during post-rabi season with optimum potassium application
	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Groundnut (S2) Cotton (S1) Maize (S2)	c) Maize can be grown in soils of Pullagiri series with depth > 50 cm
	Vertic Haplustepts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage.	High levels of sodium. Potential deficiency of micronutrients.	Rice (S1) Cotton (S2) Maize (S2) Rice (S1)	a) Yield of cotton, maize and rice can be increased if the subsoil sodicity is reclaimed with gypsum application. Gypsum at the rate of 3.2 t ha <sup>-1</sup> should be applied at the onset of monsoon or irrigation should be provided after its application in soil.
Ippalapally	Sodic Haplusterts	-do-	Tillage is difficult when too dry or too moist. Potential deficiency of P and micronutrients.	Cotton (S2) Maize (S2)	b) The above crops are sensitive to zinc deficiency and micronutrient fertilizers such as ZnSO <sub>4</sub> ·5H <sub>2</sub> O (19% Zn) and borax (10.5% B) should also be applied to alleviate the deficiency of zinc and boron, respectively.
	Sodic Haplusterts	-do-	-do-	Rice (S1) Cotton (S2)	c) Required quantity of urea could be applied along with farm yard manure or compost to supply nitrogen and reduce the soil pH
	Sodic Haplusterts	-do-	-do-	Maize (S2) Cotton (S2) Maize (S2)	a) Rice cultivation with ammonium sulphate as nitrogen source along with organic manures may reduce the sodicity problem in long-term.
	Sodic Haplusterts	-do-	-do-	Maize (S2) Rice (S1)	b) Gypsum application (3.0 – 3.6 t ha <sup>-1</sup> ) is essential for growing cotton and maize. Watermelon can be grown with residual moisture in post-rabi season.
Buddasamudram	Vertic Haplustepts	-do-	High levels of sodium. Potential deficiency of micronutrients.	Cotton (S2) Maize (S2) Rice (S1)	a) High ESP limits the yield of cotton and maize. Soil application of micronutrients may lead to fixation due to high pH and hence, foliar application of the same is essential.
	Vertic Haplustepts	-do-	High levels of sodium. Potential deficiency of micronutrients.	Cotton (S2) Maize (S2) Rice (S1) Groundnut (S2)	b) The soils can be cultivated to watermelon and chilli with residual moisture in the rabi season. Rice ( <i>kharif</i> ) followed by maize ( <i>rabi</i> ) can be remunerative cropping system for farmers under irrigated conditions.
	Vertic Haplustepts	-do-	High levels of sodium. Potential deficiency of micronutrients.	Cotton (S2) Maize (S2) Rice (S1)	a) Soils are highly suitable for rice. Application of soil test based fertilizers with respect to nitrogen (urea/ammonium sulphate) and phosphorus (di-ammonium-phosphate) along with foliar application of micronutrients Fe, Zn, Cu and B should be practiced for sustaining or increasing the yield of rice.
	Vertic Haplustepts	-do-	High levels of sodium. Potential deficiency of micronutrients.	Cotton (S2) Maize (S2) Rice (S1)	b) Groundnut can be grown in <i>kharif</i> season which can improve soil nitrogen followed by rice (irrigated) in the <i>rabi</i> season.
Marepally	Vertic Haplustepts	-do-	High levels of sodium. Potential deficiency of micronutrients.	Cotton (S2) Maize (S2) Rice (S1) Groundnut (S2)	a) Groundnut cultivation with soil test based fertilizer application is a remunerative option instead of cotton and pigeon pea
	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Cotton (S1) Maize (S2) Rice (S1)	b) The soils of <i>Typic Rhodustalfs</i> were deficient in P. In these soils, cotton, maize, pigeon pea and rice can be successfully grown in these with optimum fertilizer application and irrigation.
	Typic Usfluvents	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity	High infiltration and poor water holding capacity and leaching loss of nutrients.	Cotton (S1) Maize (S2) Rice (S1) Groundnut (S1) Cotton (S3) Maize (S3) Rice (S3)	c) The soils of <i>Vertic Haplustepts</i> need reclamation of sodicity and rice crop can be grown under irrigated conditions along with foliar application of micronutrients and other essential nutrients.
	Sodic Haplusterts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage	Tillage is difficult when too dry or too moist. Potential deficiency of P and micronutrients.	Cotton (S2) Maize (S2) Groundnut (S2)	a) The soils were sodic and deficient in nitrogen, zinc and boron. These soils are deep to very deep and have clay content more than 30% to retain soil moisture for longer period.
Vedirepally	Vertic Haplustepts	-do-	High levels of sodium. Potential deficiency of micronutrients.	Cotton (S2) Maize (S2) Groundnut (S2)	b) Subsoil sodicity is the major problem and the soils need to be reclaimed with gypsum application based on the magnitude (3.0-5.5 t ha <sup>-1</sup> ) of sodicity and organic manures.

(continued on next page)

Table 9 (continued)

Village	Major Soils	Soil limitations	Interpretation after interaction between scientists and stakeholders	Crops (LSI)	Agriculture land use plan
Thimmaipet	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Cotton (S1) Maize (S2) Groundnut (S1)	a) Growing cotton and maize should be avoided in Typic Ustifluvents as these soils are not suitable due to sandy texture and poor water holding and nutrient supplying capacity.
	Sodic Haplusterts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage	Tillage is difficult when too dry or too moist. Potential deficiency of P and micronutrients.	Cotton (S2) Maize (S2)	b) Groundnut is comparatively better suited crop than others considering the characteristics of soils.
	Typic Ustifluvents	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity	High infiltration and poor water holding capacity and leaching loss of nutrients.	Groundnut (S2) Cotton (S3) Maize (S3)	c) Cotton and maize can be grown in Typic Rhodustalfs with optimum fertilizer application and supplemental irrigation and in Sodic Haplusterts with management measures to reclaim subsoil sodicity.
	Lithic Ustorthents	Depth is the major limitation for crop cultivation	Soil moisture is limiting factor. Germination problems are experienced if first rains are sporadic	Groundnut (S2) Maize (S3)	a) The village is situated in the higher elevation and the soils were shallow, eroded and poor in nutrients and water holding capacity. The LSI indicates that growing of cotton, pigeon pea and rice in these soils should be avoided.
Gorita	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Cotton (S1) Maize (S2) Rice (S1)	c) Groundnut can be cultivated with soil conservation measures. They may be used for raising grasses or pasture development which can be used for cattle grazing.
	Typic Ustifluvents	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity	High infiltration and poor water holding capacity and leaching loss of nutrients.	Pigeon pea (S2) Cotton (S3) Maize (S3) Rice (S3)	a) Red and black soils occur in association with micro-topographical variations in Gorita. Hence, management options should consider the characteristics of soils.
	Sodic Haplusterts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage	Tillage is difficult when too dry or too moist. Potential deficiency of P and micronutrients.	Pigeon pea (S3) Cotton (S2) Maize (S2) Rice (S1)	b) The soils in the higher elevation, mostly <i>Typic Rhodustalfs</i> , should be cultivated with maize, groundnut, sorghum and pigeon pea across the slope to arrest soil erosion during rainy seasons.
					d) The soils in the lower topographic positions can be cultivated with rice and cotton except in <i>Typic ustifluvents</i> for which groundnut is the most suitable crop.
Cheguntha	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Pigeon pea (S2) Cotton (S1) Maize (S2) Rice (S1) Groundnut (S1)	a) The soils have high potential for irrigated agriculture and if managed well with sufficient quantity of applied fertilizer and irrigation, most of the crops can be successfully cultivated.
	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Cotton (S1) Maize (S2) Rice (S1) Groundnut (S1)	b) They were acutely deficient in Zn and B and soil application of $ZnSO_4 \cdot 5H_2O$ (19% Zn) and borax (10.5% B) is recommended for improving their available content in soils.
	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Cotton (S1) Maize (S2) Rice (S1)	a) The soils of <i>Typic Rhosudalfs</i> occur in higher topographical positions and soil conservation measures should be adopted to prevent soil erosion.
	Sodic Haplusterts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage	Tillage is difficult when too dry or too moist. Potential deficiency of P and micronutrients.	Groundnut (S1) Cotton (S2) Maize (S2) Rice (S1)	b) Cultivation of cover crops like cowpea, groundnut and maize in the rainy season can arrest the soil erosion.
Gummakonda	Lithic Ustorthents	Depth is the major limitation for crop cultivation.	Soil moisture is the most limiting factor. Germination problems are experienced if first rains are sporadic	Maize (S3) Groundnut (S2)	c) The <i>Sodic Haplusterts</i> , occurring in lower topographical positions can be cultivated with rice and cotton with gypsum application to reclaim the sodicity.
	Typic Rhodustalfs	Low in nutrient status and water holding capacity.	Poor nutrient supply limits crop yield. High in P fixation capacity.	Maize (S2) Groundnut (S1)	a) The soil depth varied from very shallow to deep. The <i>Lithic Ustorthents</i> occupied major area and were eroded, very shallow with poor nutrient and water holding capacity. These soils can be used for raising grasses or cultivated with groundnut in rainy season.
	Typic Ustifluvents	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity.	High infiltration and poor water holding capacity and leaching loss of nutrients.	Cotton (S3) Maize (S3) Groundnut (S2)	b) The deep soils, <i>Typic Rhosudalfs</i> can be cultivated with cotton and maize with required quantity of fertilizers and supplemental irrigation.
	Typic Haplusteps	Depth, poor nutrient supplying capacity and water holding capacity.	Erosion prone soils need conservation measures.	Cotton (S2) Maize (S2)	a) The soils were intensively cultivated with application of fertilizers and higher in Appajipally than other villages.

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Table 9 (continued)

Village	Major Soils	Soil limitations	Interpretation after interaction between scientists and stakeholders	Crops (LSI)	Agriculture land use plan
Koduparthi	Vertic Haplustepts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage	High levels of sodium. Potential deficiency of micronutrients.	Groundnut (S2)	c) The soils were deficient in Zn and B and soil application of $ZnSO_4 \cdot 5H_2O$ (19% Zn) and borox (10.5% B) should be followed.
				Rice (S2)	
	Typic Ustifluvents	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity	High infiltration and poor water holding capacity and leaching loss of nutrients.	Cotton (S2)	a) Major soils are <i>Typic Ustifluvents</i> and <i>Typic Rhodustalfs</i> . Cotton and maize occupy 91% of the cultivated area. b) However, the soils of <i>Typic Ustifluvents</i> were only marginally suitable for them. Hence, groundnut, which is better suited, should be cultivated in these soils. c) The soils of <i>Typic Rhodustalfs</i> could be cultivated with cotton and maize.
				Maize (S2)	
				Groundnut (S2)	
Allampally	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Rice (S1)	
				Cotton (S1)	
	Vertic Haplustepts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage	High levels of sodium. Potential deficiency of micronutrients.	Maize (S2)	
				Groundnut (S1)	
				Cotton (S2)	
Bhawajipally	Typic Ustifluvents	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity.	High infiltration and poor water holding capacity and leaching loss of nutrients.	Maize (S2)	a) The soils of <i>Typic Ustifluvents</i> need to be managed similar to Koduparthi.
				Cotton (S3)	
	Typic Haplustepts	Depth, poor nutrient supplying capacity and water holding capacity	Erosion prone soils need conservation measures.	Maize (S2)	b) The soils of <i>Typic Haplustepts</i> were moderately deep, erosion prone and occupied 60% of the cultivated area. c) Soil conservation <i>viz-d-viz</i> cultivation with cover crops is essential to prevent physical degradation of soils.
				Cotton (S2)	
				Rice (S2)	
Bhawajipally	Typic Rhodustalfs	Low in nutrient status and water holding capacity	Poor nutrient supply limits crop yield. High in P fixation capacity.	Maize (S2)	
				Cotton (S1)	
	Typic Rhodustalfs	Low in nutrient status and water holding capacity.		Rice (S1)	a) The soils of <i>Typic Rhodustalfs</i> occupied 70% of the cultivated area. These soils were used for cultivation of many crops and have the potential to support high yielding varieties if managed well. b) They were low in CEC and hence their nutrient supplying power is limited. c) Soil test based fertilizer application along with irrigation can increase yield of fertilizer responsive crops like maize and cotton.
				Cotton (S1)	
				Maize (S2)	
Pothreddipally	Lithic Ustorthents	Depth is the major limitation for crop cultivation.	Soil moisture is most limiting factor. Germination problems are experienced if first rains are sporadic.	Pigeon pea (S2)	
				Groundnut (S1)	
	Vertic Haplustepts	Sub soil sodicity, poor saturated hydraulic conductivity and drainage.	High levels of sodium. Potential deficiency of micronutrients.	Maize (S3)	
				Groundnut (S2)	
				Cotton (S2)	
Pothreddipally	Typic Rhodustalfs	Low in nutrient status and water holding capacity.	Poor nutrient supply limits crop yield. High in P fixation capacity.	Maize (S2)	a) Severe deficiency of nitrogen, zinc and boron limit the crop productivity in soils of Pothreddipally village. b) The soils of <i>Typic Rhodustalfs</i> and <i>Typic Haplustepts</i> occupied 90% of the cultivated area. Major crops grown in these soils were maize, cotton, rice (irrigated) and pigeon pea mostly under rainfed conditions. c) Soil application of $ZnSO_4 \cdot 5H_2O$ (19% Zn) and borox (10.5% B) should be followed to improve the Zn and B content in soils, respectively. d) The SQI of these soils indicate that crop productivity in these soils can be increased with irrigation and soil test based fertilizer application.
				Rice (S1)	
	Typic Haplustepts	Depth, poor nutrient supplying capacity and water holding capacity.	Erosion prone soils need conservation measures.	Pigeon pea (S2)	
				Groundnut (S1)	
				Maize (S2)	
Pothreddipally	Typic Haplustepts	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity.	High infiltration and poor water holding capacity and leaching loss of nutrients.	Cotton (S2)	
				Rice (S2)	
	Typic Ustifluvents	Sandy texture, structure less in sub surface, poor root anchorage, leaching loss of nutrients, poor water holding capacity.		Pigeon pea (S2)	
				Groundnut (S2)	
				Maize (S3)	

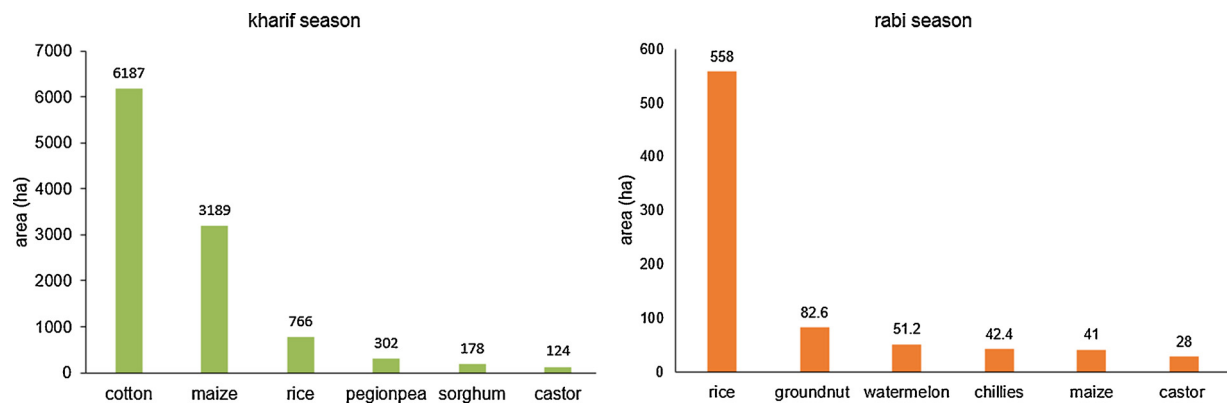


Fig. 8. Average cultivated area of major crops in the study area in the two crop seasons (monsoon season, *kharif* and winter season, *rabi*) during 2003–2015.

Therefore, the involvement of the farmers of the study area assumes greater significance in the decision-making processes, preparation and implementation of ALUP. In addition, the interaction between various stakeholders like agricultural extension workers, state government officials, and farmers with soil scientists is required to create awareness about the importance of sustainable management of soil resources (Jónsson et al., 2016). Thus, as suggested by Wiggering (2013), from a scientific perspective, we emphasize the need to increase the interaction between various specialist disciplines of natural resource management, to innovate and develop sustainable approaches for soil management. Moreover, Wiggering and Steinhardt (2015) suggested that an agricultural land use plan should be resource conserving and specific to the land characteristics. To demonstrate the applicability, practicability, and most importantly, the sustainability of proposed land-use plans, coordinated implementation strategies are necessary. As agricultural land use is determined by the will and interests of individual farmers, the choice of crop understandably follows current or expected future market conditions (Zhang et al., 2007; FAO, 2011). But, as observed in the present study, cultivation of deep rooted crops like cotton and pigeon pea in soils of Gummagonda and Pullagiri leads to unsustainable productivity and natural resource degradation. Hence,

apart from present study, future research programs focussing on evaluating the ALUP at field level could serve as a promotional approach to implement them in a sustainable manner. In addition, as suggested by Alkemade et al. (2014), research institutions should aim to contribute to the decision-making process by providing scientific knowledge and periodical monitoring. Also, from a scientific perspective alone, the various specialist disciplines must increase their interactions to develop systemic approaches for developing sustainable agricultural land use plans (Wiggering, 2013). Thus, given the less probability of cropland expansion, a further increase in food production can be achieved by facilitating proper crop allocations so as to adapt to the changing environment.

#### 4. Conclusions

- 1 For agricultural land use planning at village level, detailed soil resource inventory using LISS IV and DEM data helped to identify and map six soil series in a semi-arid dry agro-ecological region in the southern Telangana and the soils varied in depth, texture, water holding capacity, hydraulic conductivity, pH, organic carbon and other inherent properties.

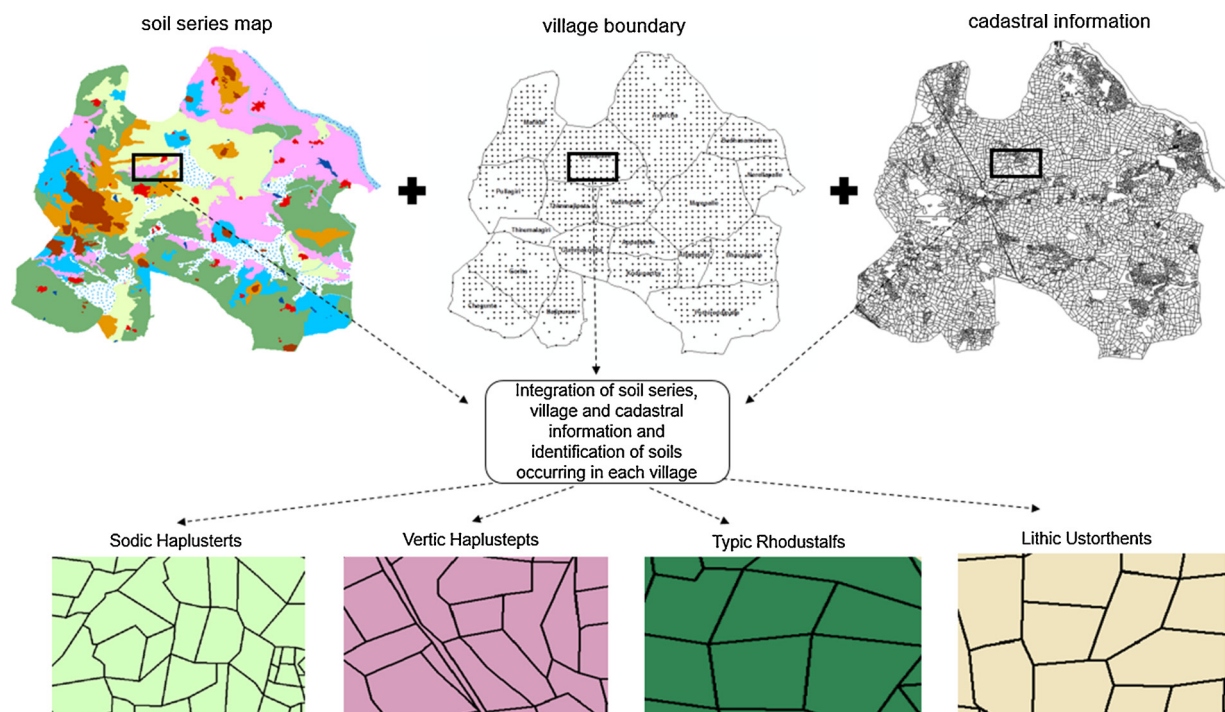


Fig. 9. Cadastral and village boundary superimposed on the soil map and integrated in GIS to extract the soil information at village and cadastral level.

- 2 A comparison of three land suitability evaluation methods using the soil-site characteristics showed that multi-criteria land suitability evaluation (MC-LSE) method performed better than parametric and Storie index (SI) methods in predicting the land suitability for major cultivated crops. The Kappa coefficient (K) showed moderate agreement between MC-LSE and parametric methods by poor agreement between MC-LSE and SI methods. Thus, our study demonstrated that care should be employed in selecting a method for evaluating land suitability for crop cultivation specific to agro-ecological conditions.
- 3 The high correlation of LSI derived by MC-LSE with crop yield proved the hypothesis of consideration of inherent soil properties will better represent the soil suitability for a given agricultural land use.
- 4 Integration of soil series data and their distribution, their constraints and potentials, the status of available nutrients, and suitability for cultivated crops helped profusely to derive a plan which could sustain agricultural production. However, the proposed agricultural land use plans need to be evaluated for their applicability, practicability, and sustainability. Hence, we emphasize that research institutions should aim to contribute to the decision-making process by providing scientific knowledge and periodical monitoring.

## Declaration of interest

The authors have no conflict of interest.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.landusepol.2018.08.007>.

## References

- Abrol, I.P., Dahiya, I.S., Bhumbla, D.R., 1975. On the method of determining gypsum requirement of soil. *Soil Sci.* 120, 30–36.
- Akinchi, H., Ozalp, A.Y., Turgut, B., 2013. Agricultural land use suitability analysis using GIS and AHP technique. *Comput. Electron. Agric.* 97, 71–82.
- Alkemada, R., Burkhard, B., Crossman, N., Nedkov, S., Petz, K., 2014. Quantifying ecosystem services and indicators for science, policy and practice. *Ecol. Indic.* 37, 161–162.
- Bai, Z., Dent, D., Wu, Y., de Jong, R., et al., 2013. Land degradation and ecosystem services. In: Rattan (Ed.), *Ecosystem Services and C Sequestration in the Biosphere*. Springer, Dordrecht Heidelberg, NY, London.
- Balakrishnan, S., Hanson, G.N., Rajamani, V., 1990. Pb and Nd isotope constraints on the origin of high-Mg and tholeiitic amphibolites, Kolar Schist Belt, South India. *Contrib. Mineral. Petrol.* 107, 279–292.
- Berger, K.C., Truog, E., 1939. Boron determination in soils and plants. *Ind. Eng. Chem. Anal. Ed.* 11, 540–545.
- Bhattacharyya, T., Pal, D.K., Deshpande, S.B., 1993. Genesis and transformation of minerals in the formation of red (Alfisol) and black (Inceptisols and Vertisols) soils on Deccan basalt in the Western Ghats. *India. Journal of Soil Science.* 44, 159–171.
- Bhattacharyya, T., Pal, D.K., Easter, M., et al., 2007. Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030. *Agric. Ecosyst. Environ.* 122, 84–94.
- Bhattacharyya, T., Chandran, P., Ray, S.K., Mandal, C., Tiwary, P., et al., 2015. Walkley Black recovery factor to reassess soil organic matter: indo Gangetic Plains and Black Soil Region areas case studies. *Commun. Soil Sci. Plant Anal.* 46 (20), 2628–2648.
- Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), *Methods of Soil Analysis Part 1, Physical and Mineralogical Methods*. SSSA Book Series No.5, second ed. SSSA and ASA, Madison, Wisconsin, USA, pp. 951–984.
- Bonfante, A., Bouma, J., 2015. The role of soil series in quantitative land evaluation when expressing effects of climate change and crop breeding on future land use. *Geoderma* 259–260, 187–195.
- Bouma, J., 1989. Using soil survey data for quantitative land evaluation. In: Stewart, B.A. (Ed.), *Advances in Soil Science Vol. 9*. Springer Verlag, New York, pp. 177–213.
- Bouma, J., 1994. Sustainable land use as a future focus for pedology? *Soil Sci. Soc. Am. J.* 58 (3), 645–646.
- Bray, R.H., Kurtz, L.T., 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.* 59, 39–45.
- Central Ground Water Board, 2013. *Ground Water Year Book 2012–13*. Ministry of Water Resources. Govt. of India, Faridabad.
- Chatterji, S., Tiwary, P., Sen, T.K., et al., 2014. Land evaluation for major crops in the Indo-Gangetic Plains and black soil regions using fuzzy model. *Curr. Sci.* 107 (9), 1502–1511.
- Chaturvedi, A., Hajare, T.N., Patil, N.G., Chaturvedi, A., Mungole, A., Kamble, R., 2015. Land use planning issues in management of common property resources in a backward tribal area. *Land Use Policy* 42, 806–812.
- Chaudhari, S.K., 2001. Saturated hydraulic conductivity, dispersion, swelling and exchangeable sodium percentage of different textured soils as influenced by water quality. *Commun. Soil Sci. Plant Anal.* 32, 2439–2455.
- Chauhan, R.P.S., Chauhan, C.P.S., 1979. A modification to Schoonover's method of gypsum requirement determination of soil. *Aust. J. Soil Res.* 17 (2), 367–370.
- Chesnin, L., Yien, C.H., 1950. Turbidimetric determination of available sulphates. *Soil Sci. Soc. Am. Proc.* 15, 149–151.
- Cohen, J., 1960. A coefficient of agreement for nominal scales. *Educ. Psychol. Meas.* 20, 37–46.
- Dagar, J.C., Sharma, H.B., Shukla, Y.K., 2001. Raised and sunken bed technique for agroforestry on alkali soils of northwest India. *Land Degrad. Dev.* 12, 107–118.
- De la Rosa, D., Anaya-Romero, M., Diaz-Pereira, E., Heredia, N., Shahbazi, F., 2009. Soil-specific agro-ecological strategies for sustainable land use - a case study by using MicroLEIS DSS in Sevilla Province (Spain). *Land Use Policy* 26, 1055–1065.
- Dutta, D., Ray, S.K., Reddy, R.S., Budihal, R.S., 2001. Characterization and classification of paleosols in part of South India. *J. Indian Soc. Soil Sci.* 49, 726–734.
- El Baroudy, A.A., 2016. Mapping and evaluating land suitability using a GIS-based model. *Catena* 140, 96–104.
- Elsheikh, R., Rashid, A., Shariff, B.M., Amiri, F., Ahmad, N.B., Balasundram, S.K., Soom, M.A.M., 2013. Agricultural Land Suitability Evaluator (ALSE): a decision and planning support tool for tropical and subtropical crops. *Comput. Electron. Agric.* 93, 98–100.
- Erickson, D.L., Lovell, S.L., Méndez, V.E., 2013. Identifying, quantifying and classifying agricultural opportunities for land use planning. *Landsc. Urban Plan.* 118, 29–39.
- FAO, 1976. *A Framework for Land Evaluation*. Food and Agriculture Organisation of the United States. Soil Bulletin No.32. FAO, Rome.
- FAO, 1996. *Guidelines for Agricultural Land Use Planning*. FAO Development series I, Rome.
- FAO, 2011. *Save and Grow: A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*. Food and Agriculture Organization of the United Nations, Rome.
- Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., et al., 2005. Global consequences of land use. *Science* 309, 570–574.
- Foley, J.N., Ramankutty, K.A., Brauman, E.S., Cassidy, J.S., et al., 2011. Solutions for a cultivated planet. *Nature* 478, 337–342.
- Fontes, M.P.F., Fontes, R.M.O., Carneiro, P.A.S., 2009. Land suitability, water balance and agricultural technology as a Geographic-Technological Index to support regional planning and economic studies. *Land Use Policy* 26, 589–598.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soil Analysis Part 1, Physical and Mineralogical Methods*. SSSA Book Series No.5, second ed. SSSA and ASA, Madison, Wisconsin, USA, pp. 383–412.
- Geetha Sireesha, P.V., Naidu, M.V.S., 2013. Studies on Genesis, characterisation and classification of soils in semi-arid agro-ecological region: a case study in Banganapalle mandal of Kurnool district in Andhra Pradesh. *J. Indian Soc. Soil Sci.* 61 (3), 167–178.
- Goel, V.L., Behl, H.M., 2002. Selection of *Leucaena* species for afforestation and amelioration of sodic soils. *Land Degrad. Dev.* 13, 387–393.
- Gupta, R.N., Singh, A.N., 2005. A modified Schoonover method for determining gypsum requirement of saline sodic soils. *J. Indian Soc. Soil Sci.* 53 (1), 123–124.
- Gupta, R.N., Singh, K., Singh, S., 2001. Suggestions for improvement of Schoonover method for determination of gypsum requirement for sodic soils. Presented at 66<sup>th</sup> Annual Convention of Indian Society of Soil Science at Udaipur.
- He, Y., Yao, Y., Chen, Y., Ongaro, L., 2011. Regional Land suitability assessment for tree crops using remote sensing and GIS. *Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM) IEEE* 354–363.
- Jónsson, J.O.G., Davíðsdóttir, B., Jónsdóttir, E.M., Kristinsdóttir, S.M., Rognarsdóttir, K.V., 2016. Soil indicators for sustainable development: a transdisciplinary approach for indicator development using expert stakeholders. *Agric. Ecosyst. Environ.* 232, 179–189.
- Kadu, P.R., Vaidya, P.H., Balpande, S.S., Satyavathi, P.L.A., Pal, D.K., 2003. Use of hydraulic conductivity to evaluate the suitability of Vertisols for deep-rooted crops in semi-arid parts of central India. *Soil Use Manag.* 19, 208–216.
- Keren, R., Kauschansky, P., 1981. Coating of calcium carbonate on gypsum particle surfaces. *Soil Sci. Soc. Am. J.* 45, 1242–1244.
- Klingebiel, A.A., Montgomery, P.H., 1966. *Land capability classification*. Agricultural Hand Book No. 210. USDA, Washington.
- Klute, A., 1986. Water retention: laboratory methods. In: A. Klute (ed) *Methods of Soil Analysis*. 2nd ed., pt. 1, Madison, WI: pp. 635–662.
- Klute, A., Dirksen C., 1986. Hydraulic conductivity and diffusivity: laboratory measurements. In: A. Klute (ed) *Methods of Soil Analysis*, 2nd edition, pt. 1, Agron.

- Monograph No. 9, Madison, WI: pp. 687–734.
- Lal, R., 2012. Restoring degraded lands and the flow of its provisioning services. *Proceedings of the 4th International Conference on Drylands, Deserts and Desertification Ben Gurion University of the Negev, Sde-Boqer*. p. 65.
- Lindsay, W.L., Norvell, W.A., 1978. Development of DTPA soil test for zinc, iron, manganese and copper. *Soil Sci. Soc. Am. J.* 42, 421–428.
- Lu, H.W., Huang, G.H., Zhang, Y.M., He, L., 2012. Strategic agricultural land-use planning in response to water-supplier variation in a China's rural region. *Agric. Syst.* 108, 19–28.
- Macedo, M.N., DeFries, R.S., Morton, D.C., Stickler, C.M., Galford, G.L., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proc. Natl. Acad. Sci. U. S. A.* 109, 1341–1346.
- Maji, A.K., Obi Reddy, G.P., Thayalan, S., Walke, N.J., 2005. Characterization and classification of land forms and soils over basaltic terrain in Sub-humid tropics of Central India. *J. Indian Soc. Soil Sci.* 53 (2), 154–162.
- Mandal, D.K., Mandal, C., Velayutham, M., 2001. Development of land quality index for sorghum in Indian semi-arid tropics. *Agric. Syst.* 70, 335–350.
- Mandal, C., Mandal, D.K., Bhattacharyya, T., Patil, N.G., et al., 2014. Revisiting agro-ecological sub-region of India – a case study of two major production zones. *Curr. Sci.* 107, 1519–1536.
- Mishra, V., 2002. Population growth and intensification of land use in India. *Int. J. Popul. Geogr.* 8, 365–383.
- Mishra, A., Sharma, S.D., Khan, G.H., 2002. Rehabilitation of degraded sodic lands during a decade of *Dalbergia sissoo* plantation in Sultanpur district of Uttar Pradesh, India. *Land Degrad. Dev.* 13, 375–386.
- Mosleh, Z., Salehi, M.H., Fasalhod, A.A., Jafari, A., Mehnatkesh, A., Borujeni, I.E., 2017. Sustainable allocation of agricultural lands and water resources using suitability analysis and mathematical multi-objective programming. *Geoderma* 303, 52–59.
- Mubarak, A.R., Nortcliff, S., 2010. Calcium carbonate solubilization through H-proton release from some legumes grown in calcareous saline sodic soils. *Land Degrad. Dev.* 21, 24–31.
- Nayak, R.K., Sahu, G.C., Nanda, S.S.K., 2002. Characterisation and classification of the soils of central research station, Bhubaneswar. *Agropedology* 12, 1–8.
- Nguyen, T.T., Verdoodt, A., Tran, V.Y., Delbecq, N., Tran, T.C., Ranst, E.V., 2015. Design of a GIS and multi-criteria based land evaluation procedure for sustainable land-use planning at the regional level. *Agric. Ecosyst. Environ.* 200, 1–11.
- O'Geen, A.T., Southard, S.B., Southard, R.J., 2008. A Revised Storie Index for Use With Digital Soil Information. ANR publication 8335, pp. 1–11.
- OECD-FAO, 2009. OECD-FAO Agricultural Outlook 2009–2018. OCED Publishing and FAO, Italy.
- Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of Available Phosphorus in Soils by Extraction With Sodium Bicarbonate. Circular of United States Department of Agriculture pp.939.
- Pal, D.K., Bhattacharyya, T., Sahrawat, K.L., Wani, S.P., 2016. Natural chemical degradation of soils in Indian semi-arid tropics and remedial measures. *Curr. Sci.* 110 (9), 1675–1682.
- Pandey, B., Seto, K.C., 2014. Urbanization and agricultural land loss in India: comparing satellite estimates with census data. *J. Environ. Manage.* 148, 53–66.
- Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate smart soils. *Nature* 532, 49–57.
- Piper, C.S., 1966. *Soil and Plant Analysis*. Reprinted by Hans Publishers, Bombay, India (1966).
- Prasad, J., 2000. Application of fertility capability classification system in soils of a Watershed in semi-arid tropics. *J. Indian Soc. Soil Sci.* 48 (2), 329–338.
- Primdahl, J., Swaffield, S. (Eds.), 2010. *Globalisation and Agricultural Landscapes – Change Patterns and Policy Trends in Developed Countries*. Cambridge University Press, Cambridge.
- Prokop, P., Poreba, G.J., 2012. Soil erosion associated with an upland farming system under population pressure in northeast India. *Land Degrad. Dev.* 23, 310–321.
- Qadir, M., Schubert, S., Ghafoor, A., Murtaza, G., 2001. Amelioration strategies for sodic soils: a review. *Land Degrad. Dev.* 12, 357–386.
- Reddy, R.S., 2006. Methodology for correlation of soil series in soil survey and mapping. *Agropedology* 16 (1), 1–11.
- Rhebergen, T., Fairhurst, T., Zingore, S., Fisher, M., Oberthür, T., Whitbread, A., 2016. Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana. *Eur. J. Agron.* 81, 1–14.
- Richards, L.A., 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. USDA Agric. Handbook 60, Washington, D. C.
- Riquier, J., Bramao, D.L., Comet, J.P., 1970. A new system of soil appraisal in terms of actual and potential productivity. *FAO Soil Resources, Development and Conservation Service, Land and Water Division*. FAO, Rome 38p.
- Sarkar, A., Ghosh, A., Panik, A., 2014. Multi-criteria land evaluation for suitability analysis of wheat: a case study of a watershed in eastern plateau region, India. *Geo-Spatial Inform. Sci.* 17 (2), 119–128.
- Schafer, W.M., Singer, M.J., 1976. A new method of measuring shrink-swell potential using soil pastes. *Soil Sci. Soc. Am. J.* 40, 805–806.
- Schollenberger, C.J., Simon, R.H., 1945. Determination of exchange capacity and exchangeable bases in soil by Ammonium acetate method. *Soil Sci.* 59, 13–24.
- Soil Survey Staff, 2014. *Keys to Soil Taxonomy*, twelfth ed. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC.
- Srinivasarao, Ch., Lal, R., Prasad, J.V.S.N., et al., 2015. Potential and challenges of rainfed farming in India. *Adv. Agron.* 133, 1–69.
- Stavi, I., Lal, R., 2015. Achieving zero net land degradation: challenges and opportunities. *J. Arid Environ.* 112, 44–51.
- Storie, R., 1978. *Storie Index Soil Rating*. University of California Division of Agricultural Sciences Special Publication, Oakland 3203.
- Subbiah, B.V., Asija, C.L., 1956. A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci.* 25, 32.
- Sumner, M.E., Miller, W.P., 1996. Cation exchange capacity and exchange coefficients. In: Sparks, D.L., Page, A.L., Helmke, P.A. (Eds.), *Methods of Soil Analysis. Part 3, Chemical Methods*. Soil Science Society of America, Madison, Wisconsin, USA, pp. 1201–1229.
- Sys, C., Van Ranst, E., Debaveye, J., 1991. *Land Evaluation, Part I. Principles in Land Evaluation and Crop Production Calculations*. General administration for development cooperation, Brussels, pp. 40–80.
- Sys, C., Van Ranst, E., Debaveye, J., 1993. *Land Evaluation. Part 3: Crop Requirements*. Agricultural Publications 7, 3. General Administration of Development Cooperation of Belgium, Brussels pp.199.
- Tamgadge, D.B., Gajbhiye, K.S., Bankar, W.V., 2002. Evaluation of soil suitability for paddy cultivation in Chhattisgarh – a parametric approach. *J. Indian Soc. Soil Sci.* 50, 81–88.
- Vara Prasad Rao, A.P., Naidu, M.V.S., Ramavatharam, N., Rama Rao, G., 2008. Characterisation, classification and evaluation of soils on different landforms in Ramachandrapuram mandal of Chittoor district in Andhra Pradesh for sustainable land use planning. *J. Indian Soc. Soil Sci.* 56 (1), 23–33.
- Varughese, G., Lakshmi, K., Kumar, A., Rana, N., 2009. *State of Environment Report: India, 2009*. State of Environment Report: India, 2009.
- Vasu, D., Singh, S.K., Tiwary, P., Chandran, P., Ray, S.K., Duraisami, V.P., 2017. Pedogenic processes and soil-landform relationships for identification of yield limiting properties. *Soil Res.* 55 (3), 273–284.
- Verhoeve, A., Dewaelheyns, V., Kerselaers, E., Rogge, E., Gulinck, H., 2015. Virtual farmland: grasping the occupation of agricultural land by non-agricultural land uses. *Land Use Policy* 42, 547–556.
- Walke, N., Obi Reddy, G.P., Maji, A.K., Thayalan, S., 2012. GIS-based multi criteria overlay analysis in soil-suitability evaluation for cotton: a case study in the black soil region of Central India. *Comput. Geosci.* 41, 108–118.
- Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29–38.
- Wen-bin, W., Qiang-yi, Y., Peter, V.H., Liang-zhi, Y., Peng, Y., Hua-jun, T., 2014. How could agricultural land systems contribute to raise food production under global change? *J. Integr. Agric.* 13 (7), 1432–1442.
- Whitney, D.A., 1998. Soil salinity. In: Brown, J.R. (Ed.), *Recommended Chemical Soil Test Procedures for the North Central Region*. North Central Regional Publication. 221 (Revised). Missouri Agric. Exp. Stn. Bull., pp. 59–60 SB1001.
- Wiggering, H., 2013. The geology – land use – nexus. *Environ. Earth Sci.* 71 (12), 5037–5044.
- Wiggering, H., Steinhardt, U., 2015. A conceptual model for site specific agricultural land use. *Ecol. Modell.* 295, 42–46.
- Williams, C.H., Steinbergs, A., 1959. Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Aust. J. Agric. Res.* 10, 340–352.
- Yalew, S.G., van Griensven, A., van der Zaag, P., 2016. AgriSuit: a web-based GIS-MCDA framework for agricultural land suitability assessment. *Comput. Electron. Agric.* 128, 1–8.
- Yu, J., Chen, Y., Wu, J., 2011. Cellular automata based spatial multi-criteria land suitability simulation for irrigated agriculture. *Int. J. Geogr. Inf. Sci.* 25 (1), 131–148.
- Zhang, W., Ricketts, T.H., Kremen, C., Carney, K., Swinton, S.M., 2007. Ecosystem services and dis-services to agriculture. *Ecol. Econ.* 64, 253–260.
- Zolekar, R.B., Bhagat, V.S., 2014. Use of IRS P6 LISS-IV data for land suitability analysis for cashew plantation in hilly zone. *Asian J. Geoinform.* 14 (3), 23–35.