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Quantitative land evaluation based on fuzzy-multi-criteria spatial model for sustainable land-use planning

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Abstract

Evaluating land according to its suitability and soil mapping is an important contribution for agricultural land use planning. Therefore FAO system was used to produce suitability sub classes for horticultural and field crops. Land capability map was produced at a scale of 1:10,000 using soil information according to USDA criteria. All attributed insight analysis were ranked according to them priority and performed with analysis criteria to provide the spatial extent of soil suitability and capability. Also a new dimension was added in the spatial model to determine capability index for soil suitability to different irrigation methods. The overall accuracy of used spatial model is 89% and the validation was carried out through field work. The significance of the created model for mapping is being at a detailed survey level. The landforms were mapped using SRTM combined with sentinel satellite image of the studied area. Accordingly landforms were represented by 33 soil profiles collected in 2015. Another 32 auger profile samples were dug to identify the boundaries among landform units. The capability units were produced in association with geomorphology units. The study shows that 662.4 km^2 (33%), 715.9 km^2 (35.6%), 85.8 km^2 (4.3%), 25.4 km^2 (1.3%), 490.6 km^2 (24.4%) and 30.0 km^2 (1.5%) of the area were categorized in II, III, IV, and V, VI (sand dunes and quarries (and VII (Rock outcrops) land classes respectively. The produced suitability subclasses demonstrates that the land use must be planned for according to identified land capability classes (LCC) to maximize agricultural productivity and sustain the land resources for future generations.

Keywords Land capability · Land forms · Soil data · Spatial analysis · Land use planning

Introduction

Proper productivity and its sustainability require appropriate management of land resources. To develop a sustainable management plan requires identifying a specific factor for agricultural production using a selected land evaluation system. Spatial modeling provides a good platform for integration of multi-criteria factors to obtain a single product.

Land is a limited valuable resource; therefore a wise management should be strictly applyed for the maximum avails (Panhalkar 2011; Panhalkar et al. 2014; AbdelRahman et al. 2017). FAO land evaluation (LE) procedure and USDA land capability classification (LCC) were utilized for quantitative land evaluation (QLE) for soil site suitability. Land suitability (LS) has been used to assess suitability subclasses for different crops and hence, help in generating cropping pattern. LE is following a scientific procedure used to assess land constraints and its potential for agricultural purposes (Rossiter 1996; FAO 2007). LE is a useful tool to identify a specific part of land for specific crops to attain highest possible yield (Elsheikh 2015). LE is the process stablished to predict land performance over time depending on particular kinds of uses (Van Diepen et al. 1991; Rossiter 1996; FAO 2007). These estimated predictions are the guide used in the strategic land use decision making (Mohammd et al. 2011). Therefore, soil resource inventories are the primarily traditional bases for LE, obtained through soil surveys. Land forms and features are affecting soils and influence their geomorphic evolution (Schaetzl and Anderson 2005). Detailed soil properties in association with land forms units are initially used mainly to match the requirement of different crop production systems i.e.(crops, fertilization, rotations,

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varieties conservation measures, and other land practices) (Bibby et al. 1991; Klingebiel 1991).

This system of the land capability (LC) approach, the general classes is grouped depending on soils types and their ability for production in term of agricultural use (Rossiter and Van 1997). The soil map is a remarkable potential complex of scientific nature to solve agriculture problems in practice (Rushemuka et al. 2014). However, its information must be explained in an easy way that has meaning to the end user. This could solve the challenges of using these maps to work in a trans-disciplinary fashion (Wielemaker et al. 2001; Bui 2004). Those challenges could be solved by using GIS spatial model. The soil map offers a remarkable potential to constitute a tool to solve agriculture problems, in practice; however, it remains underutilized because of its complex scientific nature (Rushemuka et al. 2014). Soil scientists have realized the challenges of using these maps to work in a trans-disciplinary fashion (Wielemaker et al. 2001; Bui 2004). The information of the soil map must be explained in an easy way that has meaning to the land owners, decision makers and land-use managers.

The developing countries are nominated by over-exploitation of natural resources, scarcity of inputs like chemical fertilizers and intensive agriculture (Fresco et al. 1991; Lanen et al. 1992). All of this could lead to over-misuse of normal assets. Analysis of LE for crop suitability is resolving these glitches by giving better land-utilize alternatives to the agriculturists (Martin and Saha 2009). Constant routine with regards to fixed pattern of single cropping system lead with time to deterioration of soil health, which reduce soil pliability for preserving productivity (AbdelRahman et al. 2016). Consequently results in yield decrease, and even use of mineral composts cannot enhance the productivity as required. (Oz and Friedman 2001). Hence LCC and LE analysis for crop suitability is essential under various soil systems. LE cannot be driven from remote sensing (RS) data alone unless the soil and climate data are integrated with RS data in GIS platform for any specific area. Through RS data; various physiographic units and site characteristics are delineated. However, profiles analyses of physio-chemical and biological characteristics of the soils are essential inputs for commencing LE. Soil survey data is a major input for generation of soil map which helps in deriving LE for a specific crop and cropping system analysis. For this purpose the geographical information system (GIS) is used to integrate RS data and soil survey information to assess both of LE and LCC. Profitable agricultural products are not being gained merely by intensive mechanization and fertilizer application without the correct land use (Taffa 2002). Therefore LE is needed to develop an optimal decision to support the agricultural development in the study area. Most of the study area is a recent reclaimed area through the last three decades, located adjacent to the old Nile valley in west

Minya Governorate in Egypt. The uncontrolled use of land resources caused degradation of the soil and the overexploitation of groundwater (Hamade 2012). Such new reclaimed areas in Egypt are suffering from long standing water management problems (Azzam 2016).

The geodatabase of land use/land cover and temperature was generated from data derived from Landsat OLI RS satellite, soil survey and climatic data of the nearest station then integration analysis of all these data performed in the geographic information system GIS environment. The USDA LCC was used to delineate arable and non-arable lands then non-arable areas were removed from the database using mask analysis to be evaded from LE analysis. All LE parameters, viz. soil depth, slope, texture, course fragments, and erosion under various land units were estimated and evaluated to determine suitability subclasses.

The study area "west Minya Governorate" was chosen between the old Nile valley and the promising reclamation area "west-west Minya" according to the state development plan. Agricultural expansion in the area is carried out by the local population and some agricultural companies. The importance of expanding agricultural investment is to ensure that the needs of the Egyptian population are met. The Land Evaluation (LE) is a site assessment system that helps in making decisions for suitable land use. Combined with climatic parameters and soil characteristics, LE considers site of the land resource, meanwhile each land parcel is weighted with numerically rank based on soil profile location. This help to build a technical framework for sustainable use of the resources. For agriculture, each soil is classified according to LE into groups rated to its suitability for a specific agricultural use, either field and horticultural crops or both. Then, a relative value is determined for each group. The land evaluation is based on data from Soil Survey, soil analysis, and environmental parameters. Identifying areas of highly suitable for agricultural is a main input to plan a reclamation development. Therefore the main objective of this study is to create Fuzzy-Multi-Criteria spatial model to quantitatively assess land evaluation based for sustainable land use planning.

Materials and methods

Study area

The study area is located between latitudes 27°35′ and 28°47′ N and longitudes 30°20′ and 30°43′ E, at the western of River Nile as shown in Fig. 1. It covers around 2010 km^2 in El-Minya Governorate, Egypt. The area bounded by River Nile from the East, the limestone plateau in the West, Beni Suef Governorate from the North and Assiut Governorate from the South. The total area of El-Minya Governorate is
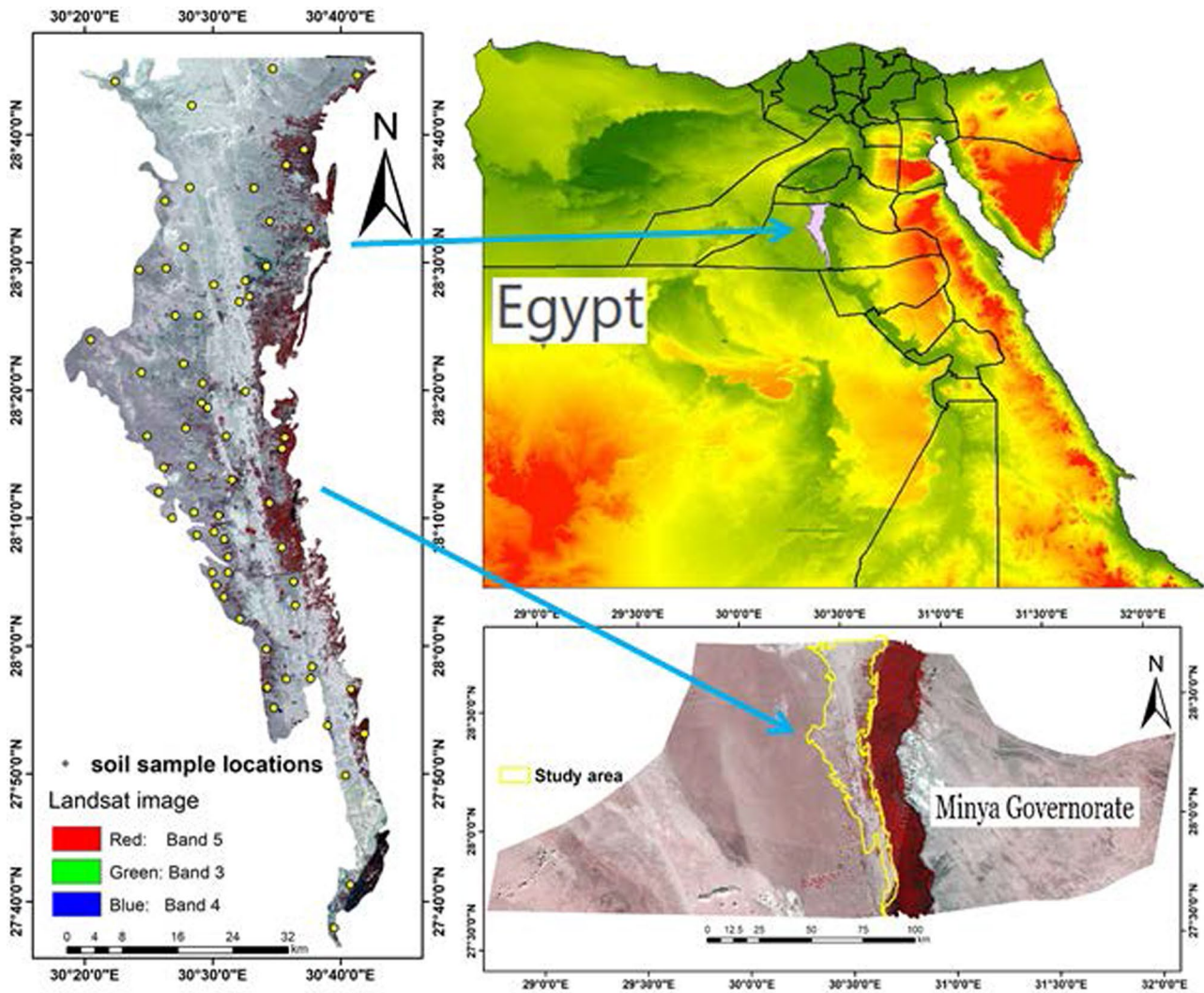
Fig. 1 Location map of the study area

32,279 km^2, from which 30,439 km^2 is desert lands while the rest of the governorate is agricultural lands.

Remote sensing data and generation of thematic maps

Remote sensing data used in this study are Landsat satellite (OLI), for land use and land cover mapping, and SRTM data for generating length and degree of slope from 1 to 3 arc-seconds SRTM data (downloaded from http://www.usgs.gov). ArcGIS 10.4.1 was used to produce all maps including land form units. The rating developed by FAO (2007) was used to reclassify different thematic layers using reclassify tool. All layers of the different levels of soil parameters were weighted and overlay to produce soil capability units and to define land suitability subclasses. The overall accuracy of classified image was of 93.7% and Kappa coefficient was

of 0.83. Generally, classification result with Kappa value between 0.70 and 0.85 is believed to be acceptable (Monserud 1990; Temesgen et al. 2017a, b). Thus, the classified image was in agreement with validated information built in the data set.

Climate, geomorphological and geological setting

According to Korany et al. (2006) the area climate is classified as arid to semi-arid; rainless, dry. the region is having a hot summer while winter is mild. Winter has rare precipitation. In the last 15 years; average rainfall values roved from nearly 23.10–33.20 mm/year, while was 4897.90 mm/year for the evapotranspiration at El Minia. The temperatures are ranged from 4.5 °C to 20.5 °C and from 20.5 °C to 37.7 °C during January and August respectively. Relative humidity in the area is varying with small scale from 68% to over

70% in January and June respectively. Two high calcareous plateaus are bounding the River Nile and it runs between both to the east and west. The plateaus' slope is about 0.1 m/km from south to north (Korany et al. 2006). According to the climatic data, soil temperature and moisture regimes are thermic and torric respectively, according to soil taxonomy classification 2014. According to Ahmed et al., (2016) Geomorphologically, in the area from west to east, two units are dominated; (a) limestone plateau and (b) old alluvial plain. (a) Sands and gravels alluvial deposits cover the limestone plateau. This structural formation is bounding both sides east and west of the Nile Valley from, and (b) in the western side of the valley, lies adjacent to the cliff of plateau. It includes the new reclaimed land in west of the valley which irrigated by groundwater in the western desert.

Soil-physiography

Physiographic map has been generated using the analysis introduced by Zinck and Valenzuala (1990) by overlaying Landsat image over SRTM data. The locations of digged soil profiles sited in transects cover all mapping units. 33 profiles were digged, and described according to the FAO guide (1990). Samples analyzes were estimated for their main characteristics of physical and chemical properties according to (USDA 2012). Consequently (USDA 2014) was used to produce Soil Taxonomy of the investigated soil profiles. Azzam (2016) found that there are two soil orders are detected in the west of Minya Governorate i.e. Aridisols, prevailing soil order in the examination territory and Entisols.

Spatial model

Fuzzy Overlay (Spatial Analyst) model was used in this study to combine fuzzy membership of all raster data together, based on selected overlay type determined with the rate and weight of each soil parameters. It required to be applied to raster with values that range between 0 and 1. Fuzzy Membership were implement to transform the input raster into a 0 to 1 scale, which used as indicating the strength of a membership in a set, based on a specified fuzzification algorithm.
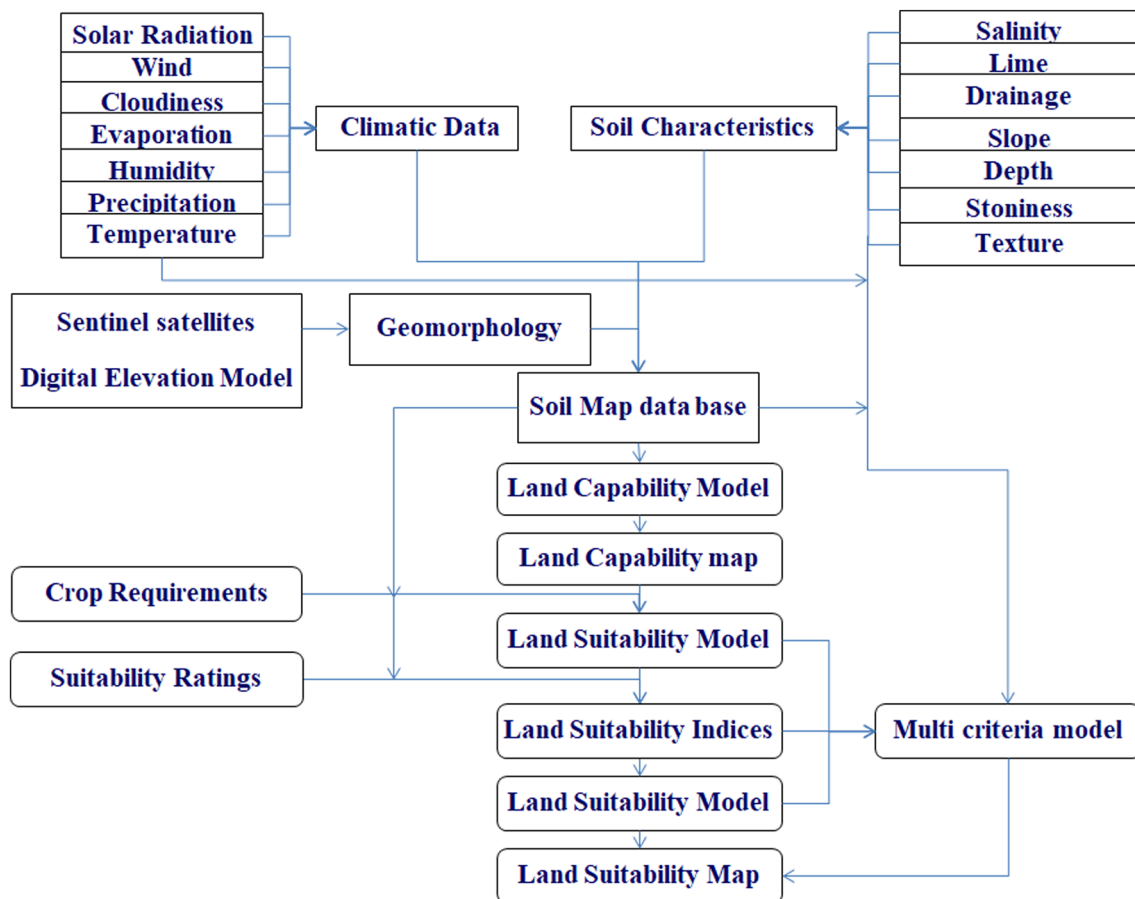

Fig. 2 Data processing flow chart for generating land evaluation maps

Land evaluation classification (LEC)

The studied soils were examined for their suitability for agriculture development sing FAO system (2007). Also soils were examined for their capabilities and limitations using U.S.SCS (1992). The followed steps of the methodology procedures are diagramed in the next flow chart (Fig. 2).

The capability factor maps were developed using RS data, i.e. slope in percent was generated using ASTER GDEM and land use map was produced using Landsat-8 OLI_TIRS 2017. The different layers of the different LC criteria were determined based on USDA (1973) as shown in Fig. 3, and overlaid and analyzed through intersection to obtain LCC. ArcGIS various extensions (10.4) were used to measure, compare and to analyze the land use and its capability class to plan land uses. The plant growth could be restricted by soil stoniness content and accordingly restrict land use and its management (Bibby et al. 1991; Rees 1995). Due to this fact, stoniness which was obtained from the field survey has been considered in the LCC of this study. USDA (1961) and Panhalkar (2011) stated that among the soil physical characteristics; depth and texture are the main basis used to distinguish between LC classes. Shallowness has indirect effect on crop growth. The low accessibility of soil depth

affect directly on roots zone and their hollowness from adequate ability of nutrient uptake (Bibby et al. 1991; Taffa 2002). While there are associated factors has direct effect such as texture and nutrient availability. Soil depth and texture maps were generated from field survey and laboratory analysis of the augers and profiles samples. Soil depth is a major element in the drainage system in the field. For this Rees (1995) stated the importance of estimating the drainage classes; poor and excess drainage which inhibits plant growth or moderate and well drainage which facilitate plant growth. Therefore drainage factor was considered and determined to calculate the LC classes in the area. Drainage map of the studied area obtained from the land survey and digged profiles. The thematic layers for CaCO3 and clay content, water table (WT) depth, EC, pH, SAR, OM, and Bulk density (BD) were created in ArcGIS 10.4 using the weighted average for each land from unit. These layers were matched together to assess the land capability classes.

Soil suitability for irrigation (SSI)

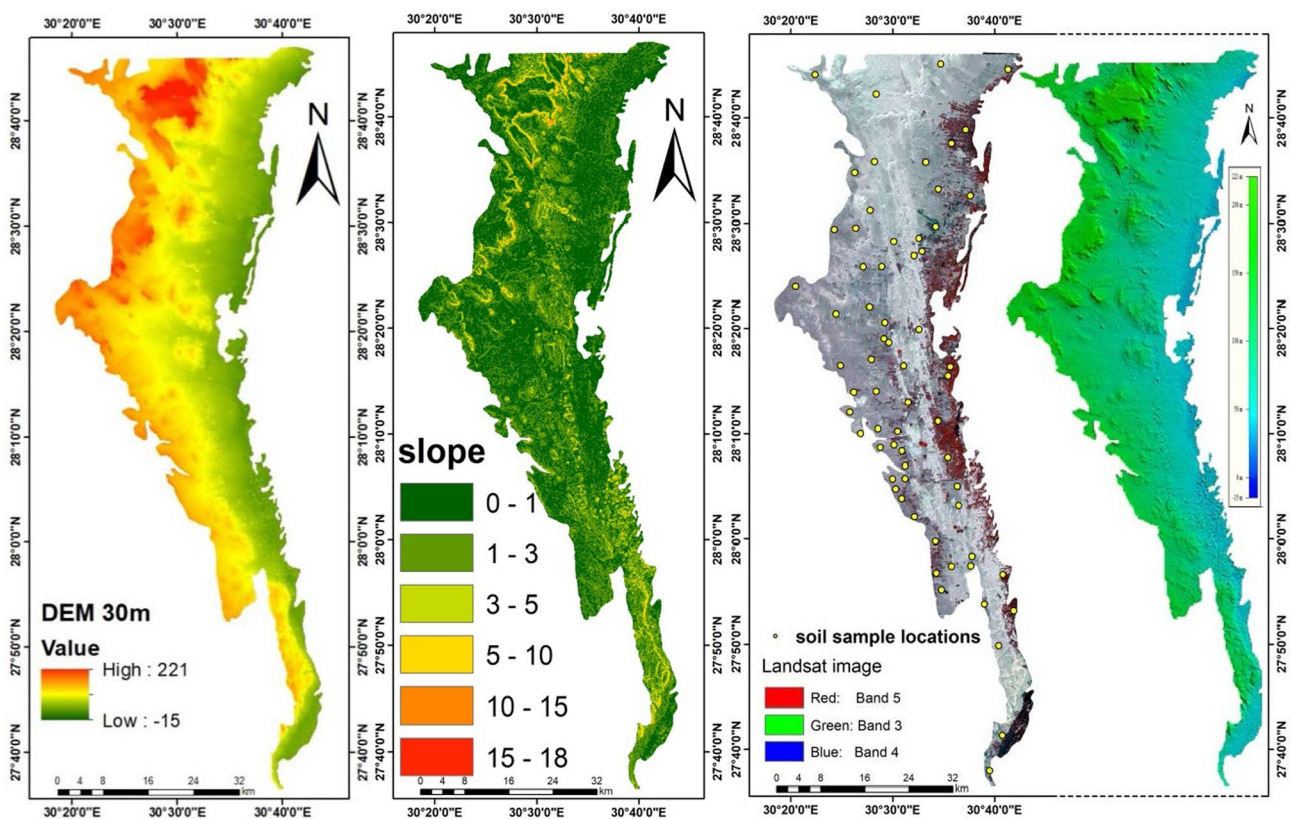Land was evaluated based on a parametric model of (Sys and Verheye 1974) for SSI. There are four groups of the factors

Fig. 3 DEM, slope, landsat image and 3D view of the area

Table 1 Suitability classes for the irrigation capability indices (Ci) classes

Ci class	Definition	Capability index
S1	Highly suitable	> 80
S2	Moderately suitable	60–79
S3	Marginally suitable	45–59
N1	Currently not suitable	30–44
N2	Permanently not suitable	< 29

which affecting SSI purposes. These factors according to Saeid et al. (2015) were divided to drainage traits and soil chemical, physical properties and land qualitative characteristics such as slope.

The following equation is used to estimate the irrigation capacity:

$$Ci = \prod_{i=1}^{n} Xi\frac{1}{n} \times \sqrt{\frac{\prod_{i=1}^{n} Xi}{100^n}}$$
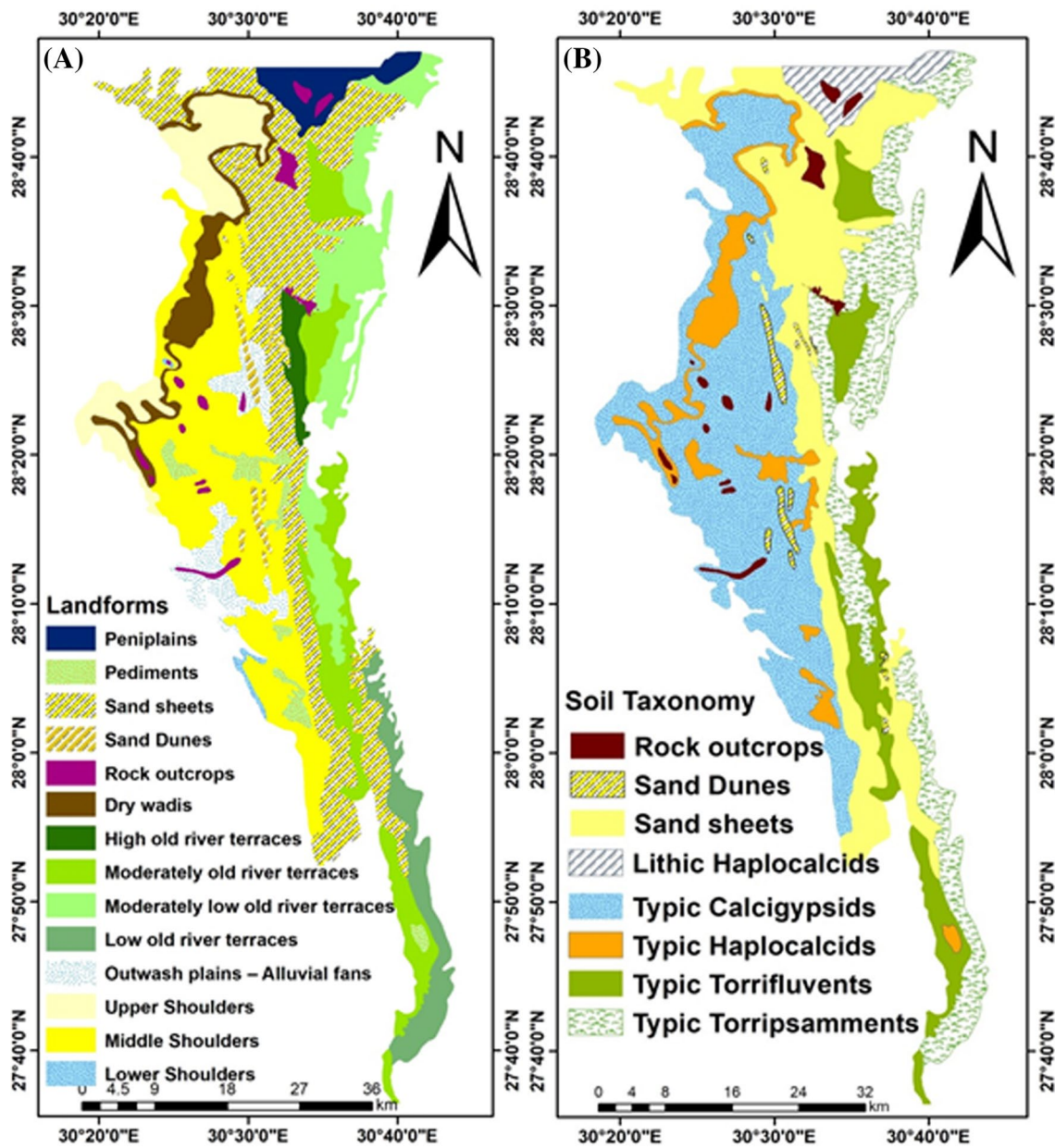

Fig. 4 **a** Landforms units and **b** soil taxonomy of the area

where: Ci is irrigation capability indices, Xi included: X1, X2, X3, X4, X5, X6, X7, X8; ratings of soil (texture, depth, calcium carbonate content, electrical conductivity, drainage, slope, gypsum content) respectively and in Sprinkle irrigation only X8 is used for rating of wind speed.

The capability index ranges their classes of consistent suitability are shown in Table 1.

The above classified layers were used to assess the land capability for irrigation, where the weighting value is considered as similar for all soil parameters.

Results and discussions

Soil-physiography

Visualizing and analyzing land form characteristics mainly depend on the Slope (Fig. 3) as a basic element (Panhalkar 2011) which assists for calculation of land capability indices (Wischmeier and Smith 1978; USDA 1961 and 1973; Wilson and Gallant 2000). ASTER Global Digital Elevation Map (ASTER GDEM) with from 30 m resolution was processed to generate the slope map (in percent). Figure 3 shows that slopes greater than 15% are located in northern west part of the study area, which indicate that steepest slopes represent low portion, 3% of the area (Fig. 3). The level slop (0–1) and nearly level slope (1–3) are mainly occupying most of the area by (67% and 13%) respectively and the area of slope (3–5%) is occupying 17% of the area.

The landform units (Fig. 4 A) were generated from field survey based on the integration of digital elevation model (DEM), slope and satellite image and were defined as old river terraces (moderately, moderatelylow, low), peniplain, outwash plains–alluvial fans, shoulders (upper, middle, lower), pediments, dry wadis, rock outcrops, sand dunes. The detailed areas of each unit are shown in Table 2. Soil taxonomic is shown in (Fig. 4 B) and presented in Table 2, units were defined as *Lithic Haplocalcids, TypicCalcigypsids, TypicHaplocalcids, TypicTorrifluvents, TypicTorripsamments*. While the unsampled areas were not classified i.e (Rock outcrops, Sand Dunes, Sand sheets)although it belong to Entisols order.

The depth of soils is varying from shallow (25–50 cm) to moderately deep (75–100 cm) and deep (> 100 cm) (Fig. 5), which cover 3.2% (64.2 km^2), 49.7% (998.2 km^2) and 20.0% (401.6 km^2), of the study area respectively. Soil texture is mainly proportion of sand with very small proportions of clay and silt. The textures of soils in the area are sandy, Loamy sand, Gravelly loamy sand, Sandy clay loam as shown in Fig. 5. The field survey showed that about 3% of the studied area is poorly drained. While moderately, well and somewhat excessively drained is accounted 30, 40, and 27% respectively.

Soil fertility status

Macronietrents status in the area reveals that soils are considered rich in potassium while moderate in phosphorus and very poor in nitrogen except in some agricultural fields as shown in Fig. 6. Soil available nitrogen status was low to medium (23.3–306.9 kg ha^{-1}) in all the pedons. Nitrogen content is decreasing with the depth in all the pedons. The high level of available nitrogen was may be due to continuous addition of fertilizers and increased level of organic

Table 2 Land Suitability classes for horticultural and field crops for each landform unit

| Landforms	Soil	Horticultural crop suitability sub classes	Field crop suitability sub classes	Capability	Area in Sq Km
Low old river terraces	*TypicTorripsamments*	S2tp	S2t	C2	109.02
Moderately low old river terraces	*TypicTorripsamments*	S2tcp	S2tc	C2	206.81
Moderately old river terraces	*TypicTorrifluvents*	S2sp	S2s	C2	214.51
High old river terraces	*TypicTorripsamments*	S2tcsp	S2tcs	C2	32.27
Outwash plains and alluvial fans	*TypicCalcigypsids*	S3tsg	S3tsg	C4	85.76
Peniplains	*Lithic Haplocalcids*	S3stpag	S3sta	C3	64.24
Pediments	*TypicHaplocalcids*	S3tcpsa	S3tcsa	C3	48.50
Dry wadis	*TypicHaplocalcids*	S2tcps	S2tcs	C2	99.75
Middle shoulders	*TypicCalcigypsids*	S3tcps	S3tcs	C3	419.61
Rock outcrops	*Rock outcrops*	N2	N2	C7	30.02
Lower shoulders	*TypicCalcigypsids*	S3tcps	S3tcs	C3	7.65
Sand dunes	Sand Dunes	N1	N1	C5	25.45
Sand sheets	Sand sheets	N1	N1	C6	490.59
Middle shoulders	*TypicCalcigypsids*	S3tcpsg	S3tcsg	C3	31.83
Upper shoulders	*TypicCalcigypsids*	S3tcspg	S3tcsg	C3	144.10
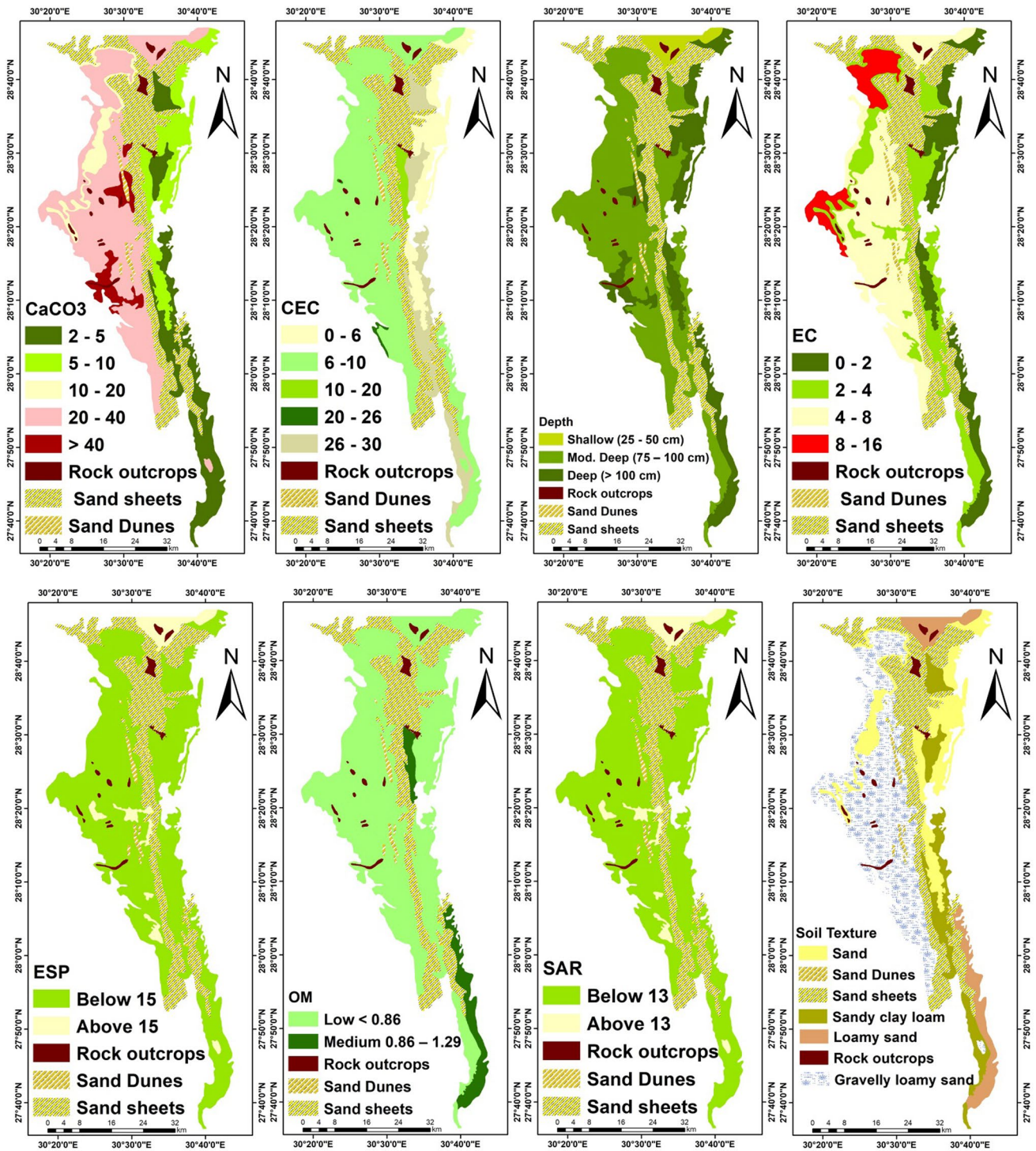
Fig. 5 Soil attributes maps of the area

carbon content in some agricultural fields. The areas having low nitrogen content due to low organic matter content in the soils of these areas. Soil available phosphorus was low to medium in all the pedons. Low status of available phosphorous was mainly attributed to its higher removal than

replenishment and also high P fixing capacity. The values indicate that small area is having medium available phosphorus content and the remaining area is having values of medium phosphorus content. Soil available potassium was ranged from low to high (63.4 kg ha^{-1} 401.3 kg ha^{-1}). Low
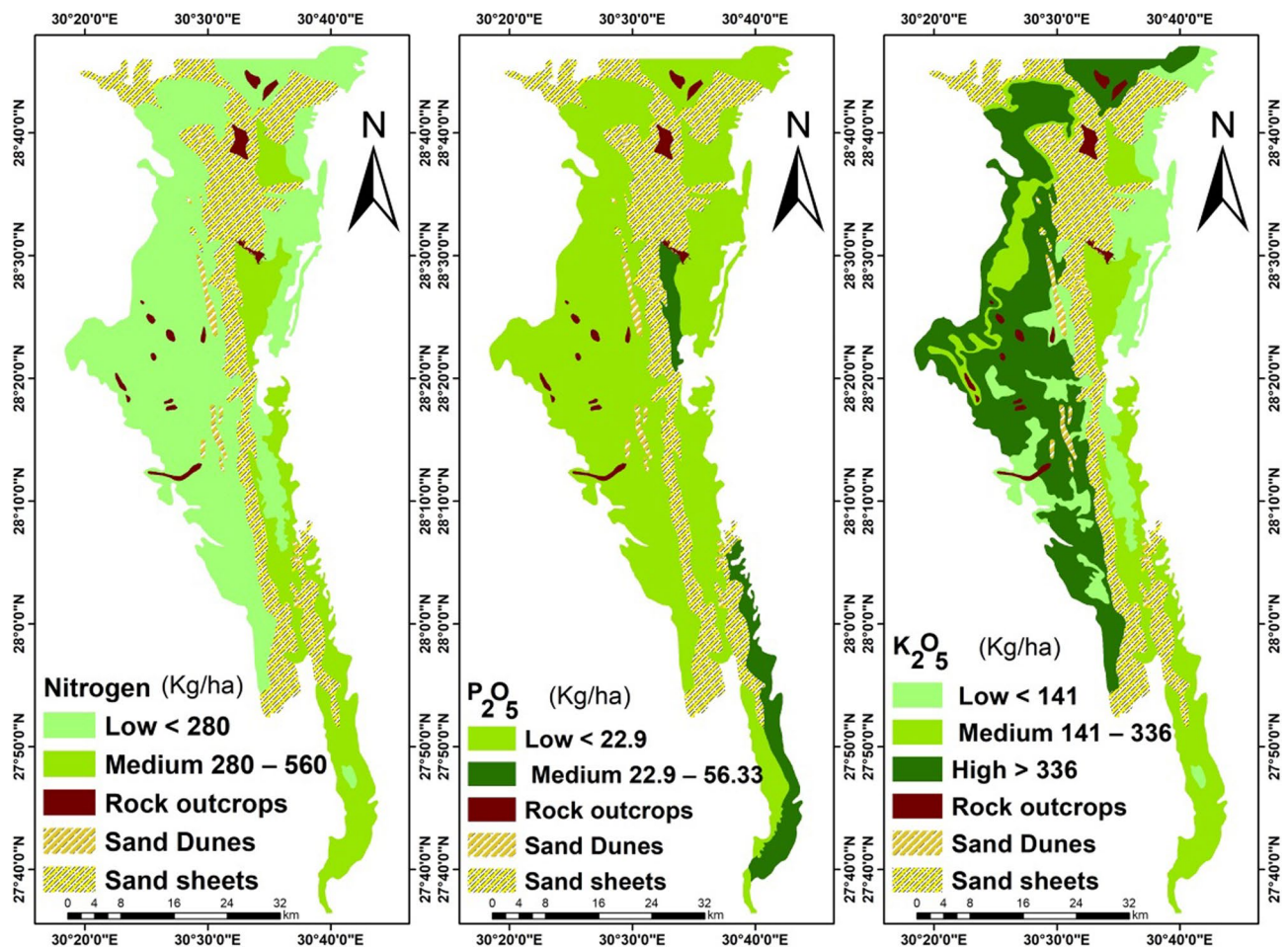
Fig. 6 Soil fertility status of macronutrients

values variation throughout the pedons due to coarse texture and gravelly nature of soils which are particularly low in available potassium. The available potassium is medium to high in most of the area soils.The available potassium content is high in surface layers and it decreases in subsurface horizons, though the soils have low potassium resources. Figure 6 shows the spatial distribution of macronutrients.

Land evaluation

Based on the natural limitations and properties of soils, land capability was estimated mainly for agriculture use. Among all capability classes, which are used for agriculture use and/or crops cultivation are the first four while the last four are not suitable for this purposes. The obtained land capability classes (Fig. 7; Table 3) are II, III, IV, V, VI and VII comprised 33.0, 35.6, 4.3, 1.3, 24.4 and 1.5% of the total area, respectively.

Two classes of suitability degrees are recognized in the area within the order suitable (S2 and S3) and two classes

are recognized within the order not suitable (N1 and N2). The occupied area for each class as percentage of the total area is shown in Table 2 and Fig. 7. Land suitability subclasses reflect on the type of limitations, e.g., Limitation factors: texture (t), calcium carbonate (c), salinity (s), saturated sodium (a), available depth (p) and profile development (g), accordingly the soil characteristics of the studied area could be classified for their suitability for agriculture utilization into four classes depending on the severity of their limitations to sustained agriculture use as shown in Fig. 7 and presented in Table 2.

Soil suitability for irrigation

The obtained results (Fig. 8; Table 4) showed that sprinkler and drip irrigation are more effective methods, suitable for the area and should replace the surface irrigation system exist in the cultivated lands in the studied area. Also the results demonstrate the absence of soil series which are high suitable in respect to surface irrigation use in the area. The
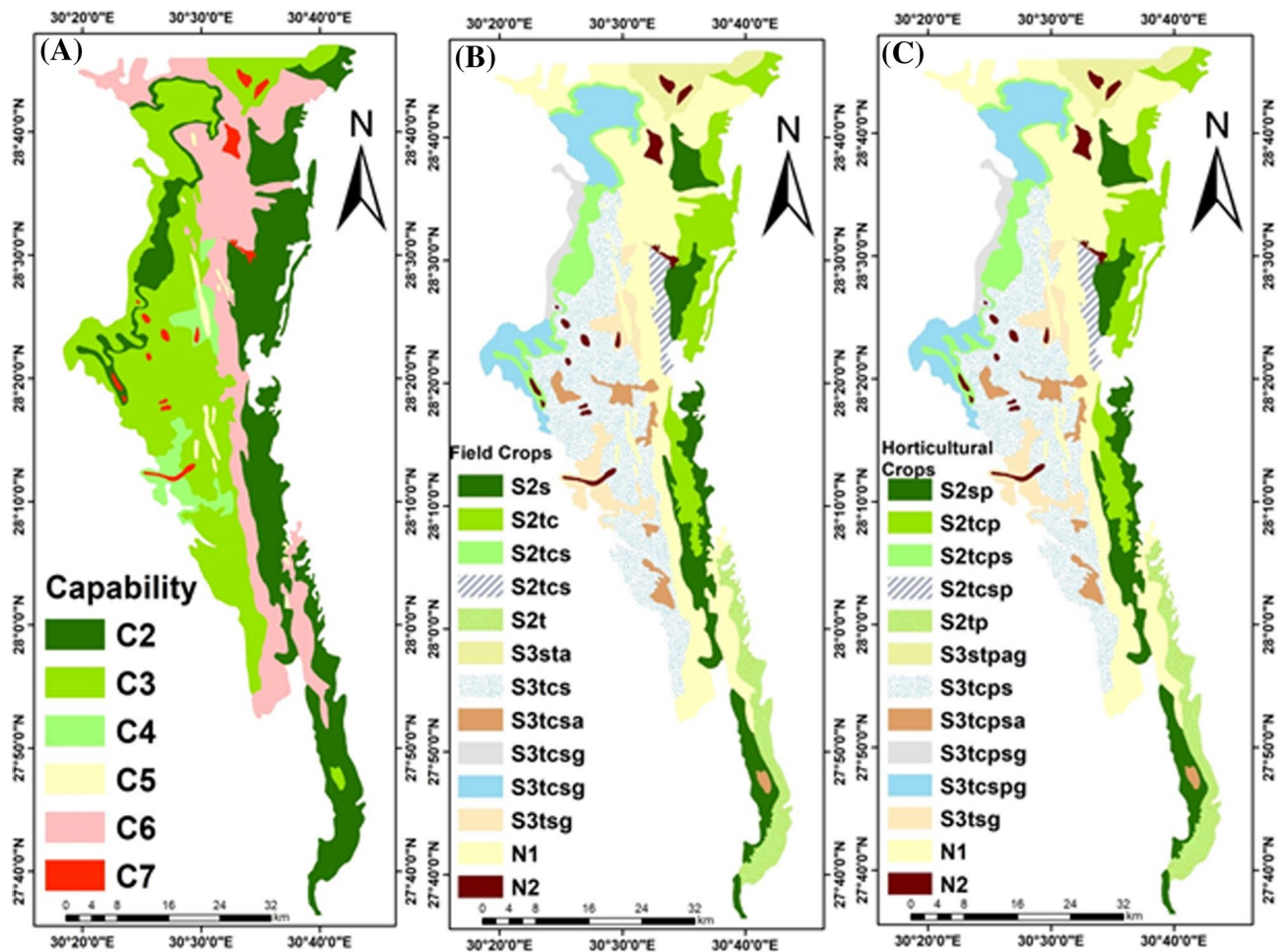
Fig. 7 **a** Land capability, **b** suitability subclasses for field crops and **c** suitability subclasses for horticultural

Table 3 Land capability classes

Capability classes	Area in km²	Area in percentage
C2 (II)	662.4	33.0
C3 (III)	715.9	35.6
C4 (IV)	85.8	4.3
C5 (V)	25.4	1.3
C6 (VI)	490.6	24.4
C7 (VII)	30.0	1.5

Limitation factors: texture (t), calcium carbonate (c), salinity (s), saturated sodium (a), useful depth (p) and profile development (g)

sprinkle irrigation method has two major/most factors limiting its use in the area, confined in wind speed and soil texture. While the drip irrigation method mainly limited by soil texture factor in the area. Soil suitability is moderate to high for the entire area in respect to drip and sprinkle irrigation except for sand dunes and rock lands (Fig. 8).

Mean of capability index was 39.4, 69.2 and 75.9 for irrigation methods of surface, sprinkle and drip respectively. These results demonstrate the area suitability for all irrigation methods. Meanwhile the soil texture factor highlights the importance of replacing the surface irrigation method with the sprinkle and drip irrigation methods. The sprinkle irrigation method is high appropriate in the area. But based on the obtained capability index for irrigation, applying drip irrigation system will be having High efficiency more than other irrigation techniques. And consequently improves the irrigation purposes and land suitability for different crops.

Conclusion

Based on the results, new land suitability subclasses maps were created. The area could be used for cultivation purposes. Despite that, areas of sand dunes and rock outcrop lands are not suggested for agriculture use since these areas are risk prone to sand dunes movement. Continue using
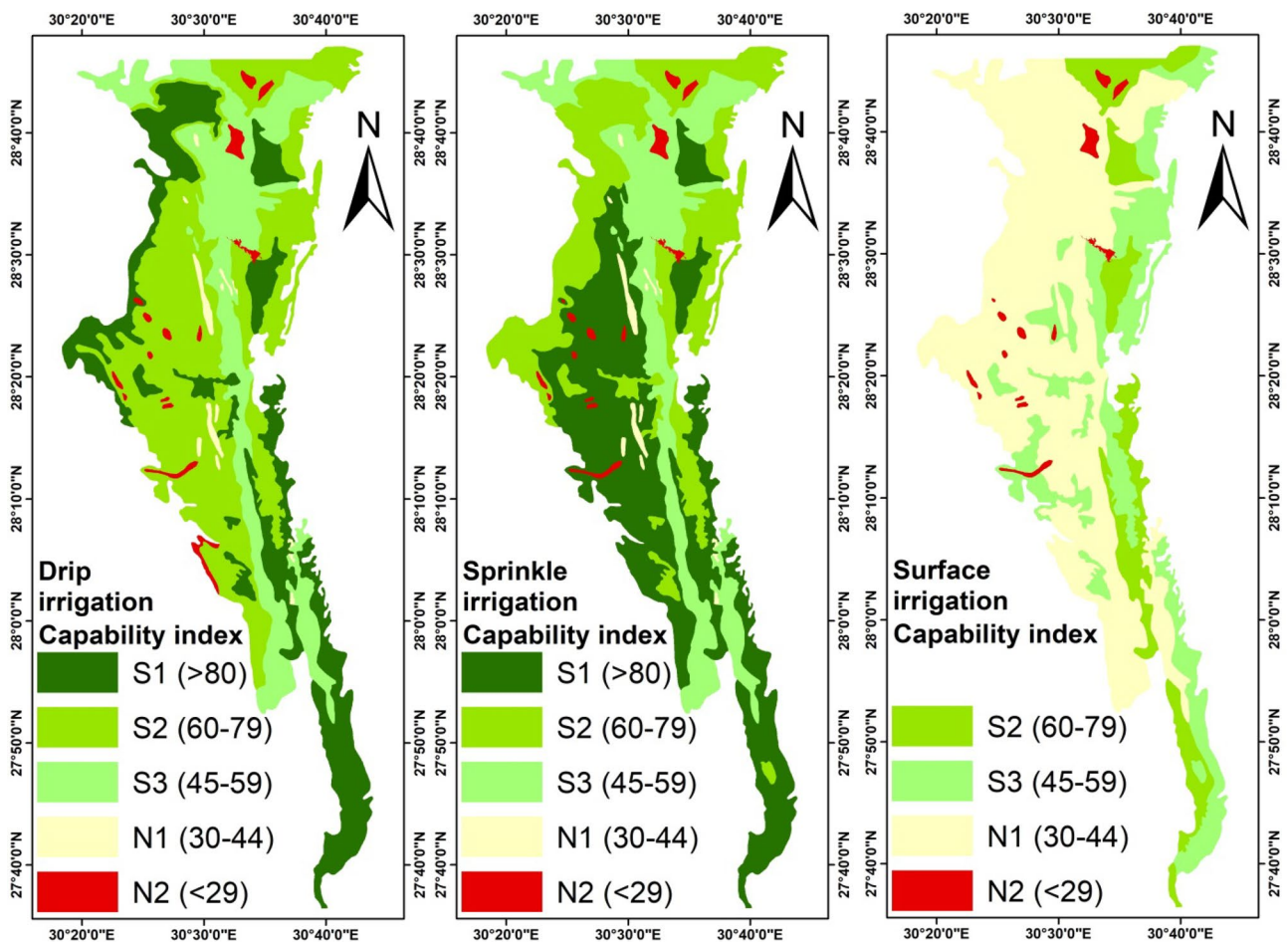
Fig. 8 Capability index for soil suitability to different irrigation methods

Table 4 Suitability classes of surface, sprinkle and drip irrigation for each soil series

Landforms	Soil	Suitable Irrigation system			Area, Km^2
		Surface	Sprinkle	Drip	
Low old river terraces	*TypicTorripsamments*	S3	S1	S1	109.02
Moderately low old river terraces	*TypicTorripsamments*	S3	S2	S2	206.81
Moderately old river terraces	*TypicTorrifluvents*	S2	S1	S1	214.51
High old river terraces	*TypicTorripsamments*	S3	S2	S2	32.27
Outwash plains û Alluvial fans	*TypicCalcigypsids*	S3	S1	S2	85.76
Peniplains	*Lithic Haplocalcids*	S2	S2	S2	64.24
Pediments	*TypicHaplocalcids*	S3	S2	S1	48.50
Dry wadis	*TypicHaplocalcids*	N1	S2	S2	99.75
Middle Shoulders	*TypicCalcigypsids*	N1	S1	S2	419.61
Rock outcrops	Rock outcrops	N2	N2	N2	30.02
Lower shoulders	*TypicCalcigypsids*	N1	S1	N2	7.65
Sand Dunes	Sand Dunes	N1	N1	N1	25.45
Sand sheets	Sand sheets	N1	S3	S3	490.59
Middle Shoulders	*TypicCalcigypsids*	N1	S2	S1	31.83
Upper Shoulders	*TypicCalcigypsids*	N1	S2	S1	144.10

surface irrigation, agricultural production and the soil quality will not be sustained for long term because it depends on ground water for irrigation. Therefor it is very important for forcing the use of the high suitable sprinkle and drip irrigation methods instead of exited low suitable surface irrigation method in the area. Even the results stated that the soils series which are high suitable for surface irrigation methods, not existed in the area. The presented approach added a new dimension of applying spatial models techniques in soil evaluation by considering the scale of surveyed area.

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