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RESEARCH ARTICLE

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Geospatial Approach in Assessing Agro-Climatic Suitability of Soybean in Rainfed Agro-Ecosystem

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Abstract The present study demonstrated the methodology to assess agro-climatic suitability of the soybean crop through integration of crop suitability based on FAO framework of land evaluation and biophysical (water limited) yield potential in the rainfed agro-ecosystem. A long term climatic database (1980–2003) was prepared to compute decadal rainfall and temperature variations of 13 IMD stations in part of Madhya Pradesh state. The climatic database was used in soil water balance software–BUDGET to compute crop specific length of growing period (LGP) and biophysical production potential such as water limited crop yield potential of each soil types for soybean crop. Water limited crop yield potential of soils were found to be varied from 33 to 100 and LGP ranged from 65 to 180 days in the area. FAO based land suitability was analyzed in association with the water limited yield potential for better appraisal of land potential and assess their suitability in rainfed area. FAO based land suitability indicated 2.45 % area as highly suitable and 57.49 % area as moderately suitable. However, integration of water limited crop yield potential with FAO based land suitability lead to agro-climatic suitability analysis indicated 17.60 % and 40.03 % area, respectively as highly suitable and moderately suitable. FAO based land evaluation showed 88.13 % of plains as moderately suitable whereas agro-climatic suitability indicated only 47.79 %. Agro-climatic suitability analysis revealed undulating plateau and undulating plains as most suitable for soybean crop.

Keywords Land evaluation · Water limited yield potential · LGP · Rainfed agriculture · Soybean crop

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Introduction

Rainfed agro-ecosystem constitutes 67 % of the net cultivated area in India, even though it has not received much technological breakthrough from productivity view point. Technological development to accelerate crop productivity in rainfed lands needs to have major emphasis on crop planning and optimal utilization of scarce water resources. Land-use planning is important policy-oriented activity to mitigate the negative effects of land use and to enhance the efficient use of resources with minimal impact on future generations. Land evaluation as tool addresses land potential for optimal land use planning. Earlier land evaluation based on physical (soil and terrain) characteristics basically known as physical land evaluation but with time, now more scientific approach to deal with land evaluation for rainfed and irrigated lands being developed (FAO 1983). Advancement in land evaluation has focused on use of more detailed and quantitative elements to assess the agronomic potential of the biophysical resources. The potential of rainfed lands for crop production is mostly constrained by water availability and soil health due to their close association with climatic variables, soil types, terrain condition and physiography of the region. As crop production potential in rainfed lands mainly conditioned by water availability, inclusion of concept of length of growing period (LGP) referred as period available for crop production in terms of water availability holds immense significance.

In recent decades, advent of new tools (e.g. remote sensing, GIS, GPS and ecological models) has been providing newer dimensions to address problems related to rainfed agriculture. GIS technology is capable of assembling, storing, manipulating, and displaying voluminous spatially and geographically referenced information. Interfacing output of models with geographic information system (GIS) increases the scope of applicability of the models for regional level planning (Hartkamp et al. 1999; Heinemann et al. 2002). Decision makers usually need information at broader spatial scales at country, watershed or state levels. Several studies have demonstrated coupling between crop models and GIS for improving water balance estimates, productivity assessment, crop suitability assessment and large-scale land use planning. (Beinroth et al. 1998; Lal et al. 1993; Smith 2000). Availability of crop models and integration their output with GIS helped in spatial assessment of crop suitability and preparing land use plan. Crop models also became a part in land evaluation and land use planning exercise at regional to global scale (FAO 1993).

The present study describes a geospatial methodology to assess agro-climatic suitability for soybean crop in rainfed region by evaluating crop suitability following FAO framework of land evaluation and climatic potential expressed as water limited yield potential. A soil-water balance model was used in the study to compute crop specific length of growing period (LGP) and water limited yield potential of major crops in semi-arid part of Madhya Pradesh state. The model output such as LGP and water limited crop yield potential were spatially represented using GIS. Further, soil suitability for crop was assessed accounting its climatic potential for better crop planning in the area.

Study Area

The study area falls in agro-ecological sub-regions of 5.2 and 10.1 comprising vast plateau mountains to the north of Narmada River and the adjoining areas of Malwa Plateau and Gangetic Plains form the Vindhyan cover in Madhya Pradesh. It covers an area of 50,046 Sq. Km. comprising nine districts namely Bhopal, Hoshangabad, Indore, Devas, Harda, Narsimhapur, Raisen, Sehore, Ujjain of Madhya Pradesh state having a geographical extent of 21° 54’ 19.60 N to 23° 53’ 48.12 N and 75° 08’ 00.64 E to 79° 38’ 17.48 E (Fig. 1). The temperature during summers ranges from maximum of 44 °C and minimum of 19 °C. The average annual rainfall varies from 700 to 1,418 mm. The length of growing period ranges from 90 to 180 days (Velayutham et al. 1999). The region characterized by semi-arid sub-tropical climate. The major crops practiced in this region are rainfed during Kharif season. Soybean is dominant leguminous cash crop grown in the region. The dominant soils of the area is characterized as fine loamy to fine texture, well to moderately well drained, moderately deep to deep and belongs to Lithic Ustorthents, Typic Haplustalfs, Vertic Ustochrepts, Typic Ustochrepts and Chromic Haplusterts at sub-group levels as per soil taxonomy.

Material and Methods

Materials

(i). Soil map (NBSS & LUP) at 1: 250, 000 scale and long term climatic data base of 24 years (1980–2003) obtained from IMD (Indian Meteorological Department) stations in Madhya Pradesh were used to prepare soil and climatic data base for the study.

(ii). Soil-water balance program–*Budget Program* (Raes 2005) was used to simulates the water storage in a cropped soil profile as affected by the input and withdrawal of water for a given period. The program is comprised of a set of validated subroutines describing the various

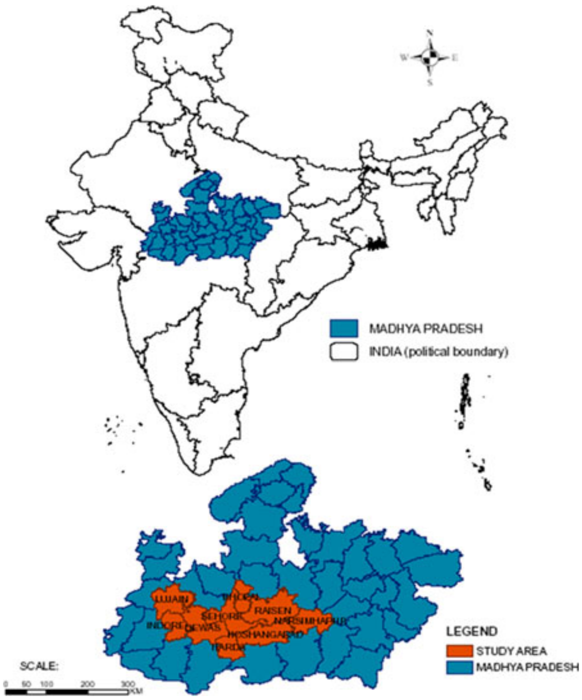

Fig. 1 Location map of the study area

processes involved in the water extraction by plant roots and water movement in the soil profile. It requires climatic input of daily, mean 10-day or monthly evaporation and rainfall data. Soil parameters such as available water holding capacity and effective root zone were defined. Crop parameters were also defined as rooting depth, sensitivity of crop growth stages to water stress. The BUDGET program simulates key water balance component for specific crop at critical growth stages and associated relative yield based on yield response to water stress..

(iii). *GIS Software*: Arc-GIS (ver. 9.2) was used for the spatial data preparation and analysis.

Methodology

Climate Data Base

The daily rainfall and temperature were compiled on a decadal (10 days) and monthly basis for a period of 24 years (1980 to 2003). Then, Decadal potential evapotranspiration (PET) was calculated using decadal mean temperature using Thornthwaite's PET method (Thornthwaite 1948). Thereafter, 24 years average decadal rainfall and PET was computed as input to Budget program.

Geospatial Soil Database

The vector coverage of soil map (Tamgadge et al. 1996) at 1: 500, 000 scale was prepared in Arc-GIS. Soil and land characteristics viz. soil texture class at family level, depth, drainage, soil pH, EC, base saturation (BS), cation exchange capacity (CEC) of dominant soil of each soil map units were stored as attribute data base for assessing crop suitability following FAO framework of land evaluation. Available water holding capacity (AWHC) was estimated for the soil map units accounting water holding capacity at field capacity and permanent wilting point of the soil (Tamgadge et al. 1999). Soil depth (horizon) wise AWHC of soils of map units were estimated maximum up to 100 cm depth defined as rooting depth or up to actual depth for other soils less than 100 cm depth. Climate station was assigned to soil map units considering landforms and distance of the stations to compute water limited crop yield potential and LGP.

Water-Limited Crop Yield Potential

Water limited crop yield potential is considered as a land quality indicator and indicates relative yield of crop under limited supply or availability of water. It is defined as climatic yield potential which considers both climate (temperatures and rainfall factors) and soil factors (depth and texture) to determine the crop growth. It is quantified as possible attainable yield under varying water scarcity, considering all other factors of production at their optimum level. It was estimated using BUDGET program, which takes into account decadal rainfall and PET, specific crop parameters (rooting depth, depletion factor, growth stage's length, Kc values and yield response factor (Ky)) and soil parameters (depth, texture, AWHC). Budget program was run to compute ETc and Eta of soybean crop at crop growth stages showing specific water balance. A multiplicative formula (Doorenbos and Kassam 1979) was used to estimate bio-physical yield potential (crop water limited yield potential):

$$\frac{Ya}{Ym} = \prod_{i=1}^{N} \left[1 - Ky_i \left(1 - \frac{ETai}{ETpi} \right) \right]$$

Where,

Ya is actual harvested crop yield (%)
Ym is the maximum crop yield under given management conditions (100 %)
ETai is the actual evapotranspiration
ETpi is the evapotranspiration for non-limiting water conditions during the ith stage of growth Ky_i to water stress.

Budget program also computed the water storage in the soil as affected by the input and withdrawal of water for a given period. It was based on decadal/monthly rainfall and PET as inputs to compute pseudo daily estimates of actual ETa and potential ETp. Thus, the growing days were added to compute LGP for the crop. Thus, LGP for soybean crop of the soil map units were computed and represented spatially through GIS platform, to reflect a general trend of the crop specific growing days in the area.

Agro-Climatic Suitability Assessment

Climate is one of the most important factors governing the soil resource potential for land use planning in rainfed region. Water limited crop production potential as climate potential reflects crop production constrain due to water availability which is vital to consider the land resource evaluation in the rainfed condition. Thus, FAO based land suitability along with their climatic potential was integrated to assess agro-climatic suitability based on decision criteria.

FAO Based Land Suitability

Soil-terrain suitability of soybean crop was assessed by comparing soil and land characteristics of soil-mapping units with the requirements of the soybean crop following FAO Framework of Land Evaluation (FAO 1976). The soil and land characteristics considered were slope, soil texture, depth, drainage, coarse fragment, erosion condition, soil pH, base saturation (BS) and cation exchange capacity (CEC).

Agro-Climatic Suitability

FAO based soil-terrain suitability and water limited yield potential for each soil map units were stored as attribute data in Arc-GIS to generate soil suitability and water limited crop yield potential maps. Water limited crop yield potential was classified as high (>50 %), moderate (35–50 %) and marginal to low potential (<35 %) as S1, S2 and S3 suitability classes, respectively. FAO based soil suitability was spatially analyzed in relation to water limited yield potential. The FAO soil suitability was modified accounting the water limited yield potential of the soil with a decision criterion to assess agro-climatic suitability for the crop. FAO soil suitability was modified assuming that if the soil suitability is of a lower order (S2) and water limited yield is of higher order (S1), then the resultant suitability would be upgraded to one class higher. Similarly, if the soil is moderately suitable (S1) but water limited crop yield potential is of lower order (S3), then the resultant suitability would be downgraded to one class for the crop. If soil is not suitable (N) but its water limited crop yield potential shows marginal suitability then it was upgraded as marginal suitable (S3). Agro-climatic suitability ensure that with proper management practices the constraint posed by the lower order soil suitability could be mitigated, under climatically suitable conditions indicated by water limited yield potential

Results and Discussion

The study area comprised of 131 soil map units. FAO land suitability of each map units was assessed. The

Table 1 LGP and water limited yield potential of soil of map unit- 371 distributed in various districts

S. no.	Districts	FAO based suitability	Av. rainfall (mm) (May–October)	LGP	Water limited yield (%)
1.	Bhopal	S2	1037.8	145	23.17
2.	Hoshangabad	S2	1150.0	157	33.30
3.	Indore	S2	921.8	152	60.56
4.	Panchmari	S2	1366.9	146	59.42
5.	Ratlam	S2	929.9	131	37.56

Table 2 Areal extent of agro-climatic suitability in relation to FAO based suitability in various landforms

S. no.	Landforms	Area (%)	Percentage area under agro-climatic suitability (FAO based)			
			S1	S2	S3	N
1.	Hill range	8.21	44.33 (4.99)	10.57 (39.35)	0.00 (10.57)	45.12 (45.12)
2.	Residual hills	7.56	1.89 (0.76)	41.48 (16.81)	0.00 (59.54)	56.67 (22.97)
3.	Plateau	25.93	3.95 (0.00)	42.11 (54.56)	11.20 (2.78)	42.75 (42.75)
4.	Undulating plateau	5.12	25.37 (2.59)	55.69 (49.93)	18.65 (47.57)	0.34 (0.0)
5.	Plains	35.87	9.06 (0.38)	47.79 (88.13)	32.32 (0.67)	10.92 (10.92)
6.	Undulating plains	14.96	51.66 (9.19)	34.53 (61.46)	3.53 (19.11)	10.37 (10.28)
7.	Valley	2.00	0.00 (0.00)	0.00 (0.00)	91.20 (100)	8.80 (0.00)
8.	Flood plains	0.40	100 (100)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

soil map units falls within the climatic station was used to define weather data for the soils while running the budget program to compute their water limited yield potential. Finally, FAO land suitability, water limited yield based suitability and agro-climatic suitability of map units were computed and spatially represented for the area. As an example, agro-climatic suitability of the dominant soil of a map unit-371 mapped in six districts (Table 1) having varying climatic conditions is explained here in detail. Dominant soils of the map unit-371 was characterized as very deep, moderately well drained, fine texture class and classified as Typic Haplusterts at sub-group level. The map unit 371 was computed available water of 153 mm up to 100 cm depth. Soils of the map unit was assessed as moderately suitable (S2) based on FAO land evaluation method but its climatic potential (water limited crop yield potential) varied from 23.17 (S3) to 60.56 (S1). Analysis revealed that same soil will be performing differently in various climatic conditions expressed as water limited crop yield potential depending to the availability of water during the crop growing period. Thus, FAO based land suitability was modified (upgraded and downgraded) considering their climatic potential. The analysis showed that the climatic potential of the map unit 371 in Bhopal is low (>33 %) whereas in Indore and Panchmarhi is high (>50 %), therefore its agro-climatic suitability was modified as marginally suitable (S3) and highly suitable (S1), respectively. In the same way, land suitability analysis was carried out for all 131 map units based on FAO, climatic potential (water limited crop yield) and integration of both to assess agro-climatic suitability in GIS environment.

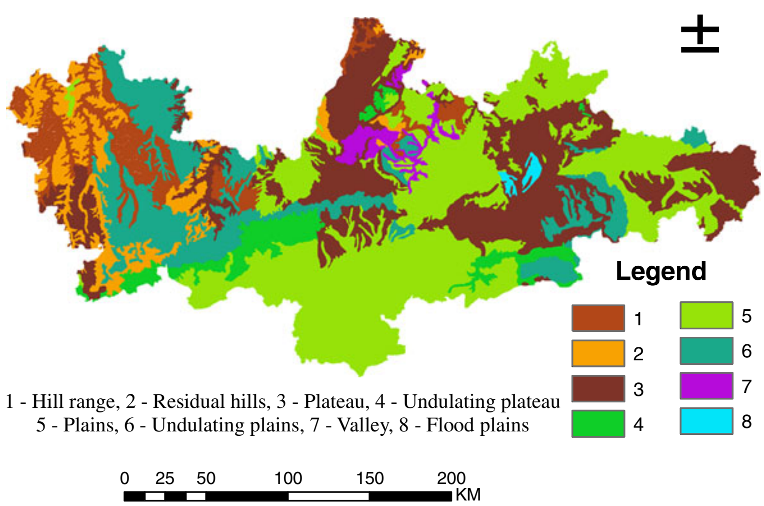

Fig. 2 Landforms in the study area

Table 3 Areal extent of agro-climatic suitability in relation to FAO based suitability for soybean crop

S. no.	Suitability class	Areal extent (%)		
		FAO based suitability	Climatic yield potential based suitability	Agro-climatic suitability
1.	Highly suitable (S1)	2.45	42.09	17.60
2.	Moderately suitable (S2)	57.49	40.13	40.03
3.	Marginally suitable (S3)	17.97	17.79	17.75
4.	Not Suitable (N)	22.09		24.62

Land Suitability Based on FAO Framework

The study area comprised of various landforms such as (Table 2, Fig. 2) hill ranges (8.21 %), residual hills (7.56 %), plateau (25.93 %), undulating plateau (5.12 %), plains (35.87 %), undulating plains (14.96 %), valley (2.0 %) and flood plain (0.4 %). Dominant soils in the hill range were characterized as very deep (>100 cm), moderately well drained and fine to fine loamy textural class that belongs to Typic and Vertic Ustochrepts at sub-group level as per soil taxonomy. These soils were assessed as moderately suitable (S2) to soybean crop. Other soils in the hill range were characterized as shallow to moderately deep, somewhat excessively drained and loamy textural class that was classified as Lithic Ustorthents and Lithic Ustochrepts. Suitability of these soils ranged from marginal (S3) to not suitable (N). Soils of Residual hills are mainly well to somewhat excessively drained, very shallow to shallow of loamy skeletal or loamy soil textural class and belongs to Typic Ustochrepts and Lithic Ustorthents at sub-group level. These soils were found marginally (S3) to not suitable (N). Undulating plains soils were well drained, deep and fine to fine loamy textural class and classified as Typic Haplusterts and Typic Haplustalfs at sub-group level. These soils were assessed as moderately suitable (S2). This physiographic unit had another soil type classified as Chromic Haplusterts and Typic Haplusterts was characterized as moderately well drained, deep and fine soil textural class and found marginal suitable (S3) to the crop. Major soils in the plains were characterized as moderately well, deep and fine textural class belongs to Typic Haplusterts sub-group level. The soils were found moderately suitable (S2).

Dominant soils in plateau were well drained, moderately deep (75–100 cm) to deep and fine, clayey soil textural class and classified as Typic Ustochrepts and Vertic Ustochrepts. These soils were assessed as moderately suitable (S2). Other soil associated with the landscape was very shallow, somewhat excessively drained, loamy skeletal in textural class and classified as Lithic Ustorthents. These soils were found not

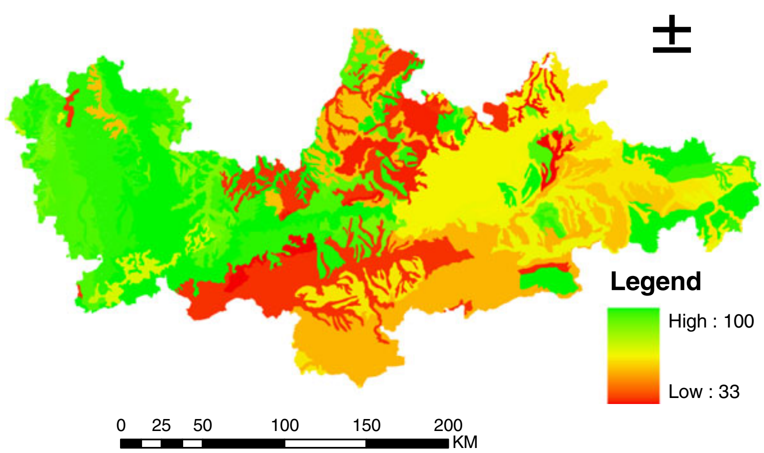

Fig. 3 Water limited yield potential for soybean crop

Table 4 Average LGP and water limited yield potential in various landforms

S. no.	Landforms	LGP (SD)	Climatic (water limited) yield potential (SD)
1.	Hill range	163 (16.9)	94.33 (9.53)
2.	Residual hills	150 (38.9)	89.40 (14.94)
3.	Plateau	140 (22.6)	72.71 (20.0)
4.	Undulating plateau	152 (39.4)	75.28 (25.21)
5.	Plains	133 (29.9)	58.21 (18.96)
6.	Undulating plains	167 (22.7)	88.27 (19.70)
7.	Valley	121 (20.3)	44.95 (21.69)
8.	Flood plains	180 (0)	98.44 (6.9)

SD Standard deviation

suitable (N) for the crop. Soils in the undulating plateau were moderately well drained, deep, fine textured and classified as Typic Haplusterts. These soils were moderately suitable (S2). The land unit also had well drained, shallow and clayey texture class soils of Typic Ustochrepts which was assessed as marginal suitable (S3). The study area had minor area under valley fills and flood plains. Soils of valley fills were well to moderately well drained, moderately deep to deep, fine to fine loamy texture class and classified as Typic Ustochrepts. These soils were found marginal suitable (S3). Soils of flood plains were well drained, deep and fine loamy texture class and were assessed as highly suitable (S1).

FAO based land evaluation analysis (Table 3, Fig. 4) revealed that 2.45, 57.49, and 17.97 % of the area were highly (S1), moderately (S2) and marginally (S3) suitable, respectively. Nearly 22.09 % area was found not suitable (N) in the area.

Land Suitability Based on Water Limited Crop Yield Potential

Flood plains, hill range, residual hills and undulating plains showed higher average climatic potential (>85 %) favoring to good crop yield potential (Table 3, Fig. 3) whereas plains and valley lands had lower average climatic potential. Analysis indicated 42.09 % area had high (>50 %), 40.13 % area as moderate (35–50 %) and 17.79 % as marginal to low water limited crop yield potential (<35 %) and classified as highly (S1), moderately (S2) and marginal (S3) suitability classes, respectively. Spatial analysis revealed that most of the hill range was found highly suitable whereas nearly 71 % and 29 % area of residual hills was assessed as S1 and S2 suitability classes. Plateau landscape had showed their 38 % area as S1 and 51 % as S2 whereas 57 % area as S1 and 22 % as S2 for the undulating plateau. The undulating plains were found most suitable with

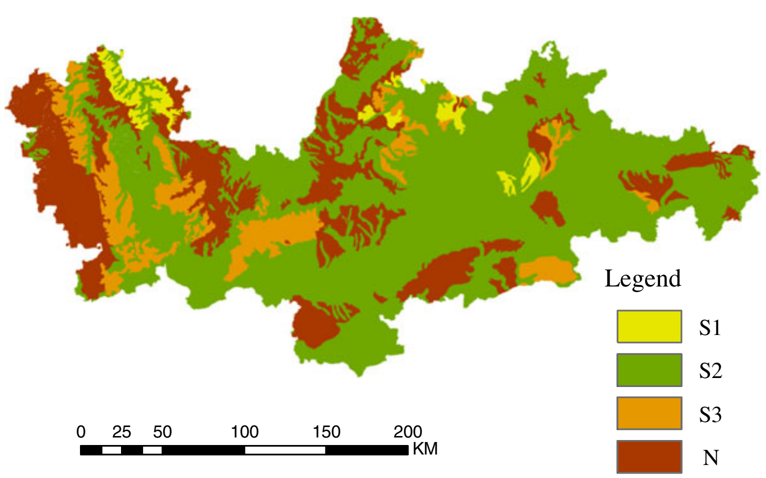

Fig. 4 FAO based land suitability classes for soybean crop

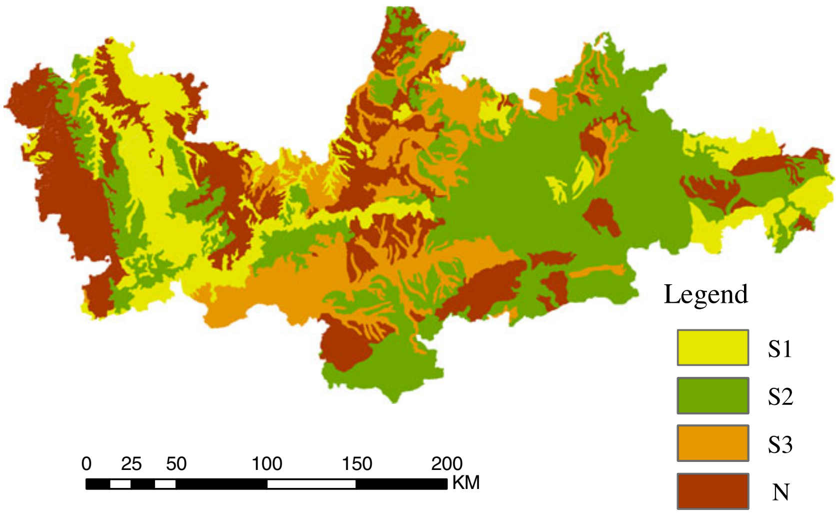

Fig. 5 Agro-climatic suitability for soybean crop

81 % and 15 % area as highly (S1) and moderately (S2) suitable. Plains had largest area and was assessed as moderately (58 %) and not suitable (32 %). Valley landscape was found marginal suitable whereas floodplains as highly (S1) suitable.

Agro-Climatic Suitability (Biophysical Suitability)

The agro-climatic i.e. biophysical suitability analysis revealed that 17.60, 40.03, 17.75 % area qualify for highly (S1), moderately (S2), marginal (S3) suitability for the soybean crop (Table 3, Fig. 5) in the area, respectively. 24.62 % area was assessed as not suitable (N) for the crop. FAO framework of land evaluation revealed that only 2.45 % whereas water limited yield potential indicated 42.09 % of the area as highly suitable for the crop. Analyzing suitability accounting FAO based and climatic potential leading to agro-climatic suitability assessment showed that 17.60 % area qualify as highly suitable (S1) to the crop. FAO based method assessed 57.49 % area as moderately suitable (S2) but agro-climatic suitability analysis revealed that 40.13 % area as moderately suitable (S2). Agro-climatic suitability analysis revealed undulating plains and undulating plateau are most suitable for the crop (Table 2). A large area of moderately suitable (S2) soils qualified to the highly suitable (S1) class as there water limited potential was high and the soil suitability was upgraded to highly suitable. Similarly with the area of marginal suitability class was observed. Soils having lower FAO based land suitability but higher water limited yield potential

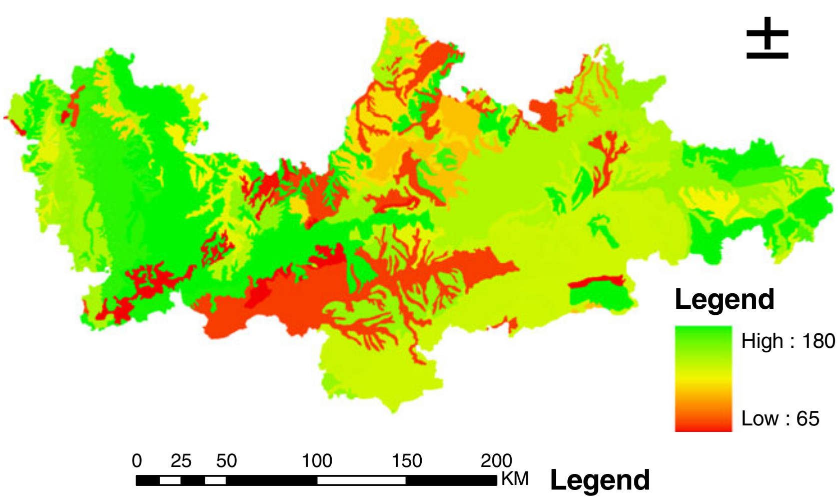

Fig. 6 Length of growing period (LGP) for soybean crop

Table 5 Areal distribution of LGP (days) in various FAO based land suitability classes

S. no.	Land Suitability class	LGP Classes (Area %)			
		< 75 days	75-100 days	100-150 days	>150 days
1.	Highly Suitable (S1)	1.42	–	–	1.09
2.	Moderately Suitable (S2)	–	12.99	22.00	19.77
3.	Marginally Suitable (S3)	–	1.54	12.96	14.33
4.	Not Suitable (N)	–	0.15	5.82	7.95
	Total	1.42	14.67	40.77	43.14

insure availability of water at critical growth stages controlled by weather parameters. It favours denoted as agro-climatic suitability in rainfed conditions. Thus, the integration of water limited yield potential with FAO based suitability helped in better assessment of land suitability in the rainfed region.

Spatial Pattern of LGP and FAO Based Land Suitability

Average LGP estimated in various landforms (Table 4) indicated that flood plains had highest (180 days) followed by undulating plains (167 days) and hill ranges (163 days) and lowest in valleys (121 days). Spatial pattern of LGP showed its increase from west to east in the area (Fig. 6). Analysis revealed that 43.14 and 40.77 % area had LGP >150 and 100–150 days, respectively. However, its 14.67 % area was found to qualify for LGP of 75–100 days whereas 1.42 % area for <75 days. The FAO based land suitability was spatially analyzed with respect to LGP of the crop (Table 5) revealed highly suitable area has LGP of >150 days. The moderately suitable (S2) land had area under LGP classes of 75–100 days, 100–150 days and >150 days in 12.99, 22.0 and 19.77 % area, respectively. The marginal suitable (S3) land had area under LGP of 100–150 days and >150 days in 12.96 and 14.33 % of area, respectively. LGP estimation may help in guiding for selecting suitable crop variety in various land suitability classes to obtain optimal crop production. It indicates that inclusion of LGP will lead to some improvement in crop suitability analysis however, solely it cannot be considered as criteria for assessing crop suitability. Newly, available CPC and DEM data may help in better characterization of soil-terrain-climatic condition for improving LGP estimation.

Conclusions

FAO based land suitability consider inherent physico-chemical characteristics of soils whereas water limited crop yield potential accounts availability of soil water determined by climatic condition to assess land performance for crop suitability. Integration of water limited crop yield potential with FAO based land suitability in the study was used to assess agro-climatic suitability of crops in rainfed areas for better appraisal of land resources potential. Soil water balance model–Budget was used to assess climatic yield potential as water limited crop yield potential. The study indicated that highly suitable area based on FAO Framework was very much under estimated at regional scale due to broad range criteria of crop requirement. FAO based physical land suitability area was refined and better spatially appraised with integration of climatic potential. The agro-climatic suitability assessment showed a large area qualifies as highly suitable for soybean crop. Spatial analysis of FAO based soil suitability assessment for crops (LUTs) and their water limited crop yield potential along with crop specific LGP estimation helped to identify area with highest potential for crop production in rainfed area to optimize crop production.

Thus, biophysical production potential as water limited crop yield potential in association with FAO based land suitability assessment of crops can be used as potential land evaluation tool for agro-climatic suitability analysis and better land use planning in rainfed region.

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