

Revisiting agro-ecological sub-regions of India – a case study of two major food production zones

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The sustenance of food and nutritional security are the major challenges of the 21st century. The domestic food production needs to increase per annum at the rate of 2% for cereals and 0.6% for oilseeds and pulses to meet the demand by 2030. The Indo-Gangetic Plains (IGP) and the black soil regions (BSR) are the two major food production zones of the country. Since irrigation potential is limited and expansion of irrigated area is tardy, rainfed agriculture holds promise to satisfy future food needs. Frontline demonstrations of these two regions have shown that there is a large gap at the farmers' and achievable levels of yields. This gap can be filled by adopting scientific approach of managing the natural resources. There is tremendous pressure of biotic and abiotic stresses hindering the crop production and that warrants for a systematic appraisal of natural resources. The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) under the Indian Council of Agricultural Research (ICAR) divided the

country into 60 agro-ecological sub-regions (AESRs) in 1994 by superimposing maps on natural resources like soils, climate and length of growing period (LGP) for crops and other associated parameters. With the passage of nearly two decades and the advent of modern facilities of database management and improved knowledge base on natural resources, a need was felt to revise the existing AESR map to reach near the ground reality of crop performance. The new database stored in soil and terrain digital database (SOTER) has helped in modifying the AESR delineations of the BSR (76.4 m ha) and the IGP (52.01 m ha). The estimated available water content, saturated hydraulic conductivity and use of pedo-transfer functions in assessing the drainage conditions and soil quality have helped in computing with improved precision the LGP, and revise the earlier AESRs in BSR and IGP areas. This innovative exercise will be useful for the future AESR-based agricultural land use planning.

Keywords: Agro-ecological sub-regions, food production zones, land-use planning, length of growing period.

Introduction

RAINFED agriculture occupies nearly 58% of cultivated area, contributes 40% of food production and supports

40% of human and 60% of livestock population of India¹. To meet the food and nutritional security on sustainable basis is the challenge of the 21st century. Domestic production of cereals must increase at 2% per annum and that of oilseeds at 0.6% per annum; and the overall agricultural growth rate must be > 4% per annum. Presently, the IGP represents an intensively irrigated area and is the lifeline of our granary basket. Since the pace of expansion

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for achieving maximum irrigational potential of 140 m ha is tardy, and irrigation so far achieved is only 91 m ha (2012–2013)², improving water-use efficiency (WUE) under rainfed situation holds promise in increasing the productivity. Even under irrigated agriculture, the frontline demonstration results have shown a large gap between farmers' and realized yields. Scientific management of natural resources can fill this gap³. The problem is aggravated by climatic variability, as observed in the Indian subcontinent. Intensity of short-duration rainfall encourages soil degradation in arid to semi-arid areas dominated by Vertisols and vertic intergrades⁴. Rainfed cultivated area to the total cultivated area is highest in Jharkhand (91%), followed by Maharashtra (81%), Chhattisgarh (74%), Andhra Pradesh (53%) and Karnataka (71%)⁵.

Managing natural resources for agriculture needs information and distribution of various kinds of soils and knowledge of agronomic principles. It ensures the efficiency of resources and to develop crop genetic bases, various constraints and instructions among biotic and abiotic stresses should be considered⁶. Research was undertaken to assess land/water and climate resources to develop a near homogenous integrated system, where a group of crops and cultivar thrives, where best scientific knowledge and agricultural technology are helpful to harness optimum energy of the system through effective policy implementation by public and private institutions. The near homogenous soil-climatic zones, which are similar in soil bioclimate and length of moisture availability period related to crop production, are known as agro-ecological regions (AERs)⁷. FAO's exercises concentrated on creation of broad crop feasibility zones based on length of moisture availability period superimposed on FAO/UNESCO global soil terrain map on 1 : 5,000,000 scale. The agro-ecological zones (AEZs) so created are very broad to use for crop planning both at the state and district levels.

In India, several attempts were made in the past to classify the land area into climatic regions. Krishnan and Singh⁸ delineated soil climatic zones by superimposing moisture index and mean air temperature isopleths on broad soil types of India. Murthy and Pandey⁹ brought out a map with eight AERs based on physiography, climate (rainfall and potential water surplus/deficit), major soils and agricultural regions. These two approaches were the modest beginnings of agro-ecological zoning of the country. However, they suffer from several limitations. The areas, having different physiography, temperature and soils in a zone, for example, Rajasthan desert, the Indo-Gangetic Plains (IGP) and Eastern Himalayas were grouped in one AER. Likewise, Jammu and Kashmir, Himachal Pradesh and northwestern Uttar Pradesh also were grouped into the same region¹⁰. Based on the concept of index of moisture adequacy (IMA) ($AE/PET \times 100$), Subramaniam¹¹ delineated 29 AEZs with 36 combinations

of IMA and dominant soil groups of FAO/UNESCO soil map¹². However, this attempt did not consider other important parameters such as physiography and bioclimate. This inadequacy resulted in grouping both cold arid and warm humid regions of Jammu and Kashmir in one zone. Similarly, northwest and northeast Himalayas having contrasting agro-climatic conditions were also classified in one zone. Therefore, this approach did not permit bringing out a uniform AEZ for practical crop planning. The Planning Commission of the Government of India, divided the country into 15 broad agro-climatic zones (ACZ)¹³ based on physiography and climate, with a view to develop the resources and their optimum utilization in a sustained manner within the framework of resource constraints and potential of each region. Following this, the state agricultural universities (SAUs) were advised to divide each zone/state, into sub-zones under the National Agricultural Research Project (NARP). Accordingly, 127 sub-zone maps, based primarily on rainfall, existing cropping pattern and administrative units were developed. However, uniform environmental conditions, namely soil, water and climate were not considered. Moreover, use of units based on state boundaries for sub-divisions resulted in many sub-zones showing similar agro-climatic characteristics.

Development of AEZs – NBSS&LUP concept

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP; ICAR) mooted the concept of length of growing period (LGP)¹⁴ to address inadequacies in the above-mentioned protocols for developing agro-ecological zones/regions. The LGP is an index of crop production, because it takes soil-water balance into consideration, which is a direct function of moisture availability in a land-form, rather than the total annual rainfall. The map boundaries, depicting 20 AERs were delineated by superimposing bioclimate and LGP on soil-scape. The LGP classes were further grouped into different feasible cropping systems in an agro-environment¹⁵. While developing the AER, only five LGP classes were developed, considering crop duration classes, such as short (< 90 days), medium (90–150 days), long (150–180 days), relay cropping (180–210 days) and double cropping (> 210 days). Considering the importance of narrower LGP interval of 30 days for diverse crop feasibility and also the need to further sub-divide the bioclimate and some important soil quality parameters like depth and available water capacity (AWC), the NBSS&LUP divided 20 AERs into 60 agro-ecological sub-regions (AESRs)¹⁰.

Usefulness of the 60 AESRs was demonstrated by estimating soil carbon and available potassium stocks of the IGP and black soil region (BSR), and prioritizing areas for carbon sequestration¹⁶ and potassium management in different crops and cropping systems of the IGP

and BSR¹⁷. Still, there is a need for further refining AESR boundaries to match the new information on soils (soil resource mapping at 1 : 250,000 scale) and moisture availability after cessation of rainfall. Moisture availability is a function of rainwater stored in the soil profile, and its availability is controlled by soil minerals and exchangeable Na⁺ and Mg²⁺ ions, especially in soils of semi-arid tropical (SAT) environments. Therefore, raising *rabi* (winter) crops in the SAT environment still poses a challenge. However, to address this issue, there is a need to quantify the antecedent soil moisture, after the cessation of rains (rainfall (*P*) falls short of 0.5 potential evapotranspiration (PE))³. Moreover, information on soil modifiers (gypsum, zeolite, palygorskite and CaCO₃) that influence soil quality in controlling its moisture content and availability should be included in fine-tuning the LUP computation^{18–20}.

Background for the revision of AESR boundaries

IGP areas

The IGP (with 52.01 m ha area) stretches about 3000 km extending from Punjab in the west to West Bengal and Tripura in the east, having contrasting climatic regimes represented by arid, semi-arid, sub-humid, humid and perhumid systems with mean annual rainfall varying from less than 800 to more than 2000 mm (Figure 1).

Recent pedological studies of the IGP^{21,22} have indicated that the extensive fluvial plains originated from the alluvial deposits of various river systems which came into existence following the collision of Indian and Chinese plates during middle of Miocene period²³. The IGP is a gently easterly sloping plain with convexity towards southeast. It shows a series of terraces, bars, meandering scars, with micro-high and micro-low areas on apparently smooth topography. The overall topographic situation is uniform with elevation of about 50 m amsl in the Bengal basin in the east and 300 m amsl in Punjab plain in the west. While generating AESR map during 1994, poor saturated hydraulic conductivity (sHC) and increase in

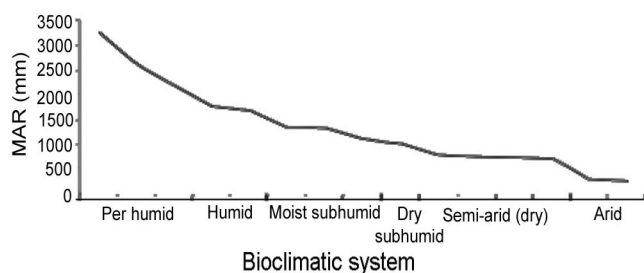


Figure 1. Variation of rainfall in different bioclimatic systems in the Indo-Gangetic Plains.

bulk density (BD) were not considered due to paucity of sufficient data. During our revisit in 2010 to the IGP, we generated sHC data from about 400 soil profiles. These new datasets have helped us in correcting and redrawing the boundaries of AESR.

The on-farm (farmers' field) and on-station (agricultural research station) yield of rice–wheat of different AESRs of the IGP indicated that, there is a large yield gap across different AESRs (Table 1). For example, in the same AESR 9.2 representing Pantnagar, Faizabad and Varanasi, the yield of rice in Varanasi is 33% less than that at Pantnagar and 12.5% less than at Faizabad. The same yield scenario, is also reflected in wheat production. This suggests that there is a need for modification of AESRs.

BSR areas

Traditionally black soils (Vertisols and intergrades) are confined to the Peninsular region. The areas of BSRs are spread mainly in Maharashtra, Madhya Pradesh, Gujarat, Tamil Nadu, Karnataka, Andhra Pradesh, Uttar Pradesh and Rajasthan with a total of 74.6 m ha. The agricultural practices and increased aridity accelerated the chemical degradation in vertisols resulting in increased ESP with depth, which has adversely affected the hydraulic properties. The high values of COLE (> 0.1) and enhanced ESP cause dispersion of clay, which has adversely affected hydraulic properties of these soils. Earlier studies on the chemical degradation of Vertisols of central India²⁴ indicate that in soils with ESP < 5, sHC was affected by exchangeable magnesium percentage (EMP), suggesting that saturation of Vertisols, not only with Na⁺ ions, but also with Mg²⁺ ions, leads to greater clay dispersion. We did not get significant positive correlation between sHC and EMP, and EMP and water dispersible clay (WDC) in spite of a favourable role of Mg ions in improving soil structure²⁵. This suggests that the release of Ca²⁺ ions from zeolites in the soil undermines the influence of Mg²⁺ ions and also in yielding very small amounts of water-dispersible fine clay particles. In many Vertisols, the favourable release of Ca²⁺ ions from zeolites has enhanced sHC in spite of high ESP and that is reflected in higher productivity of *kharif* and *rabi* crops. A significant negative correlation between sHC and ESP, sHC and WDC and a negative correlation between ESP and EMP, as well as between ESP and exchangeable Ca/Mg justify the differential crop productivity. In non-zeolitic sodic black soils (Vertisols), impairment of hydraulic properties has been observed at an ESP between 5 and 15, as indicated by low sHC value of < 10 mm h⁻¹. For similar Vertisols of Central India, hydraulic properties were impaired even at an ESP as low as 5 (refs 26, 27). Serious structural degradation of some Australian swelling clay soils has been reported, even at an ESP as low

Table 1. Potential, on-research station and on-farm yields of rice and wheat in different zones of IGP*

IGP zone	AESR old	AESR new	Site	Potential yield (Mg ha ⁻¹)	On-station yield	On-farm yield	Yield gap (I)	Yield gap (II)
Rice	9.1	9.1b	Ludhiana	10.7	5.6	5.6	47.6	47.6
	4.1	4.1b	Karnal	10.4	6.8	3.8	34.6	63.5
	4.3	4.3b	Kanpur	9.5	4.5	2.8	52.1	70.5
	9.2	9.2a	Pantnagar	9.0	5.5	4.2	38.9	53.2
	9.2	9.2a	Faizabad	9.2	4.1	3.2	55.4	65.2
	9.2	9.2b	Varanasi	9.1	4.2	2.8	53.8	69.2
Wheat	9.1	9.1b	Ludhiana	7.9	4.7	4.3	40.5	45.6
	4.1	4.1b	Karnal	7.3	4.6	3.6	37.0	50.7
	4.3	4.3b	Kanpur	7.0	4.6	2.8	34.3	60.0
	9.2	9.2a	Pantnagar	6.5	3.9	4.2	40.0	35.4
	9.2	9.2a	Faizabad	7.0	3.8	3.2	45.7	54.3
	9.2	9.2b	Varanasi	6.7	3.4	2.8	49.2	58.2

*Source: Singh⁴⁷; AESR, Agroecological sub-region⁴⁸.

as 6 (ref. 28). This ESP value is low when compared with the minimum value of 15 adopted by USDA as the criterion for a sodic soil²⁵. Research efforts in India^{24,26,27} and Australia²⁹ have suggested that an ESP much lower than 15 seriously affects physical properties of swelling clay soils. It has been reported that sHC of 10 mm h⁻¹ represents the lower limit for a satisfactory physical condition in highly smectitic shrink–swell soils where Mg²⁺ ions behave negatively^{26,27}. This strongly suggests that sHC alone is a better diagnostic soil parameter than ESP in view of its considerable relevance in use and management of Vertisols in sub-humid to arid climates. Studies³⁰ indicated that an optimum yield of cotton in Vertisols of Central India can be obtained when the soils are non-sodic (ESP < 5) and have sHC ≥ 20 mm h⁻¹. Furthermore, about 50% reduction in yield occurs when soils are sodic (ESP > 5), having sHC < 10 mm h⁻¹, which is substantiated by the following examples.

Akola, Amravati and Nagpur districts of Maharashtra represent the sub-humid dry to semi-arid moist bioclimatic zones and belong to contiguous AESRs 10.2 and 6.3. The water balance from these districts, based on climatic data (30 years) indicates that the length of growing period (LGPs) are 150, 152 and 183 days respectively³. Both Amravati and Akola districts have shorter humid periods (6 days) and length of growing periods. Under similar soil management in deep cracking clay soils (Vertisols) having similar soil moisture and temperature regimes, yield of cotton (seed + lint) was found better in soils of Nagpur (1.0–1.8 t ha⁻¹), Amravati (0.6–1.7 t ha⁻¹) and Akola (0.6–1.0 t ha⁻¹). This happened in spite of similar LGP (152–158 days). The subsoils in the western part of Amravati and Akola districts are becoming sodic due to accelerated rate of formation and accumulation of pedogenic CaCO₃ (ref. 31). This impairs hydraulic conductivity of Vertisols, which affects cotton yield³. This relation exists despite the fact that both the soils have

considerable amount of AWC³, which has no practical relevance in releasing water between the rains under SAT environment. Thus for raising suitable crops, knowledge of the antecedent soil water after the cessation of rain becomes important. This particular scenario demands a revised concept for quantification of LGP to make it more reliable and comprehensive as crop-linked soil–climate parameter.

Deep and cracking clay soils (Vertisols) at Sokhda and Semla in Gujarat represent semi-arid (dry) and arid (dry) bioclimatic zones (AESR 5.1) and are cultivated for cotton. Despite climatic aridity-related soil degradation³², cotton yields are 1.8–2.0 t ha⁻¹ in Sokhda and Semla, which are comparable to similar crop performance in wetter parts of the country represented by AESRs 10.2 and 6.3. Presence of Ca-zeolites in the drier parts creates a better sHC and thus acts as natural soil modifier to ward-off the adverse effects of Na⁺ ions. The improved sHC and better storage of soil water and its release between the rains under SAT environment helps produce crop yield similar to wetter climate³³. The example of Jhalipura soils of Rajasthan that grow wheat is worth mentioning. Under semi-arid dry bioclimate, these soils support a wheat yield of 4.5 t ha⁻¹, which is almost comparable to Punjab and Haryana. Presence of zeolites helps attain a bumper crop and thus can overcome the adverse climatic conditions of SAT. This shows that different AESRs, can capture similar performance of cotton in Vertisols under the favourable influence of soil modifiers like Ca-zeolite. Examples shown here indicate how a natural modifier can help cut across the boundaries of AESR, if crop performance is considered as an important parameter. This suggests that assuming a value of 100 mm (ref. 34) as the quantified moisture stored in shrink–swell soils after rains for estimating LGP is inappropriate. Instead, antecedent soil moisture after the cessation of rains becomes essential while estimating the LGP.

Generation of new data

Soil database

The state soil resource mapping project completed by NBSS&LUP on 1 : 250,000 scale forms a major source of information on soils. The association of more than one soil type in a polygon is representative of one dominant and another sub-dominant unit in a polygon. Normally, if there are two soil associations in a polygon, the dominant and sub-dominant occupy 60% and 40% each; in the case of three associations, the dominant occupies 50% and sub-dominant 30% and 20% respectively. The raster map also contains a unit defined as miscellaneous land unit or 'non soil' unit, viz. rock outcrops, rocky land, marshy land, land occupied by rivers and glaciers. In updating the present soil map, various other datasets for India that are available in the world, such as FAO/UNESCO digital soil map of the world³⁵⁻³⁷ were also referred. NBSS&LUP's SOTER data developed in GeoSIS Project³⁸ were useful for the present study. At a small scale, the location of individual soil types cannot be delineated; therefore, the database in the polygon represents the location of groups of soil types known as soil association, also referred to as soil mapping unit. The criteria for soil association and soil mapping unit delineations reflect the pedological relationship within the landscape.

Data processing

In the first step, raster database on 1 : 250,000 scale was converted into vector polygons to facilitate cartographic generalization, like merging of soil polygons with similar soil properties. Micro polygons, corresponding to a terrain, were merged with adjacent and large soil polygons. The soil polygons smaller than 0.25 cm (ref. 39) were retained as inclusions for the legibility of the map. At this stage, coarser information from FAO/UNESCO/ISRIC map was referred to.

In the second step, point (pedon) data was first georeferenced using the *Google Earth* map (datum WGS 84). The state/district boundaries were put on the map to retain the accuracy of the location of the point data. Raster point data were polygonized on ArcInfo platform. The soil polygon, physiography map (NATMO)⁴⁰ and ASTER DEM (30 m resolution) data were harmonized for correction of soil polygon boundaries. Thus the total number of unique polygons developed for IGP and BSR were 349 and 282 respectively, in the revised 1 : 1 million soil map (Figure 2).

We worked in the IGP with 417 soil pedon data (point) to cover an area of 52.01 m ha, where each pedon represents 1.2 lakh ha. The BSR, on the other hand, is represented by 425 pedons covering an area of 76.4 m ha, where each pedon covers an area of 1.8 lakh ha. Most of the

pedons represent the benchmark (BM) soils of the IGP and BSR. The other pedon data are collected from district and watershed/village reports on 1 : 50,000 scale or larger ones surveyed by NBSS&LUP from time to time.

Computation of length of growing period

In the FAO method, the LGP is computed from monthly/decade precipitation (P) and potential evapotranspiration (PET)⁴¹. Reassessment of LGP values in the BSR is necessary due to various reasons which require explanation. Available water holding capacity of soils was computed considering the available water of all the soil layers to a depth of 1 m or up to least permeable layer (sHC < 10 mm h⁻¹). Some of the measured sHC of the pedons (Table 2), indicated that the values vary from 4 to

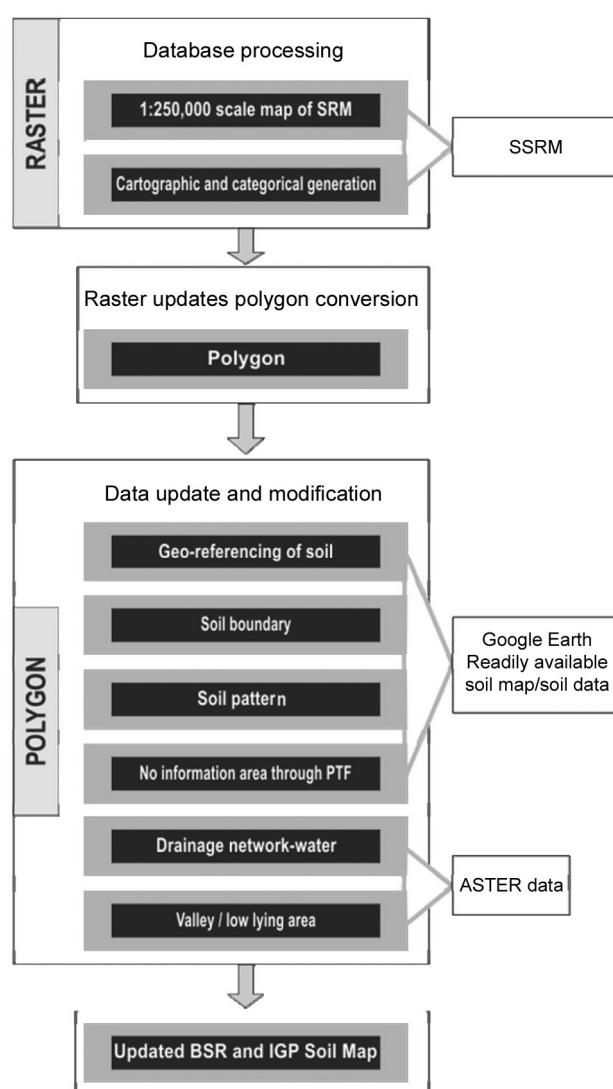


Figure 2. Flow chart showing different steps of database processing for soil map preparation.

Table 2. Selected physical characteristics of representative soils from BSR*

Horizon	Depth (cm)	AWC (%)	HC (mm h ⁻¹)	Size class and particle diameter (mm)
				Total clay (<0.002)
Nagpur: Very fine, smectitic, hyperthermic Typic Haplusterts				
Ap	0–13	12.5	20.3	61.2
A12	13–28	13.8	18.9	62.6
Bw	28–50	14.2	18.2	63.0
Bss1	50–75	18.0	17.3	65.0
Bss2	75–102	19.0	16.2	66.0
Bss3	102–126	18.1	16.2	65.0
Bss4	126–144	20.4	4.9	65.7
BC	144–160	19.3	4.5	64.4
Nagpur: Very fine, smectitic, hyperthermic Typic Haplusterts				
Ap	0–16	22.9	21.8	64.8
Ap1	16–30	16.1	19.8	65.6
A12	30–46	18.7	18.3	66.5
Bw	46–66	20.6	16.8	68.2
Bss1	66–98	21.2	16.9	69.4
Bss2	98–111	21.4	15.4	69.8
Bss3	111–149	22.7	14.3	70.0
BC	149–164	17.4	12.8	59.2
Amravati: Very fine, smectitic, hyperthermic Aridic Haplusterts				
Ap	0–14	15.1	6.9	53.0
Bw1	14–36	17.2	1.8	51.1
Bw2	36–60	15.6	0.9	55.1
Bss1	69–120	13.3	0.1	53.4
Bss2	120–140	12.7	0.2	52.9
Bss3	140–155	13.0	0.1	56.3
Amravati: Very fine, smectitic, hyperthermic Sodic Haplusterts				
Ap	0–12	15.8	8.3	66.3
Bw1	12–41	14.6	7.5	68.2
Bss1	41–60	19.3	2.7	65.3
Bss2	60–86	19.9	1.9	72.5
Bss3	86–112	19.3	0.5	69.2
Bss4	112–150	20.1	0.5	71.3
Akola: Very fine, smectitic, hyperthermic Aridic Haplusterts				
Ap	0–14	16.8	4.0	69.6
A12	14–27	16.3	5.0	69.3
Bss1	27–57	17.4	2.6	72.2
Bss2	58–135	21.2	1.7	70.3
BC	135–150	18.6	2.4	56.8
Akola: Very fine, smectitic, hyperthermic Sodic Haplusterts				
Ap	0–21	20.0	3.0	61.8
Bw	21–69	17.1	0.8	65.3
Bss1	69–113	19.5	0.3	66.8
Bss2	113–142	20.2	0.3	59.1

*Source: Kadu *et al.*³². AWC, Available water capacity; sHC, Saturated hydraulic conductivity.

20 mm h⁻¹ and rapidly decrease with depth, even though the clay content with soil depth is almost uniform³⁰. The sHC values of soils of Amravati and Akola are in the range < 1–12 mm h⁻¹ (Table 2). The Bss (slickensides) horizons of soils of Amravati and Akola having ESP 6 and sHC < 1 mm h⁻¹ indicate very poor internal drainage conditions. Such conditions occur in similar soils, even at an ESP values as low as 5 (ref. 30). It is noticed that, for two different subgroups of Vertisols, viz. Typic Haplustert and Aridic/Sodic Haplusterts, there is a difference of

20 days in LGP, although both the soils occur in the same bioclimate. This suggests that there is a need for correcting LGP and in turn AESRs.

Estimation of sHC

The soil–moisture dynamics is greatly influenced by sHC, which in turn is affected by physical and chemical properties of soils with special reference to ESP. Besides,

Georeferenced SIS for agricultural LUP

Table 3. Soil drainability limits for black soils with typical mineralogy

Soil class (mixed characteristics)*	Type	Lower drainability limit (kPa)**	Suggestions
Typic Haplusterts***	Non-sodic Non-zeolitic Non-palygorskitic	1500	Farmers may venture double cropping
Typic Haplusterts (palygorskitic)	–	1500	Single crop
Sodic Haplusterts (non-zeolitic)	–	1500	Single crop
Sodic Haplusterts (zeolitic)	–	1500	Single crop

Source: Bhattacharyya *et al.*¹⁹.

*Mixed in terms of various minerals present other than smectite as the dominant phyllosilicate mineral.

**Presence of high level of sodium and palygorskite will reduce water-holding capacity. However, Ca-zeolite may mask the effect of high Na, making these soils similar to normal black soils.

***These soils do not contain soil modifiers, viz. zeolites and palygorskite.

Table 4. Saturated hydraulic conductivity, length of growth period (LGP) and crop performances of BSR

District	Pedon no.	Soil taxonomy	AWC (%)	sHC (mm h ⁻¹)	ESP	Exch. Ca/Mg	Cotton yield (q ha ⁻¹)	LGP*
Nagpur	1	Typic Haplustert	19	7.7	1.2	2.1	13	210
	2	Typic Haplustert	18	7.6	4.6	1.6	17	210
	3	Typic Haplustert	16	17.8	2.6	1.7	13	210
	4	Typic Haplustert	20	4.2	11.2	2.0	9.5	160
Amaravati	9	Sodic Haplustert	18	8.8	15.7	3.2	7.5	150
	10	Aridic Haplustert	20	18.7	4.3	3.6	15	170
	11	Aridic Haplustert	13	15.7	0.8	3.3	16.6	160
	12	Aridic Haplustert	10	9.8	1.3	2.7	6.6	150
Akola	28	Aridic Haplustert	17	3.5	6.7	3.6	10	150
	29	Sodic Haplustert	18	1.1	19.9	3.7	6.4	135

Source: Kadu *et al.*³⁰. *The AWC dictates the quantum of moisture to be added after humid period ($P < PET$; P , Precipitation; PET = Potential evapotranspiration). ESP, Exchangeable sodium percentage.

soil modifiers, viz. gypsum and Ca-rich zeolites also influence soil moisture. Moreover, routine soil survey reports do not generally indicate sHC values. Keeping these points in view, sHC of some soils were estimated using standard methods and also through pedotransfer functions (PTFs), wherever such data were not available.

sHC of the IGP soils

Soil information of 100 layer observations from 30 pedons, representing soils of the IGP were used in developing PTF. The relevant soil parameters, viz. sand, silt, clay, pH, organic carbon (OC), water dispersible clay (WDC), ESP and BD, were selected as the predictor variables. Impairment of drainage in the soils of the IGP is caused by increased BD in the subsurface soils resulting from use of heavy farm implements. Therefore, BD is considered as one of the predictors. Stepwise regression analysis was carried out using SPSS to determine the best-fit regression model with the soil parameters like sand, ESP and BD as predictors with R^2 value of 0.65 and expressed as⁴²

$$\text{sHC (mm h}^{-1}\text{)} = 4.14 + 0.048 \times (\text{sand}\%) - 0.041 \times (\text{ESP}\%) - 2.340 \times (\text{BD}).$$

sHC of the BSR soils

The information on physical and chemical properties of cracking clay soils was collected from 62 pedons from Central India. Out of 62 pedons, 39 pedons showing 200 horizon descriptions were used to develop the PTF for sHC in non-zeolitic soils and 13 pedons with 64 layers in zeolitic soils. The soil parameters influencing, sHC, viz. silt, clay, pH, OC, CaCO₃, ESP, EMP, exchangeable calcium percentage (ECP) and exchangeable Ca/Mg were selected as the predictor variables. The best-fit regression model with the soil parameters like clay, pH and exchangeable Ca/Mg as predictors ($R^2 = 0.67$) is expressed as

$$\text{sHC (mm h}^{-1}\text{)} = 120.637 - 13.094 \times (\text{pH}) - 0.102 \times (\text{clay}\%) + 1.151 \times (\text{exchangeable Ca/Mg})$$

(for non-zeolitic soils), and

$$\text{sHC (mm h}^{-1}\text{)} = 108.098 - 12.171 \times (\text{pH}) + 0.715 \times \text{CaCO}_3; R^2 = 0.645 \text{ (for zeolitic soils).}$$

LGP for some typical locations was re-calculated, based on soil drainability limits (Table 3) and observed crop performance in typical soils with measured sHC (Table 4). LGP was computed from drainage map to arrive at AWC for black soils on the basis of observed crop performance

in the field (Table 4). Earlier 100 mm of soil moisture was uniformly used to estimate LGP, when the rainfall is less than PET at the end of the rainy season. Presently, the difference between actual moisture available between upper and lower drainability limits, is used for the computation of LGP (Table 4). Modification of AESR for the IGP and BSR involves modification of soil map, hydraulic conductivity map, AWC and LGP computation (for BSR only; Figure 3).

Results and discussion

Distribution of soils in IGP

Climatically IGP covers part of arid (≈ 218 mm) rainfall in the west to humid to perhumid (>2800 mm) in the east. Over time, differences in precipitation have contributed to variety of soils in the plains. The dominant soils represent Entisols, Inceptisols and Alfisols⁴³, of which Inceptisols account for 34.2 m ha, followed by Entisols (14.0 m ha), Alfisols (2.1 m ha), Aridisols (1.2 m ha) and Vertisols (0.5 m ha). Traditionally, IGP is dominated by alluvial soils (35.2 m ha) and terai soils (0.06 m ha). The soil map of IGP shows 51 soils, at great group association (Figure 4) with 349 polygons. The IGP data-set on soils has been further strengthened by 417 georeferenced pedon data. Nearly 10% area of the IGP has favourable BD (<1.6 Mg m⁻³; Table 5). At places, BD increases as a result of mechanized farming and use of poor quality of irrigation water. In general, soils having sHC <2 mm h⁻¹ favour rice farming.

For the IGP, LGP has not been computed, because most of the area is irrigated. Instead, only areas with poor drainage were used for refining AESR boundaries, using revised soil polygon data.

Generating sHC map

sHC map is prepared from selected observation points and values obtained from PTFs. The point data were

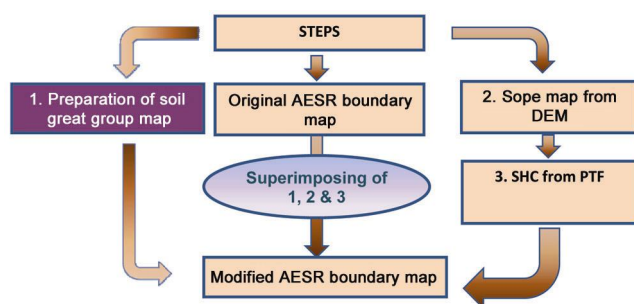


Figure 3. Schematic diagram showing different steps to modify agro-ecological sub-region (AESR) boundaries to generate revised AESR map.

polygonized in GIS platform with maximum correlation value (Figure 5). This exercise yielded different types of soil drainage conditions. These are well-drained (41.4%), moderately well-drained (23.1%) and poorly to imperfectly drained (26.2%) soils, which may be defined as land quality, and hence sHC can be used as single soil quality parameter in understanding the soil–water–plant interface.

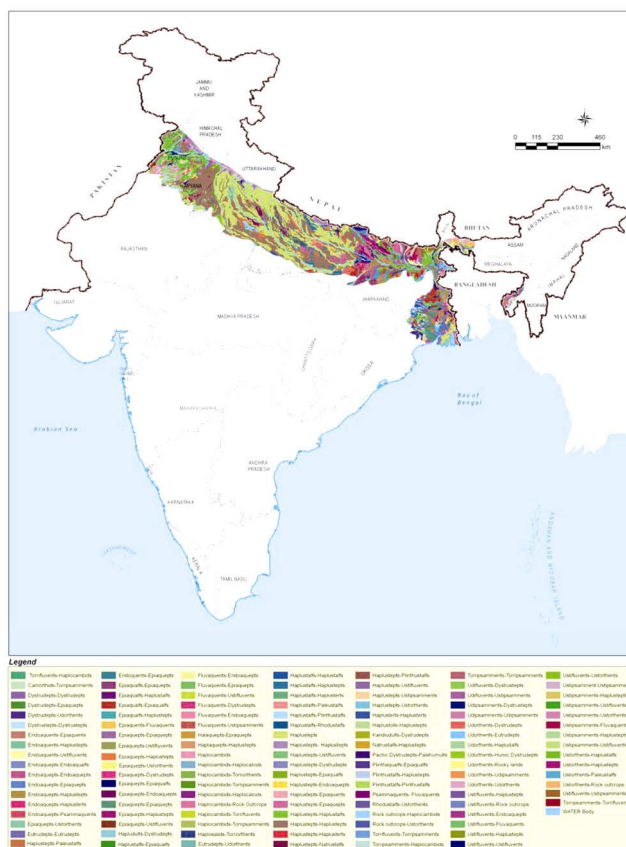


Figure 4. Revised soil map of IGP.

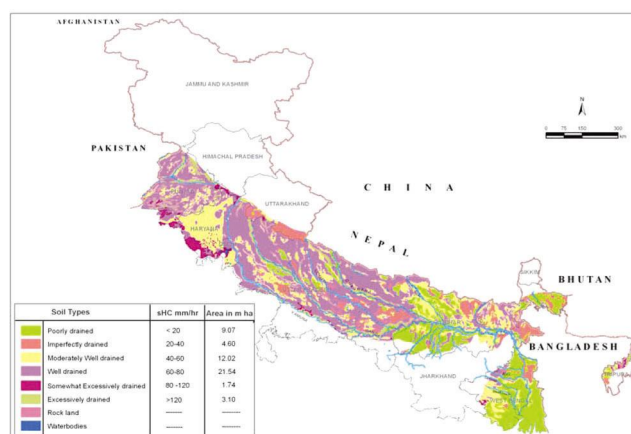


Figure 5. Saturated hydraulic conductivity map of IGP.

Georeferenced SIS for agricultural LUP

Table 5. Physical properties of Itwa (Uttar Pradesh; typic Natrustalfs) soils representing sub-humid bioclimatic system

Horizon	Depth (cm)	Size class and particle diameter (mm)			BD (Mg m ⁻³)	Water retention (kPa)	
		Total				33	1500
		Sand (2–0.05)	Silt (0.05–0.002)	Clay (<0.002)			
Ap	0–18	50.93	33.82	15.22	1.44	25.90	10.35
Bt1	18–46	37.69	32.31	30.00	1.68	25.39	12.54
Bt2	46–68	29.95	35.05	35.00	1.55	27.17	16.68
Bt3	68–87	24.87	44.38	30.75	1.47	30.38	12.72
BCK1	87–114	27.62	43.63	28.75	1.54	28.21	11.49
BcK2	114–130	15.43	58.32	26.25	1.52	31.85	10.32

BD, Bulk density.

Table 6. Distribution of black soils representing different soil orders in US soil taxonomy in BSR

Order	Area (m ha)	Percentage of total area
Vertisols	27.4	35.8
Inceptisols (Vertic)	39.7	51.9
Entisols (Vertic)	4.4	5.8
Others	4.9	6.5

Table 7. State-wise distribution of black soils in India

State	Earlier estimate* (m ha)	Revised estimate	
		m ha	Percentage
Maharashtra	24.18	20.63	27.0
Madhya Pradesh	21.16**	16.27	21.3
Gujarat	4.88	8.79	11.5
Karnataka	5.79	7.03	9.2
Andhra Pradesh	9.43	5.42	7.1
Chhattisgarh	–	4.28	5.6
Odisha	0.09	1.91	2.5
Rajasthan	1.10	1.91	2.5
Tamil Nadu	2.65	1.53	2.0
Uttar Pradesh	1.14	2.37	3.1
Bihar	0.08	0.08	0.1
Punjab	–	2.29	3.0
West Bengal	–	0.23	0.3
Jammu and Kashmir	–	0.08	0.1
Assam	–	0.0008	0.001
Kerala	–	0.08	0.1
Haryana	0.01	3.59	4.7
	70.50	76.4	100

*Bhattacharyya *et al.*⁴⁴. **Area includes Madhya Pradesh and Chhattisgarh.

Distribution of soils in BSR

Black soils (76.4 m ha) are common in the SAT, having their genesis in India mainly from basalt, although their presence in humid and arid bioclimates is not uncommon^{44,45} (Figure 6). These soils are associated with red soils and thus form a major soil group of India⁴⁶ (Table 6).

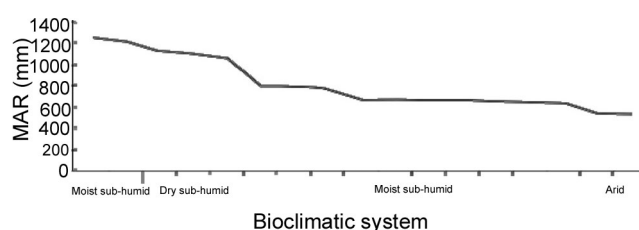


Figure 6. Distribution of black soils in different bioclimatic system. MAR, Mean annual rainfall.

The state-wise areal distribution of black soils (Figure 7 and Table 7) indicates that the highest area occupied by black soils is in Maharashtra (27%), followed by Madhya Pradesh (21%), Gujarat (11%), Karnataka (9%), Andhra Pradesh (7%) and Chhattisgarh (6%). Georeferencing of 425 pedon sites in the BSR indicates that black soils extend to West Bengal, Punjab, Assam, Jammu and Kashmir, Tripura and Kerala in patches with 284 soil mapping units (sub-group association)^{44,45}. The map also indicates that there are some areas which are not part of the Deccan Plateau; yet they have good coverage of black soils. These are Bihar (3.1%), Uttar Pradesh (2.4%) and West Bengal (3.0%), which are part of the Ganga and the Brahmaputra valley. The present findings on the occurrence of the black soils in non-basaltic area open scope for investigation for their genesis and their potential for use in such humid environments.

Generating map on length of growing period

The PTFs developed were used to generate quantitative drainage maps of BSR and IGP, and utilized for the modification of LGP and in the revision of AESR boundaries. The revised LGP values as point data representing different locations were georeferenced in ArcGIS to develop the map of LGP. The points were attached to their respective computed LGP with the help of krigging, isolines, manual and different combinations. The earlier map shows that major parts of the Deccan Peninsula are covered by

LGP of 150–180 days. However, the updated map (Figure 8) indicated that the semi-arid (Bellary, Anantapur) area of the Deccan Plateau (AESR 3.0), has LGP of < 90 days. Now the latter can be divided into two LGP classes, viz. < 90 and 90–120 days respectively. The modified LGP map also showed that the Peninsular India could be culled out into several LGP classes. But, due to scale limitation, they cannot be shown precisely according to their area. Some revised LGP computations are presented in Table 8.

Modification of AESR boundaries

The Indo-Gangetic Plains: Using the AESR modification flow diagram, several AESRs have been modified (Figure 9; Table 9). In the previous AESR map, the IGP was divided into 17 sub-regions between Punjab and West Bengal and Tripura. When the AESR map was superimposed on the newly created soil datasets (1 : 250,000) and the sHC map, it was observed that AESR 2.1 occupying (0.13 m ha) is covering well to excessively drained soils. AESR 2.3 has now been further sub-divided into AESR 2.3a and 2.3b. ASER 2.3a with total area of 2.49 m ha has well-drained to excessively drained sandy soils covering southwestern Punjab and Haryana plains

(parts of Hisar, Bhiwani and Mahaendragarh districts). AESR 2.3b is characterized by highly calcareous sandy soils occupying a small area of 0.16 m ha in Firozpur, Faridkot and Bathinda districts of Punjab. Climatically, both the sub-regions belong to arid type.

AESR 4.1 covers North Punjab plains and Ganga–Yamuna Doab. This is sub-divided into AESR 4.1a, 4.1b and 4.1c. ASER 41a with deep, alluvium-derived loamy soil, is well-drained with pockets of imperfectly drained soils; it is seen in Muzaffarnagar (part), Meerut, Ghaziabad, Bulandshahar, Aligarh, Etah, Firozabad, Mainpuri, Agra and Mathura districts of Uttar Pradesh with a total area of 2.83 m ha. AESR 4.1b consists of well-drained loamy soils with salinity and sodicity as seen in Sonipat, Rohtak, Panipat, Jind, Karnal, Kaithal districts of Haryana, and Delhi with a total area of 2.83 m ha. AESR 4.1c characterized by well-drained soils covers the northern fringe of the Punjab plains with an area of 2.54 m ha in Sangrur, Ludhiana, Ferozpur, Amritsar and Patiala (part) districts of Punjab. Climatically, AESRs 4.1a–c fall under semi-arid (moist) type.

AESR 4.3 covering Ganga–Yamuna Doab, Rohilkhand and Avadah plains (moist semi-arid climate) has been divided into AESR 4.3a and b. AESR 4.3a dominated by black soils occurring in a narrow strip of Bhind district, Madhya Pradesh with an area of 0.58 m ha. AESR 4.3b comprises deep alluvium-derived, well to imperfectly drained loamy soils covering an area of 6.32 m ha in Badaun, Shahjahanpur, Farrukhabad, Hardoi, Jaunpur, Raebareli, Pratapgarh, Unnao, Allahabad, Fatehpur, Varanasi, Etawah, Kanpur, Uttar Pradesh. The Bijaipur series (Haplustepts) represent the BM soils in this sub-region. However, some of the soils have low sHC and are imperfectly drained, represented by Sakit series (Natrustalfs).

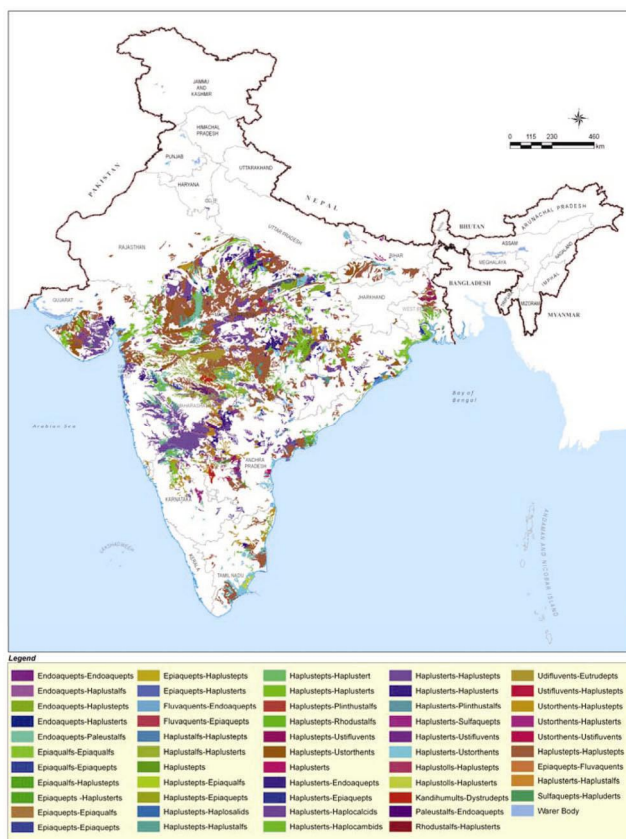


Figure 7. Revised soil map of the black soil region.

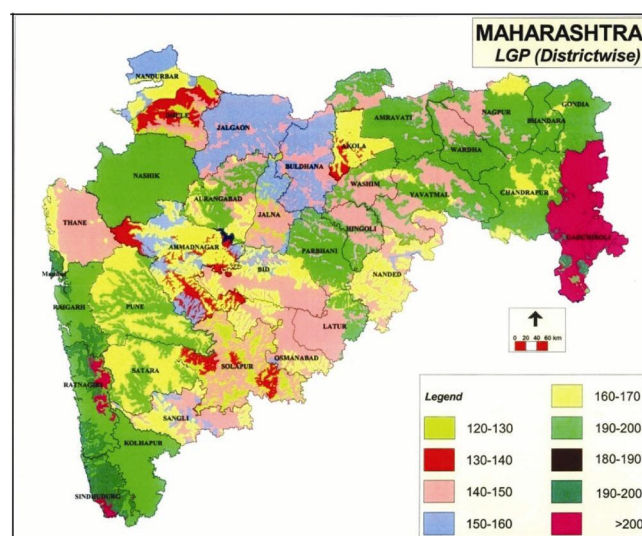


Figure 8. Revised map of Maharashtra showing variation in length of growing period (days).



Figure 9. Revised map showing different AESRs of IGP (also see Table 9).

Table 8. Revised length of growing period in selected agro-ecological sub-regions in BSR

AESR no.	Earlier LGP class (days)	Revised LGP (class days)	Remarks
3.0 (arid)	60–90	< 90	Dominantly well-drained red loamy soils
		90–120	Dominantly moderately well-drained black soils with zeolites
5.2 (semi-arid)	120–150	120–150	Poorly drained alluvium-derived soils of Sabarmati flood plain
		150–180	Well-drained black soils with zeolites
6.1 (semi-arid)	90–120	120–150	Well-drained shallow black soils
		150–180	Dominantly well-drained shallow soils, some soils with salinity and sodicity problems and also contain minerals like palygorskite
		150–180	Well-drained black soils with zeolites
6.2 (semi-arid)	120–150	150–180	Moderately well-drained black soils
		180 +	Poorly drained black soils
		180–210	Mixed red and black soils

AESR 9.1 covering Punjab and Rohilkhand plains, has been sub-divided into AESR 9.1a–c. AESR 9.1a represents deep alluvium-derived, well-drained loamy soils (1.90 m ha) in the districts of Saharanpur, Bijnor, Moradabad and Muzaffarnagar of Uttar Pradesh. AESR 9.1b covers an area of 0.49 m ha in Ambala, Kurukshetra, Karnal and Yamunanagar districts in Punjab. AESR 9.1c, mainly deciphered on the basis of soil characteristics, covers an area of 1.50 m ha in the districts of Gurdaspur, Hoshiarpur, Rupnagar, Patiala, Jalandhar and Ludhiana in Punjab. These sandy soils are deep, well-drained and comprise Sadhu (Vertic Haplustalfs) and Nabha (Udic Haplustalfs) series.

AESR 9.2 of Rohilkhand, Avadh and south Bihar plains (hot, dry sub-humid) has been divided into AESR 9.2a–c. ASER 9.2a covers an area of 2.09 m ha in the districts of Rampur, Pilibhit, Kheri, Sitapur in Uttar Pradesh. These

are deep, well-drained, loamy soils developed in alluvium (Haplustepts). AESR 9.2b is distinguished on the basis of drainage condition of the soils and is represented by Itwa soils (Aeric Endoaqualfs), which are imperfectly drained with low subsoil permeability. They cover part of Faizabad, Lucknow, Barabanki, Sultanpur, Azamgarh, Ballia, Ghazipur and Varanasi districts in Uttar Pradesh with a total area of 4.17 m ha. Soil of AESR 9.2c covers Bhojpur, Rohtas, Jahanabad, Patna, Nalanda, Aurangabad, Gaya and Nawada districts (2.64 m ha of Maharashtra). It is comprised of deep, well to imperfectly drained loamy soils.

AESR 13.1 occupies North Bihar and Avadh plains characterized by moist, sub-humid climate. This AESR has been subdivided into AESR 13.1a and 13.1b. ASER 13.1a occurs in Purab and Paschim Champaran, Gopalganj, Siwan, Muzaffarpur, Sitamarhi, Madhubani,

Table 9. Modification of agro-ecological sub-regions in the IGP: criteria and justification

Old AESR (LGP, days)	Revised AESR	Area (m ha)	Soils	Criteria for modification ^a	Average crop (rice) yield (t/ha) 2007–13	Justification ^b
2.1 (<60)	–	0.13	Well to excessively drained, sandy soil	See ^b	>4	Old polygon boundary modified
2.3 (60–90)	2.3a	2.49	Well-drained to excessively drained, sandy soil	Soils and drainage	<2.5	AESR has been divided into two
	2.3b	0.16	Highly calcareous, sandy soils			
4.1 (90–120)	4.1a	4.08	Well-drained with pockets of imperfectly drained soils	Soils/drainage/ salinity/sodicity	2–3.0	AESR has been divided into three
	4.1b	2.83	Well-drained loamy soils with salinity and sodicity		<4.0	
	4.1c	2.54	Well-drained sandy soils		>4	
4.3 (120–150)	4.3a	0.79	Dominantly black soils, well-drained	Soils	<1.5	AESR has been divided into two
	4.3b	6.32	Well-drained loamy soils, at places imperfectly drained		1.5–2.0	
9.1 (120–150)	9.1a	2.10	Well-drained loamy soils	Soils and drainage	2.1–2.5	AESR has been divided into three
	9.1b	0.55	Loamy, well-drained with pockets of imperfectly drained soils		3.0–3.6	
9.2 (150–180)	9.1c	1.66	Sandy, well-drained soils	Soils and drainage	3.0–4.5	AESR has been divided into three
	9.2a	2.09	Well-drained, loamy, alluvial soils		1.8–2.0	
	9.2b	4.17	Well to imperfectly drained, loamy alluvial soils		2.0–2.5	
	9.2c	2.64	Imperfectly to poorly drained, alluvial soils		>2.5	
12.3 (180–210)	12.3		Well-drained loamy soils with moderate to severe erosion, at places poorly drained (cracking) clay soils	See ^b	2.4–2.7	Old polygon boundary modified
13.1 (180–210)	13.1a	6.12	Imperfectly to poorly drained, loamy (at places clay) soils, pockets of moderate to severe flooding and slight salinity	Soils and drainage	0.5–1.5	AESR has been divided into two
	13.1b	2.82	Well-drained, loamy soils		1.6–2.0	
13.2 (180–210)	13.2	1.33	Well drained, loamy soils	–	2.0–<3	No changes were made
14.2 (150–210)	14.2		Deep, well-drained loamy (calc) to sandy well-drained soils	See ^b	3–4	Old polygon boundary modified
14.5 (210–240+)	14.5		Deep to moderately deep well drained loamy soils	See ^b	–	Old polygon boundary modified
15.1 (210–240)	15.1a	4.32	Imperfectly to poorly drained loamy/clay soils with moderate flooding	Soils and drainage	1.0–2.0	AESR has been divided into two
	15.1b	0.44	Poorly drained, loamy soils with severe flooding		<3	
15.3 (270–300)	15.3a	0.57	Poorly to imperfectly drained soils with occasional flooding	Soils and drainage	<3.0	AESR has been divided into two
	15.3b	0.79	Well-drained with patches of poorly drained soils		–	
16.1 (> 300)	16.1		Deep, poorly drained loamy soils	See ^b	>3.0	Old polygon boundary modified
16.2 (> 300)	16.2		Deep, imperfectly to poorly drained loamy soils with occasional flooding	See ^b	–	Old polygon boundary modified

(Contd)

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Table 9. (Contd)

Old AESR (LGP, days)	Revised AESR	Area (m ha)	Soils	Criteria for modification ^a	Average crop (rice) yield (t/ha) 2007–13	Justification ^b
17.2 (> 300)	17.2		Deep, well-drained to excessively drained loamy soils with moderate to severe erosion valleys with poorly drained loamy soils with severe flooding	See ^b	–	Old polygon boundary modified
18.5 (240–270)	18.5a	0.83	Poorly drained, clay loamy soils with severe flooding and salinity	Soils and drainage	>2.5	AESR has been divided into two
	18.5b	0.36	Imperfectly to poorly drained loamy/clay soils with moderate flooding and salinity		>2.0	

^aCriteria as soils indicate various colour, texture, drainage and length of growing period.

^bFor these AESRs, boundaries of the polygons were revised keeping in view the administrative boundaries and at places physiography, due to lack of sufficient soil data. Therefore these AESRs were not further sub-divided.

Darbhanga, Samstipur, Purnia, Saharsa and Katihar districts in Uttar Pradesh covering an area of 6.12 m ha. This sub-division is mainly based on drainage condition of soils. The soils are deep, imperfectly to poorly drained, loamy with moderate to severe flooding and slight salinity. The soils are Halaquepts, Haplaquepts and Haplustepts.

AESR 13.1b covers Avadh plains in Bahraich, Gonda, Basti, Gorakhpur, Deoria, Basti, Faizabad, Siddhartha Nagar and Maharajganj of Uttar Pradesh. These deep, well-drained, loamy soils cover an area of 2.82 m ha. The soils of the sub-region are represented by Kesarganj series (Typic Ustifluvents), which are highly calcareous and base saturated.

AESR 15.1 (Bengal Basin) is characterized by transition from sub-humid to humid climate. It has been sub-divided into 15.1a and 15.1b, on the basis of sHC. AESR 15.1a has deep, imperfectly to poorly drained loamy soils (at places clayey) with moderate flooding. It is seen in Uttar and Dakshin Dinajpur, Maldah, Bardhamam, Baharampur, Nadia, Hughly, Haora and parts of Medinipur districts in West Bengal (4.32 m ha). The region is represented by Kanagarh (Aeric Fluvaquent), Madhpur and Kuldiha (Typic Endoaqualfs) soils. AESR 15.1b covers parts of North and South 24 Parganas in West Bengal with an area of 0.44 m ha. The soils are deep, poorly drained, with severe flooding characteristics and are classified as Eutropepts, Ochraqualfs and Fluvaquents.

AESR 15.3 is represented by the Teesta and Barak valley soils. Climate here varies from humid to perhumid. AESR 15.3 has been divided into AESRs 15.3a and 15.3b. AESR 15.3a soils cover Jalpaiguri, Darjeeling and Koch Bihar in West Bengal and they are characterized by poor to imperfectly drained soils (Barak and Seoraguri series, a Halaquepts) with total area of 0.57 m ha and occur on nearly level to low-lying areas. The soils are developed on alluvial flood plains and are clayey and acidic in reaction. These are represented by Dharaichherra soils (Typic Endoaquepts) with occasional flooding.

They are acidic soils with pH < 5.0. AESR 15.3b is represented by deep, well-drained and poorly drained soils (in patches) in North Tripura district with total area of 0.79 m ha.

AESR 18.5 represents the soils of Deltaic Gangetic plains which occur in transitional zone between sub-humid and humid climate. AESR 18.5a covers the deltaic region of the Ganga in the districts of North and South 24 Parganas. The deep, poorly drained clayey soils are subjected to severe flooding and salinity. These soils originated from coastal and deltaic alluvium and are classified as Haplaquepts, Tropaquepts, Ochraqualfs and Haplustepts. The Motto (Vertic Halaquepts) and Sagar (Typic Haplaquepts) series represent the sub-division. AESR 18.5b covers an area of 0.36 m ha in the coastal part of Medinipur district; it is represented by deep, imperfectly to poorly drained, loamy to clayey soils with moderate flooding and salinity. The bifurcation of AESR (newly added 12) of the IGP into different sub-divisions vis-à-vis realized yield indicated that the bifurcation is fully justified. However, further studies are necessary at micro level to strengthen the new sub-divisions of AESR.

Black soil region

The earlier AESR map shows the distribution of 27 AESRs in BSR. AESR 3.0 of the Deccan Plateau, characterized by 60–90 days of LGP in arid climate is composed of loamy to clayey red and black mixed soils. This class has been modified into AESR 3.1 and 3.2. AESR 3.1 spread over Bijapur district (part) of Karnataka is characterized by dominantly black soils with LGP of 90–120 days. AESR 3.2 observed in parts of Raichur, Bellary districts in Karnataka and Anantpur district in Andhra Pradesh and covering a total area of 3.08 m ha is characterized by well-drained red, loamy soils and LGP of < 90 days.

Table 10. Modification of agro-ecological sub-regions in BSR criteria and justification

Old AESR (LGP; days)	Revised (AESR)	Revised (LGP; days)	Area (m ha)	Soils	Criteria for modification ^a	Average cotton yield (kg/ha) (lint) 2007–13	Justification ^b
2.4 (60–90)	2.4a	<120	2.30	Sandy loam, well-drained soils	Soils, LGP, salinity, sodicity	701	AESR has been divided into two
	2.4b	120–150	2.58	Well-drained to moderately well-drained dominantly black soils		750–812	
3.0 (60–90)	3.1	90–120	1.56	Well-drained dominantly black soils	Soils, LGP	296–374	AESR has been divided into two
	3.2	<90	3.08	Well-drained, red loamy soils		129–299	
4.3 (120–150)	4.3a			Dominantly black soils, well-drained	Soils	–	AESR has been divided into two
	4.3b					–	
4.4 (120–150)	4.4a	120–150	2.96	Mixed red and black soils with gullied land	LGP, soils	–	AESR has been divided into two
	4.4b	180–210	2.83	Dominantly black soils		–	
5.1 (90–120)	–		3.44	Dominantly black soils	–	–	No changes were made
5.2 (120–150)	5.2a	120–150	2.24	Alluvium-derived soils of Sabarmati flood plain	LGP, soils	>300	AESR has been divided into two
	5.2b	150–180	14.72	Black soils, well-drained		<150	
6.1 (90–120)	6.1a	150–180	2.77	Black soils (shallow) loamy skeletal, well-drained	Salinity, sodicity	>300	AESR has been divided into three
	6.1b	120–150	2.38	Black soils (shallow), well-drained		200–300	
	6.1c	150–180	0.97	Black soils, well-drained		581	
6.2 (120–150)	6.2a	180–210	3.75	Mixed red and black soils	LGP, soils	200–350	AESR has been divided into three
	6.2b	150–180	9.56	Dominantly black soils		350–400	
	6.2c	180–190	2.11	Dominantly black Soils		>581	
6.3 (120–150)	6.3a	180–210	2.34	Dominantly black soils, moderately well-drained	See ^b	267–389	Imperfectly drained at places leading to water logging
	6.3b	180–210	2.73	Dominantly black soils		250–300	
6.4 (150–180)	6.4a	180–210	4.67	Red loamy soils well-drained	Soils, drainage	300–400	AESR has been divided into two
	6.4b	180–210	2.08	Black soils (calcareous), imperfectly drained		<350	
7.1 (90–120)	–	150–180	9.53	Dominantly black soils	No changes were made	250–300	Old polygon boundary modified
7.2 (120–150)	7.2a	180–210	7.19	Dominantly red soils	LGP, soils	300–400	AESR has been divided into two
	7.2b	180–190	2.77	Dominantly black soils		200–300	
7.3 (150–180)	–	150–180		Deep, well-drained calcareous clay soils with occasional flooding, at places. Deep, well-drained clayey soils.	No changes were made	>500	See ^b
8.1 (90–120)	8.1	180–210	3.37	Mixed red and black soils		250–400	Old polygon boundary modified
8.2 (120–150)	–	150–180		Deep, well-drained clayey soils with moderate to severe erosion, at places imperfectly drained calcareous soils	No changes were made	>200	See ^b

(Contd)

Georeferenced SIS for agricultural LUP

Table 10. (Contd)

Old AESR (LGP; days)	Revised (AESR)	Revised (LGP; days)	Area (m ha)	Soils	Criteria for modification ^a	Average cotton yield (kg/ha) (lint) 2007–13	Justification ^b
8.3 (120–150)	8.3a	180–210	7.38	Black soils of Cauvery Delta	Soils, LGP	>300	AESR has been divided into two
	8.3b	150–180	1.15	Red loamy soils		–	
10.1 (150–180)	–	180–210	9.24	Dominantly black soils, well-drained	Soils	–	Boundary modification based on soils
10.2 (150–180)	–	180–210	4.44	Dominantly black soils	No changes were made	>200	Old polygon boundary modified
10.3 (150 – 180)	10.3a	180–210	3.83	Black soils, well-drained	LGP, soils	–	Old polygon boundary modified
	10.3b	150–180	2.41	Red loamy soils		–	
10.4 (180–210)	–	180		Deep to very deep, well-drained to moderately well-drained clay soils with moderate to slight erosion, at places calcareous and cracking clay soils	No change were made	425	See ^b
11.0 (150–180)	11.1	210 +	9.07	Black, red and yellow sandy loam	LGP, soils	200	AESR has been divided into two
	11.2	180–210	5.12	Black soils, at places imperfectly to poorly drained		>250	
12.1 (180–210)	12.1a	150–180	3.91	Dominantly black soils of Mahanadi basin, poorly to imperfectly drained	LGP, soils	–	AESR has been divided into three
	12.1b	210 +	6.70	Mixed red loamy and black soils		–	
	12.1c	180–210	8.71	Red, sandy loam soils		–	
12.2 (180–210)	–	180 +		Deep, poorly to imperfectly drained loamy to clay soils with occasional to severe flooding. At places moderate deep, well-drained loamy soils	No changes were made	–	See ^b
18.1 (90–120)	–			Deep, well-drained calcareous clayey to loamy soils, at places imperfectly drained calcareous soils	No changes were made	100–400	See ^b
18.4 (180–210)	–			Deep, poorly to imperfectly drained clayey soils with moderate flooding and slight to strong salinity. At places, deep, well-drained soils	No changes were made	>400	See ^b
19.1 (180–210)	19.1a	180–210	1.30	Red loamy soils, well-drained, severe erosion and moderate salinity	LGP, soils	–	AESR has been divided into two
	19.1b	180–210	1.87	Calcareous, well-drained black soils, slight to moderate salinity		>300	
19.3 (240–270)	–	–		Moderately deep to deep poorly drained calcareous clay soils with slight to strong salinity. At places imperfectly drained clay soils with moderate flooding and salinity	No changes were made	–	See ^b

^aCriteria as soils indicate various colour, texture, drainage and length of growing period.

^bFor these AESRs, boundaries of the polygons were revised keeping in view the administrative boundaries and at places physiography, due to lack of sufficient soil data. Therefore these AESRs were not further sub-divided.

AESR 4.4 with LGP of 120–150 days covers Madhya Bharat Pathar (Central India Plateau) and Bundelkhand Upland. It falls in moist semi-arid climate zone and comprises deep loamy and clayey mixed red and black soils. This class is subdivided into AESR 4.4a and 4.4b. AESR 4.4a covers Morena, Shivpuri, Gwalior and Bhind districts of Madhya Pradesh with a total area of 2.96 m ha; it is composed of soils dominated by mixed red and black soils represented by Singhpura series (Typic Haplustepts) with a LGP of 120–150 days. AESR 4.4b covers the districts of Datia in Madhya Pradesh and part of Lalitpur district in Uttar Pradesh with a total area of 2.83 m ha. It is dominated by black soils showing LGP of 180–210 days.

AESR 6.1 is in semi-arid dry climate zone and is composed of black soils (deep black soils as inclusion) that have shallow to medium depth. They are seen in south-western Maharashtra plateau and are characterized by LGP of 90–120 days. AESR 6.1 has been modified to AESRs 6.1a–c. AESR 6.1a covers a total area of 2.77 m ha and LGP of 150–180 days with shallow loamy skeletal, well-drained black soils represented by Pargon (Lithic Ustorthents) and Swargaon (Typic Calcicustepts) series. AESR 6.1b occurring in Bead and Osmanabad districts in Maharashtra with a total area of 2.38 m ha is characterized by with well-drained shallow black soils with LGP of 120–150 days. AESR 6.1c with a total area of 0.97 m ha covering parts of Raichur and Bijapur districts in Karnataka, consists of medium deep black soils characterized by LGP of 150–180 days.

AESR 6.2 covers central and western Maharashtra plateau and north Karnataka plateau. It is composed of shallow, medium loamy and clayey black soils (medium to deep black soils as inclusion) with LGP of 120–150 days. This sub-region is modified to AESR 6.2a–c. The AESR 6.2a covers Dhule, Nashik and Aurangabad districts of Maharashtra (3.75 m ha), where mixed red and black soils with LGP of 180–210 days are found. AESR 6.2b covers Jalna, Parbhani and Nanded districts of Maharashtra with a total area of 9.56 m ha. The soils here are characterized LGP of 150–180 days; they are dominantly black soils. AESR 6.2c (2.11 m ha) consists of black soils with LGP 180–190 days that cover Bidar and Gulbarga districts of Karnataka.

AESR 6.3 constitutes the eastern Maharashtra plateau. It consists of medium and deep clayey black soils (shallow loamy to clayey black soils as inclusion) characterized by LGP of 120–150 days. This class has been modified to AESR 6.3a and b. AESR 6.3a covering 2.32 m ha of Jalgaon, Buldhana and Amravati districts of Maharashtra, has black soils (dominant), at places imperfectly drained (prone to waterlogging). LGP of 180–210 days is characteristic of ASER 6.3a. AESR 6.3b with a total area of 2.73 m ha and a LGP of 180–210 days consists of moderately well-drained black soils and covers Akola and Yavatmal districts of Maharashtra.

AESR 6.4 covers north Sahyadris and western Karnataka plateau with shallow and medium loamy and clayey black soils (inclusion of deep clayey black soils) and LGP of 150–180 days. This class is modified as AESR 6.4a and b. AESR 6.4a with an area of 4.67 m ha is dominated by red, loamy, well-drained soils and LGP of 180–210 days. AESR 6.4b is characterized by calcareous, black and imperfectly drained soils with total area of 2.08 m ha. Following a similar analogy AESRs 2.4, 5.2, 7.2, 8.3, 11 and 12.1 have been sub-divided. With this exercise, we could add another 18 AESRs in BSR with 45 AESRs for precise crop planning. The details of criteria for modification, area coverage and average cotton yields (2007–2011) justify further subdivision of AESRs (Figure 10 and Table 10).



Figure 10. Revised map showing different AESRs in BSR (also see Table 10).

Conclusion

The AESR maps of the two major food production regions of India, namely IGP and BSR are modified based on newly acquired soil resource database and revised LGP class with greater emphasis on soil quality parameters linked with crop performance. Using this innovative approach 17 AESRs of IGP and 27 AESRs of BSR are re-delineated respectively, into 29 and 45 sub-regions. With the availability of more soil data, especially the parameters controlling movement and storage of rainwater in soil profile, along with crop performance, the present exercise can be extended to develop the modified AESR maps for the whole country. Thus soil quality-based

AESR opens a new vistas for research to link the potential of natural resources and crop performance for better and pragmatic crop use planning in the SAT of India. Since AESR-based crop planning can help identify the exact locations for soil management interaction, this concept of agro-subregion can thus act as a technology transfer tool for agricultural land-use planning, both at regional and national level.

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